PDL HANDBOOK SERIES

Fluoropolymers Applications in Chemical Processing Industries

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Plastics Design Library

Fluoropolymers Applications in Chemical Processing Industries

The Definitive User's Guide and Databook

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Dedicated to
Ghazale and Shaila

Series Editor's Preface

This is the latest book in the PDL (Plastics Design Library) Fluorocarbon Series. The original idea for the Fluorocarbon Series was conceived in the mid-1990s. Two important rationales precipitated the development of the collection. First, there were no definitive sources for the study of fluorinated polymers that included the commercial products. A researcher seeking the properties and characteristics of fluorinated plastics did not have a book that could serve as a single-source reference. Information put out by commercial manufacturers of polymers has long been the source of choice. Second, the post-war generation (a.k.a., baby boomers) were beginning to retire, thus reducing the available knowledge in the industry and academia.

The selection of the topics for the books has been made based on the importance of the practical applications of fluorinated polymers. Inevitably, a number of fluorinated macromolecule classes that are important in their own right had to be left out of the series. In each class, the size of its audience was simply too small to meet the economic requirements of publishing.

The first two books of the series cover commercial fluoropolymers (ethylinic); the third book focuses on their applications in the chemical processing industries. The fourth book deals with fluoroelastomers, the fifth with fluorinated coatings and finishes, and the sixth book is about fluorinated ionomers such as Nafion®.

The authors of these handbooks are leaders in their fields who have devoted their professional careers to acquiring substantial expertise. Each book is a product of decades of the author's experience and several years of research into the available body of knowledge.

Our hope is that these books will meet the needs of the people who work with fluorinated polymers for any reason. Future revisions are planned to keep this series abreast of progress in these fields.

Sina Ebnesajjad

July 2004

Authors' Preface

The first two books in this series dealt with fluoropolymers manufacturing, properties, and fabrication technologies. The aim of the present book is to build upon the information in the first two books to address the use of fluoropolymers in the chemical processing industry (CPI) and other allied industries. They include food, pharmaceutical, semiconductor, and pulp and paper industries. This book is both a reference and a source for learning the basics for those involved in the entire product value chains related to the chemical industries, from fluoropolymer producers all the way to the end-users. The reader will be able to read about how the unique characteristics of fluoroplastics are utilized in the design and construction of equipment exposed to harsh chemical environments. This book offers information helpful to engineers, maintenance personnel, students, material managers, and all others involved in the chemical processing industries.

This book emphasizes the practical over the theoretical. There are numerous sources for in-depth study of topics including polymerization and the polymer science of fluoropolymers. Some of these references have been listed at the end of pertinent chapters, serving as both bibliography and additional reading sources. Review papers are particularly helpful as a starting point for finding additional sources for concentrated reading in a selected area.

The chapters of this book have been written to allow sequential and independent reference to them. Chapters 1 and 2 introduce the reader to fluoropolymers, fluoroelastomers, and the other materials of construction used to manufacture parts that come in contact with chemicals in factories. Chapters 3 and 4 elaborate on the properties of fluoropolymers and their selection for various parts. Chapters 5 and 6 describe processes to convert fluoropolymers into shapes and parts. Chapter 7 covers the fabrication techniques used to finish the fluoropolymer shapes/parts. Chapter 8 reviews design and construction of the basic process components of a chemical handling plant. Chapter 9 describes the operation and maintenance of vessels and tanks. Chapter 10 provides an approach and material on laboratory techniques that can be applied to determine the cause of failure of parts. Chapter 11 offers a modeling methodology to predict and analyze failure of fluoropolymer parts, thus allowing design improvement. Chapters 12–14 are devoted to the cost analysis, safety considerations, and future trends of fluoropolymers. The "Glossary," "Appendixes," "Trademarks," and "Index" sections provide additional information and tools to facilitate finding information in the book.

We have tried to present the data in SI units in most of the book. A large number of parts are, however, still specified in English units. In such cases, conversion factors have been listed in footnotes to allow the reader to convert to metric units.

None of the views or information presented in this book reflects the opinions of any of the companies or individuals that have contributed to the book. If there are errors, they are oversights on the part of the authors. A note to the publisher indicating the specific error, for the purpose of correcting future editions, would be much appreciated.

Sina Ebnesajjad
Pradip R. Khaladkar

July 2004

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We owe the majority of our learning and experience in the field of fluoropolymers to our employment at the DuPont Company. DuPont Fluoroproducts and DuPont Engineering Technology have generously contributed to this volume by providing a great deal of the data and research material, and by supporting literature searches, securing reference material, and the preparation of the manuscript. We thank the companies that have provided us with information, photographs, and illustrations; they have been cited usually in the captions, and in some cases in the bibliography section at the end of the chapter.

A number of companies have furnished the authors with information, which has been cited in the bibliography section at the end of each chapter. The following corporations have provided the authors with the data in their commercial information bulletins: DuPont, Solexis, Daikin, Dyneon, Asahi Glass America, Atofina, Crane Resistoflex, Edlon, Dualam, RMB Co., Xomox, RL Industries, Electrochemical Engineering and Manufacturing Company, and Wisconsin Protective Coatings Co. We sincerely appreciate the contribution that the data supplied by each company have made to this book.

Special thanks go to our friend Dr. Lawrence McKeen, DuPont Fluoropolymer Solutions, for contributing the powder coating technology section included in Chapter 8. We would like to sincerely thank Dr. Jörgen Bergström and Dr. Stewart Brown from Exponent, Inc., for their generosity in contributing Chapter 11 to this book. This is a better book because of the contribution of these colleagues who are at the forefront of the science and technology.

We have made a great deal of use of data developed and organized by our colleagues and friends in the DuPont Company, S. A., in Geneva, Switzerland. We would like to specially acknowledge Dr. Theodore Schroots for data, figures, and tables that he has developed over the last three decades. Mr. Tom Johns from DuPont Information and Computing Technology conducted the literature search for this book; we thank Tom and his colleagues for the reference material, including articles, books, and patents.

Our sincere thanks go to Mrs. Jeanne Roussel and the Write One staff for converting the raw manuscript into a real book with care and patience. Editorial suggestions and support by Ms. Millicent Treloar, William Andrew Publishing, have greatly upgraded the organization and the text. It would have been impossible for us to complete this project without the many helpful suggestions and moral support of William Woishnis, CEO of Plastics Design Library, at William Andrew Publishing.

Finally, there are not enough words for the authors to thank their life partners, Ghazale Dastghaib and Shaila Khaladkar, who have provided unlimited encouragement throughout this project.

Table of Contents

1 Introduction to Fluoropolymers

1.1 Introduction

This book is about the use of fluoropolymers in chemical processing industries. These industries include those that handle chemicals, usually corrosive, during the manufacturing of diverse products. Examples of important industries include chemical manufacturing, plastics manufacturing and processing, semiconductor manufacturing, pharmaceutical and biopharmaceutical industries, and food processing. Fluoropolymers often replace exotic alloys in processes involving corrosive chemistry. This plastic family has successfully met the requirement of purity which is essential in semiconductor, food, and biopharmaceutical production. The nonstick surface and extreme temperature characteristics of fluoropolymers have reserved a special place for them in the world of construction materials. This chapter offers a brief history of the discovery and the evolution of fluoropolymers, their applications, and the introduction of various types of this plastic family.

The era of fluoropolymers began with a small mishap which did not go unnoticed by the ingenious and observant Dr. Roy Plunkett of DuPont Company.[1] In 1938, he had been at DuPont for two years, concentrating mostly on the development of fluorinated refrigerants. He was experimenting with tetrafluoroethylene (TFE) for synthesis of a useful refrigerant ($CClF_2$–CHF_2).[2] The effort was spurred by the desire to create safe, nonflammable, nontoxic, colorless, and odorless refrigerants. On the morning of April 6, 1938, when Plunkett checked the pressure on a full cylinder of TFE, he found none. However, the cylinder had not lost weight. Careful removal of the valve and shaking the cylinder upside down yielded a few grams of a waxy looking white powder—the first polymer of *tetrafluoroethylene*.[2]

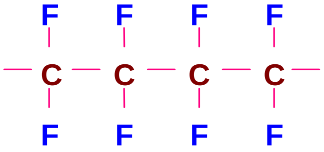
Plunkett analyzed the white powder, which was conclusively proven to be *polytetrafluoroethylene* (PTFE). The slippery PTFE could not be dissolved in any solvent, acid, or base, and upon melting formed a stiff clear gel without flow.[3] Later, research led to the discovery of processing techniques similar to those used with metal powders. At the time, the Manhattan Project was seeking new corrosion-resistant materials for gaskets, packings, and liners for UF_6 handling. PTFE provided the answer and was used in production. The US government maintained a veil of secrecy over the PTFE project until well after the end of World War II.

Large-scale monomer synthesis and controlled polymerization were technical impediments to be resolved. Intensive studies solved these problems and small-scale production of Teflon® (trademark, 1944) began in 1947. In 1950, DuPont scaled up the commercial production of Teflon® in the USA with the construction of a new plant in Parkersburg, West Virginia. In 1947, Imperial Chemical Industries built the first PTFE plant outside the US, in Western Europe. Since then, many more plants have been built around the globe. Over the last six decades, many forms of PTFE and copolymers of other monomers and TFE have been developed and commercialized.

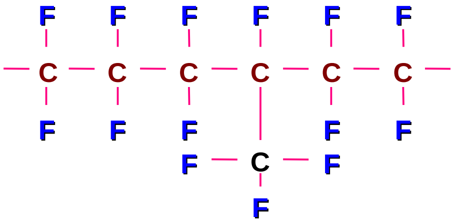
The words of Plunkett himself best summarize the discovery of PTFE. He recounted the story of Teflon® in a speech to the American Chemical Society at its April 1986 meeting in New York. “The discovery of polytetrafluoroethylene (PTFE) has been variously described as (i) an example of serendipity, (ii) a lucky accident, and (iii) a flash of genius. Perhaps all three were involved. There is complete agreement, however, on the results of that discovery. It revolutionized the plastics industry and led to vigorous applications not otherwise possible.”[2]

1.2 What are Fluoropolymers?

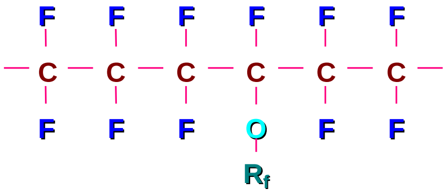
Traditionally, a fluoropolymer or fluoroplastic is defined as a polymer consisting of carbon (C) and fluorine (F). Sometimes these are referred to as *perfluoropolymers* to distinguish them from partially fluorinated polymers, fluoroelastomers, and other polymers that contain fluorine in their chemical structure. For example, fluorosilicone and fluoroacrylate polymers are not referred to as fluoropolymers. An example of a linear fluoropolymer is tetrafluoroethylene polymer (PTFE):



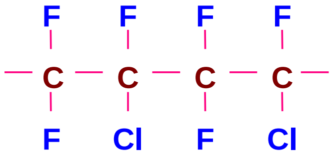
A simplistic analogy would be to the chemical composition of polyethylene [$(–CH_2–CH_2–)_n$] where all the hydrogen atoms have been replaced by fluorine atoms. Of course, in practice, PTFE and polyethylene are prepared in totally different ways. There are branched fluoropolymers such as fluorinated ethylene propylene polymer (FEP):



Oxygen (O) and chlorine (Cl) are present in the chemical structure of some commercial fluoropolymers. Examples include perfluoroalkoxy polymer and polychlorotrifluoroethylene:



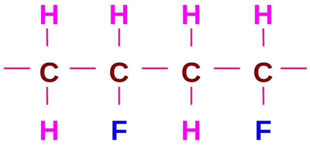
Perfluoroalkoxy polymer (PFA)



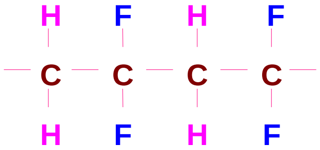
Polychlorotrifluoroethylene (PCTFE)

R_f is usually a perfluorinated group consisting of carbon and fluorine. Introduction of nonlinearity, oxygen and side chains, or chlorine invokes a variety of polymer properties such as lower crystallinity, clarity, and resistance to water vapor.

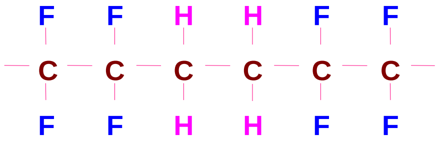
There is a second class of fluoropolymers called “partially fluorinated” in contrast to “perfluorinated” polymers. These molecules include hydrogen (H) in addition to fluorine and carbon. Examples include polyvinyl fluoride, polyvinylidene fluoride, ethylene tetrafluoroethylene copolymer, and ethylene chlorotrifluoroethylene copolymer.



Polyvinyl fluoride



Polyvinylidene fluoride (PVDF)



Ethylene tetrafluoroethylene copolymer (ETFE)

Partially fluorinated fluoropolymers are significantly different from the perfluoropolymers with respect to properties and processing characteristics. For example, perfluoropolymers are more thermally stable but physically less hard than partially fluorinated polymers. Both classes of fluoropolymers are discussed in Ch. 3.

1.3 Fundamental Properties of Fluoropolymers

The basic properties of fluoropolymers arise from the atomic structure of fluorine, carbon, and their covalent bonding in specific chemical structures. These properties are weakened as the chemical structure becomes less “perfluorinated,” as in polyvinylidene fluoride. Because PTFE has a linear structure, it is a good subject for discussion of extreme properties. The backbone is formed of carbon-carbon bonds and carbon-fluorine bonds. Both are extremely strong bonds (C–C = 607 kJ/mole and C–F = 552 kJ/mole.)[4][5] The basic properties of PTFE stem from these two very strong chemical bonds. The PTFE molecule resembles a carbon rod completely blanketed with a sheath of fluorine atoms.[6]

The size of the fluorine atom allows the formation of a uniform and continuous sheath around the carbon-carbon bonds and protects them from attack, thus imparting chemical resistance and stability to the molecule. The fluorine sheath is also responsible for the low surface energy (18 dynes/cm)[7] and low coefficient of friction (0.05–0.08, static)[6] of PTFE. Another attribute of the uniform fluorine sheath is the electrical inertness (or non-polarity) of the PTFE molecule. Electrical fields impart only slight polarization to this molecule, so volume and surface resistivity are high. Table 1.1 summarizes the fundamental properties of PTFE, which represents the ultimate polymer among all fluoroplastics.

The basic properties of perfluoropolymers provide beneficial attributes with high commercial value (Table 1.2).

Table 1.1. Fundamental Properties of PTFE

- High melting point, 342°C
- High thermal stability
- Useful mechanical properties at extremely low and high temperatures
- Insolubility
- Chemical inertness
- Low coefficient of friction
- Low dielectric constant/dissipation factor
- Low water absorptivity/adsorptivity
- Excellent weatherability
- Flame resistance
- Purity

Table 1.2. Useful Attributes of Perfluoropolymers

- Stability
    - high continuous-use temperature
    - excellent weatherability
    - excellent chemical resistance
    - excellent fire properties
- Low Surface Energy
    - good release properties
    - biological inertness
    - low friction
- Cryogenic Properties
    - retains flexibility
- Electrical Properties
    - low dielectric constant
    - low dissipation factor

1.4 Developmental History of Fluoropolymers

The development of fluoropolymers began with the invention of PTFE in 1938, continued to 1992 when a soluble perfluoropolymer (Teflon® AF) was introduced, and to 2002 when fluoroplastics polymerized in supercritical carbon dioxide were introduced. Table 1.3 summarizes the timeline for the development of fluoropolymers that have brought about major changes in properties and/or fabrication processes.

The discovery of PTFE was a major leap forward in material science. Yet the new polymer could not be fabricated by melt-processing. The next two forms of PTFE, fine powder and dispersion, were also not melt-processible. The pursuit of a more easily processible polymer led to FEP, which could be melted in an extruder. Compared with PTFE, the major disadvantage of FEP is its reduced thermal stability and lower maximum continuous-use temperature (200°C) (Table 1.3). PFA, which was introduced in 1973, offers both melt-processing and the same upper continuous-use temperature as PTFE (260°C).

Table 1.3. Commercialization Timeline of Major Fluoropolymers vs Key Processing/Application Trade-Offs

Fluoropolymer	Year Commercialized	Monomers	Trade-off +	Trade-off -
PTFE	1947	TFE	Continuous-use temperature: 260°C	Non melt-processible
PCTFE	1953	CTFE	Melt-processible/Non melt-processible	Maximum continuous-use temperature: 180°C
FEP	1960	TFE, HFP[3]	Melt-processible	Maximum continuous-use temperature: 200°C
PVF	1961	VF[1]	Thin film/weatherable	Maximum continuous-use temperature: 107°C
PVDF	1961	VDF[2]	Melt-processible	Maximum continuous-use temperature: 150°C
ECTFE	1970	CTFE, E[4]	Hardness/toughness	Maximum continuous-use temperature: 150°C
PFA	1972	TFE, PAVE[5]	Melt-processible Continuous-use temperature: 260°C	Low molecular weight
ETFE	1973	TFE, E	Hardness/toughness	Maximum continuous-use temperature: 150°C
Teflon®AF	1992	TFE, PDD[6]	Soluble in special halogenated solvents	High cost

[1] Vinyl fluoride ($CH_2{=}CHF$)

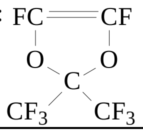
[2] Vinylidene fluoride ($CH_2{=}CF_2$)

[3] Hexafluoropropylene ($CF_2{=}CF{-}CF_3$)

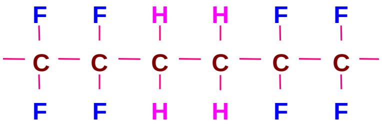
[4] Ethylene ($CH_2{=}CH_2$)

[5] Perfluoroalkylvinylether ($CF_2{=}CF{-}O{-}R_f$)

[6] 2,2-Bistrifluoromethyl-4,5-difluoro-1,3-dioxole:



ETFE addresses the need for a mechanically stronger polymer, albeit at a loss of fluoropolymer properties because of the presence of hydrogen in its molecule:



Compared to PTFE, ETFE has a lower continuous-use temperature (150°C), less chemical resistance, and a higher coefficient of friction. Mechanical properties including tensile strength, elongation at break, and tensile modulus are increased, leading to cut-through resistance.

Teflon® AF is an amorphous polymer which is soluble in select halogenated solvents. It can be applied as a solution followed by the removal of the solvent. The remaining coating will be as resistant to almost as many chemicals as PTFE. The thickness of the coating can range upward from less than a micrometer.

There are a number of other polymers in this family including polychlorotrifluoroethylene (PCTFE), polyvinyl fluoride (PVF), polyvinylidene fluoride, ethylene chlorotrifluoroethylene (ECTFE), tetrafluoroethylene/hexafluoropropylene/vinylidene fluoride terpolymers, and chlorotrifluoroethylene/vinyl ether copolymers.

1.5 Examples of Uses of Fluoropolymers

The consumption of fluoropolymers has increased over the years as technological advancement has required the properties of these plastics. The applications of fluoropolymers, in general, span all facets of human life from household uses to the aerospace and electronic industries. Useful properties (Table 1.2) of fluoropolymers in various applications include: chemical resistance, thermal stability, cryogenic properties, low coefficient of friction, low surface energy, low dielectric constant, high volume and surface resistivity, and flame resistance. Applications for fluoropolymers always exploit one or more of the properties (Table 1.4) that set them apart from other plastics.

In the chemical processing industry, for example, fluoropolymers are selected for their resistance to chemical attack. They serve as linings for carbon steel vessels, and for piping and other fluid handling components. They provide durable, low maintenance, and economical alternatives to exotic metal alloys. In these applications, fluoropolymers also offer thermal stability for use at high temperatures. And because they do not react with process streams, they help prevent contamination of products.

Electrical properties of fluoropolymers are highly valuable in electronic and electrical applications. In data communications, for example, FEP is used to insulate cables installed in air-handling spaces (plenums) in office buildings. FEP provides the excellent dielectric properties these cables require to perform well at high data-transmission rates as well as

Table 1.4. Major Applications and Some Uses of Fluoropolymers

Industry/Application Area	Key Properties	Typical Uses
Chemical Processing	Chemical resistance Good mechanical properties Thermal stability Cryogenic properties	Gaskets, vessel liners, valve and pipe liners, tubing, coatings
Electrical & Communications	Low dielectric constant High volume/surface resistivity High dielectric breakdown voltage Flame resistance, thermal stability	Wire and cable insulation, connectors
Automotive & Office Equipment	Low coefficient of friction Good mechanical properties Cryogenic properties Chemical resistance	Seals and rings in automotive power steering, transmission, and air-conditioning. Copier roller and food processing equipment covering.
Houseware	Thermal stability Low surface energy Chemical Resistance	Cookware coatings
Medical	Low surface energy Stability Excellent mechanical properties Chemical resistance	Cardiovascular grafts, heart patches, and ligament replacement
Architectural Fabric	Excellent weatherability Flame resistance Low surface energy	Coated fiberglass fabric for stadium and airport roofs
Semiconductor Fabrication	Chemical resistance Purity Non-shedding Thermal stability	Process surfaces Wafer carrier basket Tubing, valves, pumps, and fittings

long-term stability so performance will not change over the life of the cabling system. Most importantly, FEP helps these cables meet strict building code requirements for low flame spread and low smoke generation.

Fluoropolymers are used to insulate wire for critical aerospace and industrial applications where chemical and thermal resistance is essential. They are also materials of construction for connectors for high-frequency cables and for thermocouple wiring that must resist high temperatures.

In the automotive, office equipment, and other industries, the mechanical properties of fluoropolymers are beneficial in low-friction bearings and seals that resist attack by hydrocarbons and other fluids. In food processing, the Food and Drug Administration (FDA) has approved fluoropolymer grades as fabrication material for equipment due to their resistance to oil and cleaning materials, and their anti-stick and low friction properties.

In houseware, fluoropolymers are applied as non-stick coatings for cookware and appliance surfaces. These applications depend on thermal and chemical resistance as well as anti-stick performance. PTFE and ETFE are chosen to insulate appliance wiring that must withstand high temperatures.

Medical articles such as surgical patches and cardiovascular grafts rely on the long-term stability of fluoropolymers as well as their low surface energy and chemical resistance.

For airports, stadiums, and other structures, fiberglass fabric coated with PTFE is fabricated into roofing and enclosures. This architectural fabric is supported by cables or air pressure to form a range of innovative structures. PTFE provides excellent resistance to weathering, including exposure to the ultraviolet rays in sunlight, flame resistance for safety, and low surface energy for soil resistance and easy cleaning.

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2 Materials of Construction

2.1 Introduction

An engineer has a wide choice of materials of construction for corrosion control. There are three broad categories of materials, used either individually or in combination with each other: metals, polymers, and ceramics. This chapter describes the differences between them and explains the phenomenology of applications of polymer-based materials. It also places fluoropolymer materials in their appropriate contexts. Polymer-based materials are also known as *polymerics*, *polymeric materials*, or simply *plastics*, which is often not accurate and can lead to confusion.

2.2 Historical Background

Lead, wood, and rubber are probably the earliest known materials of construction for the chemical processing industry. Interestingly, it took a little more than a century for rubber to be established as a lining material after Charles Goodyear accidentally discovered vulcanized rubber in 1839. Wood is the first composite material to be used in the chemical processing industry. Until the onset of World War II, these naturally occurring materials continued to play a major role in chemical handling applications.

Although stainless steels were discovered at the turn of the century and copper silicon alloys started to emerge at about the same time, the real explosion of materials research and development began at around the beginning of World War II. Polymer science and technology were no exception. Nylon was already developed at the DuPont Company. Alloy 20 was developed by DuPont in the late thirties. At about the same time, polytetrafluoroethylene (PTFE) (Teflon®) was discovered which led to further development of fluoropolymers and ushered in an era of high-performance polymer materials for corrosion control.

The 1950s were known for the explosive development and growth in elastomers. DuPont Company developed a whole range of synthetic elastomers such as neoprene (polychloroprene), Hypalon® (chlorosulfonated polyethylene), and Nordel® (terpolymer of ethylene propylene-diene monomer). These were followed later by fluoroelastomers such as Viton® and Kalrez®. The 1960s and 1970s saw further refinement of these fluorine-containing elastomers with several new grades developed for specific needs in the chemical processing industry.

Rigid thermosetting materials have always attracted the interest of engineers in the chemical processing industry since Bakelite® (phenol formaldehyde) was put to use for commercial applications. Various fiber and particulate additives were developed to make useful structures out of these materials. The 1940s saw major initiatives in the development of polyester resins. Bisphenol A fumarate resins with unsaturation sites for crosslinking were developed for processing vessels and piping. These resins, in their reinforced forms, were the early man-made composites for the chemical processing industry. Development of vinyl esters, chlorendic anhydride, and furans added greatly to the versatility of fiberglass reinforced polyester (FRP). These became the workhorses in the chloralkali industry for handling chlorine and chlorine-containing chemicals.

While the US was pursuing the FRP route, Europeans were busy taking the lead in developing technologies using thermoplastic materials such as polyethylene, polyvinyl chlorides, and polypropylenes. The result was an increased use of these materials as self-supporting structures as well as linings. They achieved this through an effective partnership of governments, industry, and academia, which ultimately produced several autonomous testing and training centers. A major outcome was the use of low-end thermoplastics (PE, PVC, and PP) for "dual laminate" structures where the structural component is FRP and the lining is a thermoplastic material. This technology was subsequently exported to Canada and then to the US.

Manufacturing technologies (injection molding, transfer molding, contact molding, compression molding, isostatic molding, ram extrusion) and design procedures were concurrently developed to promote the use of these materials. The resin converters played a bigger role in these activities than the resin manufacturers. The creation of a multitude of materials in a relatively short time led to high expectations and less-than-careful application of some of these materials. Failures, some catastrophic, inevitably occurred. Notable among these were ruptures of FRP storage tanks and vessels resulting in total discharge of corrosive and hazardous contents. Less notable but equally damaging failures also occurred in linings of various types. The underlying causes were improper material selection, design, quality of fabrication, exceeding operating parameters, inability to adequately inspect, or some combination of these.

2.3 Definition of Polymer-based Materials

Polymers are long chain molecules made from organic chemicals. These materials are defined by three distinct characteristics.

- Organic chemistry basis
- Mechanical strength basis
- Thermal processing basis

Polymers can be distinguished from each other by their generic organic chemistry description such as polyolefins, fluorocarbons, styrenics, epoxies, etc. They can also be classified by their mechanical strength: rigid (elastic modulus > 690 MPa), semirigid (modulus between 69 and 690 MPa), and nonrigid (modulus < 69 MPa). Additionally, polymeric materials are classified by the way they are thermally processed: thermoplastics and thermosets. Thermoplastics are those which can be remelted and reprocessed repeatedly. Thermosets cannot be remelted for reprocessing since they are crosslinked (also known as vulcanized in the world of elastomers). Any attempt to remelt thermosets will result in degradation and, ultimately, charring.

Fluoropolymers are thermoplastic and nonrigid materials while fluoroelastomers have elastomeric properties. See Tables 2.1 and 2.2 for a comparison of physical and mechanical properties of select plastics and elastomers including fluorinated materials.

Elastomers are a special class of nonrigid materials distinguished by high elongation and high recovery.

A complete description of a polymer system must necessarily include references to all three categories. Some examples below illustrate the point.

1. A fiberglass tank is made of vinyl ester resin, which is a thermoset and is semirigid in its composite form
2. A rubber (elastomeric) gasket can be made of polychloroprene, which is a thermoset and is nonrigid.
3. A fluoropolymer lining for a vessel is thermoplastic and nonrigid.

2.4 Comparison Between Polymer-based Materials and Metals

There are some obvious and subtle differences between polymer-based materials and metals. The obvious differences are in strength (high for metals), elongation (high for polymers), and maximum-use temperature (much higher for metals). Not so obvious are anisotropy (polymers), homogeneity (metals), changing properties in service (plastics), responsiveness to nondestructive testing (high for metals), ability to predict remaining life (low for polymers), ability to carry out accelerated testing for corrosion rates (high for metals), and sensitivity to workmanship (high for polymers). All these factors make using plastics as effective as metals and with the same degree of confidence a challenge for the end user.

Phenomenology of corrosion for metals and polymer materials is not the same. For example, the terms such as *corrosion rate, pitting, end grain attack,* and *intergranular attack* used to describe metals' behaviors are not applicable to plastics. Not only are the terms for plastics different (*blistering, discoloration, cracking,* etc.) but they are based on a naked-eye observation and not at a microscopic level as for metals.

Table 2.1. Physical and Mechanical Properties of Plastics[1][2]

	Specific Gravity	Mold Shrinkage, %	Tensile Strength, MPa	Break Elongation, %	Tensile Modulus, MPa	Flexural Strength, MPa	Flexural Modulus, Mpa 23°C	Impact Notched Izod J/m (23°C)	Compressive Strength, MPa
Test Method ASTM	D792	D955	D638	D638	D638	D790	D790	D256	D695
Polystyrene	1.06	0.5	46	2.2	3,172	96	3,103	10.8	96.6
ABS	1.05	0.6	48	8.0	2,069	72	2,621	242	69
SAN	1.08	0.4	72	3.0	3,862	103	3,793	27	103
Polypropylene	0.90	1.5	32	15.0	1,310	41	2,069	27	34.5
Polyethylene	0.96	2.0	30	9.0	1,034	38	1,517	70	27.6
Polyacetal	1.41	1.8	61	60.0	2,827	90	2,552	70	36
Polyester	1.30	2.0	55	200.0	2,758	88	2,345	10.8	90
Polyamide, nylon 6	1.13	1.3	81	200.0	2,758	103	2,759	53.8	90
Polyamide, nylon 6,6	1.14	1.8	79	300.0	1,310	103	1,310	53.8	34
Polycarbonate	1.20	0.6	62	110.0	2,379	93	2,345	161	86
Polysulfone	1.24	0.7	70	75.0	2,482	106	2,690	32	96.6
Test Method ASTM	D792	Measured on parts	D4894-5 D1708 D638	D4894-5 D1708 D638	D638	D790	D790	D256	
PTFE	2.14–2.22	2–10	20–35	300–550	550	No break	340–620	188	34.5
PFA	2.15	3.5–6.0	20–26	300	276		551	No break	
FEP	2.15	3.5–6.0	20–28	300	345	No break	655	No break	15.2
ETFE	1.71	1–7	45	150–300	827	38	1,034–1,171	No break	17.2
PVDF	1.78	0.2–3	31–52	50–250	1,040–2,070	45–74	1,140–2,240	107–427	55–110

Table 2.2. Physical and Mechanical Properties of Elastomers[3]

Property		**Trade Name**							
		Viton®	**Aflas®**	**Fluoro-silicone**	**Kalrez®**	**Adiprene®**	**Neoprene**	**Hypalon®**	**Nordel®**
		Chemical Name							
		Fluorinated ydrocarbon	**Tetrafluoro-ethylene/ propylene copolymer**	**Fluorosilicone**	**Perfluoro-elastomer**	**Polyurethane**	**Poly-chloroprene**	**Chloro-sulfonated polyethylene**	**Ethylene/ propylene copolymer**
Continuous-use temperature, °C	Min	-29 to -57	-29	-80 to -68	-38	-54	-62	-54	-59
	Max	227	204 to 230	232	290 to 315	121	149	135	163
Tensile strength, Mpa*[1]		3.4–20.7	13.8–22.1	3.4–9.6	3.4–10.3	2.1–24.1	3.4–27.6	–	2.1–24.1
Tensile modulus at 100% elongation, Mpa*[1]		1.4–14	6.2–17.2	6.2	6.2–13.1	0.7–20.7	0.7–20.7	3.1–3.4	0.7–20.7
Hardness (durometer)		50A–95A	60A–100A	35A–80A	65A–95A	30A–90A	15A–95A	40A–100A	30A–90A
Compression set @ temperature, °C		9–16, 70h @24	25, 70h @93	17–25, 22h @149	20–40, 70h @21	20–60, 70h @100	20–60h @100	38–80, 22h @100	20–60, 70h @100
Elongation, %		100–500	50–400	100–480	60–170	100–700	100–800	100–700	100–700
*[1] To convert from MPa to psi, multiply by 145.									

2.4.1 Position of Fluoropolymers in the Materials Spectrum

Fluoropolymers are fluorine-containing polymers. They are thermoplastic in nature and are semirigid, and are classified in two ways:

- Homopolymers or copolymers (preferred by chemists)
- Fully fluorinated or partially fluorinated (preferred by engineers)

These materials have the highest chemical resistance (Tables 2.3 and 2.4) among the polymer materials, as well as maximum-use temperature. Corrosion resistance is a function of the level of fluorine, hence the fully fluorinated ones are usually preferred for tough applications.

1. Fully Fluorinated
    - PTFE (polytetrafluoroethylene)
    - FEP (fluorinated ethylene propylene) copolymer
    - PFA (perfluoroalkoxy) (perfluoropropyl vinyl ether)
    - MFA (perfluoroalkoxy) (perfluoromethyl vinyl ether)
2. Partially Fluorinated
    - ETFE (ethylene tetrafluoroethylene polymer)
    - ECTFE (ethylene chlorotrifluoroethylene polymer)
    - PVDF (polyvinylidene fluoride)

Table 2.5 presents a summary of structure-rheology-fabrication process relationship for commercial fluoropolymers.

2.5 Applications of Polymer-based Materials for Corrosion Control

Applications for corrosion control are classified as follows:

- Barrier (linings)
- Self-supporting structures
- Others (seals, gaskets, column internals, etc.)

Table 2.6 shows the applications and the materials typically used. It is clear from the table that fluoropolymers are used principally for barriers (linings) and other applications such as column internals, seals and gaskets. In rare situations they are used to construct self-supporting structures.

2.5.1 Applications of Fluoropolymers for Corrosion Control

Fluoropolymers are principally used as barriers, i.e., linings for storage vessels, reactors, columns, piping, valves, pumps, expansion joints, and hoses. In a few cases, they are also used as self-supporting structures such as piping and tubing. Linings are achieved by various manufacturing techniques such as thermoforming, welding, isostatic molding, ram extrusion, and injection molding. Sizes range from large field-erected storage tanks to packings for column internals in complex shapes. Various techniques are used to manufacture parts; these are covered in Chs. 6 and 7. Issues related to the successful use of fluoropolymers are covered in Ch. 9. Supply chains are typically long and complex; these are covered in Ch. 8. Choosing fluoropolymers implies evaluation of all candidate materials including metals and other polymers. The selection methodology is covered in Ch. 4.

This book covers the use of fluoropolymers for corrosion control in chemical processing industries (CPI).

Table 2.3. Water Absorption and the Effect* of Inorganic Chemicals on Polymers[1][2]

Material	Weak Bases and Salts		Strong Bases		Strong Acids		Strong Oxidants		24-hour Water Absorption
	25°C	93°C	25°C	93°C	25°C	93°C	25°C	93°C	Weight Change, %
Polyacetal	1–3	2–5	1–5	2–5	5	5	5	5	0.23
ABS	1	2–4	1	2–4	1–4	5	1–5	5	0.1–0.4
Nylons	1	2	2	3	5	5	5	5	0.2–1.9
Polyester	1	3–4	2	5	3	4–5	2	3–5	0.06–0.09
Polyethylene	1	1	1	1	1	1	1	1	<0.01
Polystyrene	1	5	1	5	4	5	4	5	0.03–0.60
Polysulfone	1	1	1	1	1	1	1	1	0.2–0.3
Polyvinyl chloride (PVC)	1	5	1	5	1	5	2	5	0.04–1.0
PTFE	1	1	1	1	1	1	1	1	0
PFA	1	1	1	1	1	1	1	1	<0.03
FEP	1	1	1	1	1	1	1	1	<0.01
ETFE	1	1	1	1	1	1	1	1	<0.03
PVDF	1	1	1	2	1	2	1	2	0.04
Polychloro-trifluoroethylene (PCTFE)	1	1	1	1	1	1	1	1	0.01–0.10

Table 2.4. Effect* of Organic Chemicals on Polymers[1][2]

Material	Aromatic Solvents		Aliphatic Solvents		Chlorinated Solvents		Esters and Ketones	
	25°C	93°C	25°C	93°C	25°C	93°C	25°C	93°C
Polyacetal	1–4	2–4	1	2	1–2	4	1	2–3
ABS	4	5	2	3–5	3–5	5	3–5	5
Nylons	1	1	1	1	1	2	1	1
Polyester	2	5	1	3–5	3	5	2	3–4
Polyethylene	3	4	3	4	3	4	3	4
Polystyrene	4	5	4	5	5	5	4	5
Polysulfone	4	4	1	1	5	5	3	4
PVC	4	5	1	5	5	5	4	5
PTFE	1	1	1	1	1	1	1	1
PFA	1	1	1	1	1	1	1	1
FEP	1	1	1	1	1	1	1	1
ETFE	1	1	1	1	1	1	1	1
PVDF	1	1	1	1	1	1	3	5
PCTFE	1	1	1	1	3	4	1	1

*** Tables 2.3 and 2.4:** Effect is defined by ASTM D543 and D2299: 1 = no effect or inert, 2 = slight effect, 3 = mild effect, 4 = softening or swelling, 5 = severe degradation.

Table 2.5. Summary of Structure-Rheology-Fabrication Process for Commercial Fluoropolymers[4]

Polymer	Monomer Unit	Melt Point °C (1)	Melt Viscosity, Pa•sec (2)	Melt Flow Rate, dg/min	Fabrication Technique
Granular PTFE	$-CF_2-CF_2-$	327	10^{10}–10^{12} (3)		Compression molding
Fine Powder PTFE	$-CF_2-CF_2-$	327	10^{10}–10^{12} (3)		Paste extrusion
Dispersion PTFE	$-CF_2-CF_2-$	317–337	10^{10}–10^{12} (3)		Coating methods
FEP	$-CF_2-CF_2-C(CF_3)F-CF_2-$	260–282	10^4–10^5 (4)	0.8–18 (5)	Melt processing
PFA	$-CF_2-CF_2\bullet C(O-R_f)F-CF_2-$	302–310	4×10^3–3×10^4 (4)	1–18 (6)	Melt processing
ETFE	$-CF_2-CF_2-CH_2-CH_2$	254–279	0.7–10×10^3 (7)	3.7–16 (8)	Melt processing
PCTFE	$-CClF-CF_2-$	210–215	1–10 (9)		Compression molding/melt processing
ECTFE	$-CClF-CF_2-CH_2-CH_2-$	240	-	1-50	Melt processing
PVDF	$-CF_2-CH_2-$	155–192	0.2–17×10^3	5–180 (10)	Melt processing
Polyvinyl fluoride (PVF)	$-CHF-CH_2-$	190	-	-	Melt extrusion of dispersion in latent solvent
Soluble Fluoropolymers	$-[CF_2-CF_2]_{n\text{-}m}-[C_f]_m$(11)	305	-	-	Latex application methods

(1) Second melt point for PTFE
(2) From Ch. 2 of Ref. 5
(3) Melt creep viscosity by according to procedure MVS Patent
(4) By capillary rheometer ASTM D 2116
(5) Melt flow rate by ASTM D 2116
(6) By capillary rheometer ASTM D 3307
(7) By capillary rheometer ASTM D 3159
(8) Melt flow rate by ASTM D 3159
(9) By capillary rheometer at 230°C
(10) Melt flow rate at 265°C
(11) C_f is the comonomer m > 0.2 weight fraction

Table 2.6. Overview of Polymer Materials for Corrosion Control

Polymer-based Materials

- Linings for vessels & columns
  - Thin linings (<25 mils)
    - Spray applied Epoxy & phenolic
    - Spray applied Hypalon® & Neoprene
    - Spray & baked Fluoropolymers
    - Flame spray ethylene Copolymers
  - Thick linings (>25 mils)
    - Spray or trowel applied, reinforced vinyl ester or epoxy (CS & concrete)
    - Sheet elastomeric (for vessels & piping)
      - Soft natural rubber
      - Semihard
      - Chlorobutyl rubber
      - Cured Neoprene
      - Three-ply (soft-semihard-soft)
    - Fluoropolymer
      - Fabric or glass back sheets - FEP, PVDF, PFA, ETFE (adhesively bonded)
      - Loose Linings (vessels & piping) - FEP, PVDF, PFA
      - Spray & baked - FEP, PFA, ETFE, ECTFE, PVDF
      - Dual laminate (FRP) (vessels & piping) - FEP, PFA, ETFE
      - Rotolining (vessels & piping) - ETFE, PFA
    - Thermoplastic
      - PVC sheets (bonded)
      - PE anchored sheets (for concrete)
      - PP (polypropylene) sheets (rubber back)
- Self-supporting structures (vessels, column, & piping)
  - FRP (vessels)
    - Contact molded (hand layup)
    - Filament wound
  - FRP piping
    - Custom made
    - Commodity
      - Filament wound
      - Centrifugally cast
  - Other piping
    - PE (polyethylene)
    - PVC, CPVC (chlorinated polyvinyl chloride)
    - PP
    - PVDF
  - Other vessels
    - Rotomolded PE tanks
- Other
  - Seals (“O” rings)
    - FKM (Viton®, Kalrez®)
  - Gaskets
    - Virgin & filled PTFE
    - Expanded PTFE
    - Sheet elastomers
      - Hypalon®
      - Natural rubbers
      - Neoprene
      - Nordel®
  - Column internals

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3 Properties of Neat (Unfilled) and Filled Fluoropolymers

3.1 Introduction

A fundamental property of fluoropolymers is their resistance to organic and inorganic chemicals (Fig. 3.1). Increased content of fluorine enhances the chemical resistance of the polymer. The overwhelming majority of the applications of fluoropolymers take advantage of their inertness to chemicals. Chemical properties of fluoropolymers are not affected by fabrication conditions. Another aspect of the interaction of these plastics with chemicals is permeation. Even though a reagent may not react with a fluoropolymer, it may be able to permeate through the polymer structure. The extent and rate of permeation depend on the structure and properties of the plastic article as well as the type and concentration of permeant. Temperature and pressure usually influence the permeation process. This chapter reviews chemical compatibility of fluoropolymers and their permeation behavior towards different chemicals.

This chapter has been divided based on the fluorine content of fluoropolymers, that is, perfluorinated and partially fluorinated. In general, resistance of polymers to chemicals of all types increases with an increase in their fluorine content. Therefore, the chemical resistance of ETFE, ECTFE, and PVDF is generally inferior to that of perfluorinated polymers such as PFA and FEP.

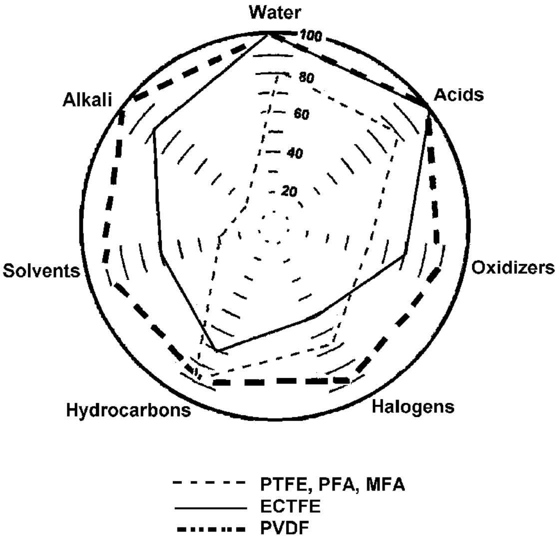

Figure 3.1 Chemical resistance of fluoropolymers.[1]

3.2 Influence of Processing on Fluoroplastics

Crystallinity affects a great number of properties of semicrystalline thermoplastics such as fluoroplastics. The degree of crystallinity in a fabricated part depends on the processing conditions such as the length of exposure to temperature above the melting point and the cooling rate. Elimination of bubbles, trapped air, and voids during processing have a major impact on a number of properties of a part including mechanical, electrical, and resistance to permeation of chemicals. A group of perfluoropolymer properties that remain relatively independent of the fabrication conditions are listed in Table 3.1. Partially fluorinated fluoroplastics contain hydrogen or chlorine and can undergo significant thermal degradation if they are overexposed during processing. Thermal degradation will alter many of the properties listed in Table 3.1 for partially fluorinated fluoroplastics.

Table 3.1. Properties of Perfluoropolymers Unaffected by Fabrication Conditions

Mechanical	Electrical	Chemical
Flexibility at low temperatures Coefficient of friction Stability at high temperatures	Dielectric constant Dissipation factor Arc resistance Volume resistivity Surface resistivity	Insolubility Chemical resistance Weatherability Surface energy Flame resistance

3.3 Chemical Compatibility of Fluoropolymers

3.3.1 Chemical Compatibility of Perfluoropolymers

Perfluoropolymers such as PTFE, PFA, and FEP are by far the most chemically resistant among thermoplastics. Few substances chemically interact with these plastics. Exceptions among commercially encountered materials include alkali metals, especially in a molten state, and gaseous fluorine at high temperatures and pressures. Perfluoropolymers are attacked by certain halogenated compounds containing fluorine such as chlorine trifluoride (ClF_3), bromine trifluoride (BrF_3), iodine pentafluoride (IF_5), and oxygen difluoride (OF_2). The inertness of these polymers arises from their molecular structure.[2]

A few chemicals have been reported to attack perfluoropolymers at or near their upper service temperature (260°C).[3] They react with 80% sodium or potassium hydroxide. They also react with some strong Lewis bases including metal hydrides such as boranes (B_2H_6), aluminum chloride, ammonia, and some amines ($R–NH_2$) and imines ($R{=}NH$). Slow oxidative attacks may take place in the presence of 70% nitric acid at 250°C under pressure. It is important to test the effect of these reagents on perfluoropolymers under the specific application temperature to determine the material limitations.

Perfluoropolymers derive their chemical resistance from an extremely strong carbon-fluorine bond and an impermeable sheath of fluorine atoms surrounding the carbon-carbon chain. Relatively high crystalline content renders these polymers insoluble in solvents.

Another commercially significant perfluoropolymer is the copolymer of tetrafluoroethylene-perfluoromethyl vinyl ether. It has chemical resistance characteristics similar to the other perfluoropolymers.

Some halogenated solvents are absorbed by perfluoropolymers without any chemical interaction or degradation. The action is strictly physical and the removal of the absorbed species restores it to its original state. Too much absorption by a perfluoropolymer sample can be an indication of excessive porosity. A highly porous sample may appear blistered due to the expansion of vapors in the surface pores. A properly fabricated part does not exhibit blistering.

Appendix I contains data about the effect of high temperature automotive fuels on the physical properties of fluoropolymers.

3.3.1.1 Effect of Ozone on Fluoropolymers

Ozone is considered a reactive substance against plastics due to its ability to readily degrade into an atom and a molecule of oxygen. The atomic oxygen is highly reactive, due to its unpaired electrons in its last orbital, allowing it to attack and etch most polymers. Polytetrafluoroethylene has been reported to be very resistant to etching by ozone in low earth-orbit environment, where atomic oxygen is the most abundant species.[4][5]

$$O_3 \rightarrow O_2 + O$$

Resistance of polymers to ozone attack is studied in space environments in “actual” applications. In the laboratory, glow discharge or plasma etching is the common method for laboratory study of ozone effect. Plasma and low earth-orbit environments are not equivalent. For instance, oxygen plasma contains a variety of other particles including electrons and free radicals in addition to atomic oxygen. In contrast, atomic oxygen is the dominant constituent of low earth-orbit.

In general, oxygen uptake was least for PTFE and most for polyethylene in experiments in which a series of fluorinated polyolefins were exposed to ozone “out of glow.” This means that plasma or glow discharge was used to produce atomic oxygen that etched the sample placed outside the discharge zone. The results of “out of glow” plasma etching and low earth-orbit, by and large, are in agreement.[6]

Maximum oxygen uptake decreases with an increase in the fluorine content of the polymers. For example, polyvinylidene fluoride took up less oxygen as a result of O_3 exposure than polyethylene, though more than PTFE, in the same experiment.[6] The exception to this trend is polyvinyl fluoride, which has a higher etch rate than polyethylene (Table 3.2). Why is PVF more susceptible to ozone attack than polyethylene?

Golub[7] has proposed an explanation attributing the high etch rate of PVF to the ease of fluorine formation from the decomposition of this polymer. Fluorine promotes degradation of molecular oxygen to its active atomic form ($O_2 \rightarrow 2O$), further reacting with PVF, thus enhancing the etch rate. Polyvinylidene fluoride and FEP molecules have lower etch rates due to the higher stability of the CF_2 group to oxygen attack than CFH in PVF or CH_2 in polyethylene. Both polyvinylidene fluoride and copolymers of tetrafluoroethylene and ethylene (ETFE, Tefzel®) have low etch rates due to the protection provided to the CH_2 groups bonded to CF_2 groups. The ultimate stability is reached in the linear PTFE chain, which consists of all CF_2 groups with the exception of the few end groups.

Table 3.2. Relative Mass Loss Rates for Polymer Films Exposed to Low Earth-orbit[6]

Polymer	Mass Loss Rate	Fluorine to Carbon Ratio
Polyimide (Kapton®)	1	0
Polyetherterphthalate (Mylar®)	1.06	0
Polyethylene (low density)	0.43	0
Polyethylene (high density)	0.80	0
Polyvinyl fluoride (Tedlar®)	1.16	0.5
Polyvinylidene fluoride (Kynar®)	0.25	1
PTFE (Teflon®)	<0.03	2
Tetrafluoroethylene/ hexafluoropropylene (Teflon® FEP)	<0.03	2

3.3.1.2 Oxygen Compatibility of PTFE

Oxygen is singled out due to its propensity to facilitate auto-ignition of organic material including plastics. Fluoropolymers are extensively used for oxygen services because of their low flammability. Oxygen does not interact with polytetrafluoroethylene under most circumstances.

Limiting oxygen index (LOI) of PTFE is greater than 95% under ambient conditions. This means that PTFE does not burn without an ignition source in an atmosphere containing less than 95% oxygen. LOI is not a complete predictor of all practical conditions in which oxygen and PTFE may interact. A number of considerations apply.

Increased pressure and temperature can accelerate auto-ignition of PTFE, that is, ignition can occur without initiation by an external source. Combinations of high temperatures and high flow rates through small orifices can initiate reaction with PTFE. Organic impurities such as grease, oil, and dirt react violently with oxygen and generate heat, which can be sufficient for igniting PTFE. Surfaces are the most common locations of contamination. Before use, all surfaces that come in contact with oxygen must be meticulously cleaned to assure that they are devoid of any organic contaminants.

Surface condition can affect the safety of liquid oxygen contact with PTFE. Despite its extremely low temperature, liquid oxygen can react with organic contamination and ignite PTFE. Thorough cleaning of the surfaces of all parts that come in contact with oxygen is required. ASTM D2512 is used to determine the compatibility of materials with liquid oxygen. This method determines the relative sensitivity of materials under impact conditions by using an impact tester developed at the Army Ballistic Missile Agency. Materials that are sensitive to impact energy are usually likely to react with oxygen when subjected to other forms of energy such as heat.

3.3.2 Chemical Compatibility of Partially Fluorinated Fluoropolymers

Partially fluorinated fluoropolymers with commercial significance include ethylene-tetrafluoroethylene copolymer (ETFE), ethylene-chlorotrifluoroethylene copolymer (ECTFE), polyvnylidene fluoride (PVDF), and polyvinyl fluoride (PVF). The presence of hydrogen in these plastics lowers the fluorine content compared to perfluoropolymers, and renders them susceptible to some chemicals. This means that care must be taken in the selection of these polymers to insure compatibility of process fluids.

ETFE has excellent resistance to a great many chemicals. It is somewhat affected by oxidizers, chlorinated solvents, ketones, and esters but resists acids, alkalis, and organic solvents. Tests should be conducted in each specific application to verify the validity of the values (data) provided.

Hydrolytic stability of ETFE is indicated by retention of its physical properties after extensive exposure to boiling water. Tensile strength and elongation changed little after 3,000 hours exposure of unfilled ETFE to boiling water.

PVDF, in general, resists inorganic acids, bases, salt solutions, oxidizing agents, and halogens. It is, however, attacked by concentrated sulfuric acid and medium concentration alkaline solutions. PVDF is unaffected by alcohols, chlorinated solvents, aliphatic and aromatic hydrocarbons, and crude oil. It swells in some polar solvents such as ketones and esters. PVDF dissolves in some polar solvents like dimethylformamide, dimethylacetamide, and N-methylpyrrolidone. Hot amines attack polyvinylidene fluoride.

ECTFE is resistant to strong mineral and oxidizing acids, alkalis, metal etchants, liquid oxygen, and virtually all organic solvents with the exception of hot amines such as aniline and dimethyl amine. ECTFE is susceptible to attack by metallic sodium and potassium; the rate of attack is dependent on the time and temperature of exposure. Certain halogenated solvents can plasticize ECTFE without impairing its usefulness. After discontinuing contact between the part and the solvent, it dries and mechanical properties recover to the original values. A conclusion of this observation is that the interaction between ECTFE and the solvents in these cases is strictly physical and not chemical. ECTFE is compatible with liquid oxygen (LOX) as measured by National Aeronautics and Space Administration (NASA) test method MSFC-SPEC-106B. It is also resistant to nitrogen tetroxide (NTO) and monomethylhydrazine (MMH).

3.3.3 Chemical Compatibility of Polychlorotrifluoroethylene

Polychlorotrifluoroethylene (PCTFE) resists attack by most industrial chemicals. The exceptions include alkali metal complexes and organic amines. Chlorine gas, nitrogen tetraoxide, and a number of halogenated solvents are absorbed by PCTFE. Most silicones induce stress cracking. Tables 3.3 and 3.4 summarize weight gain of low and high molecular weight grades after exposure to each chemical for a period of two weeks at room temperature.

3.4 Permeation Fundamentals

Permeation can be defined as the passage of gases and liquids through a second material such as a solid. It is a significant consideration in the selection of plastic material for the construction of chemical processing equipment because process fluids may travel across the thickness of the polymer by permeation. Permeated species in sufficient quantities could cause corrosion, contamination, or unacceptable environmental emission, singly or in combination.

In its simplest form, permeation can be expressed as a product of the solubility and diffusion coefficient of the permeant in the polymer. Permeation of a gas can be calculated from Eq. (3.1):

Eq. (3.1) $$P = D \cdot S$$

where P (cm^3/sec·cm·atm) is the permeability of the gas, D is the diffusion coefficient (cm^3/sec), and S (cm^3/cm^2 · atm) is the solubility coefficient. This equation is derived from Fick's first law of mass transfer. Permeation concerns the movement of a species through the molecules of another species, e.g., a gas through a polymer. It does not take into account transport of material through cracks, voids, and, in general, physical flaws in the structure of the second species such as the polymer. To be sure, both phe-

Table 3.3. Weight Gain of PCTFE after Two Weeks' Exposure to Inorganic Reagents at Ambient Temperature[8]

Reagent	Low Molecular Weight PCTFE, SG = 2.08	High Molecular Weight PCTFE, SG = 2.12
Ammonium Hydroxide	None	None
Aqua Regia	0.10	0.04
Bromine	0.15	0.1
Carbon Disulfide	0.4	0.2
Hydrochloric Acid (10%)	None	None
Hydrochloric Acid (36%)	None	None
Hydrofluoric Acid (60%)	None	None
Hydrogen Peroxide (30%)	0.23	None
Nitric Acid (10%)	None	None
Nitric Acid (70%)	None	None
Nitric Acid (Red Fuming)	0.07	0.04
Nitric Acid/Hydrofluoric Acid (50:50) (60%)	None	None
Sodium Hydroxide (50%)	None	None
Sodium Hypochlorite	None	None
Sulfuric Acid (30%)	None	None
Sulfuric Acid (Fuming 20%)	0.03	0.02

Table 3.4. Weight Gain of PCTFE after Two Weeks' Exposure to Organic Chemicals at Ambient Temperature[8]

Reagent	Low Molecular Weight PCTFE, SG = 2.08	High Molecular Weight PCTFE, SG = 2.12
Acetic Acid (3%)	None	None
Acetic Acid (Glacial)	0.09	0.03
Acetone	5.17	0.5
Acetophenone	None	None
Aniline	0.01	None
Benzaldhyde	0.02	None
Benzene	2.4	0.6
Benzoyl Chloride	0.14	None
Butyl Alcohol	-	None
Carbon Tetrachloride	4.1	1.6
Citric Acid (3%)	None	None
Cyclohexanone	0.35	None
1,2-Dichloroethane	0.11	0.03
2,4-Dichlorotoluene	0.15	0.06
Diethyl Phthalate	None	None
Dimethylhydrazine (Anhydrous)	3.9	1.8
Ethyl Acetate	7.65	6.0
Ethyl Alcohol (Anhydrous)	None	None
Ethyl Ether	5.6	5.2
Ethylene Oxide	5.8	4.0
Formic Acid	None	None
Furan (B.P. 31-32ºC)	5.4	3.7
Premium Gasoline	0.83	0.2
Heptane	None	None
Hexachloroacetone	None	None
Hydraulic Fluid	None	None
Lactic Acid	None	None
Methanol	0.10	None
Methyl Ethyl Ketone	5.9	1.2
Motor Oil	0.01	0.01
2,4-Pentanedione	0.17	0.20
Pyridine	0.55	0.10
Toluene Diisocyanate	0.44	-
1,1,2-Trichloroethane	0.04	0.02
Trichloroethylene	10.9	7.8
Triethylaluminum	0.13	0.01

nomenon result in the migration of chemicals through the structure. This means that after an appropriate plastic material has been selected to meet the permeation requirements of a process, the equipment must be fabricated carefully to avoid flaws in the polymer structure.

Several factors affect the permeation rate of the polymer. Temperature increase raises the permeation rate for two reasons. First, solubility of the permeant increases in the polymer at higher temperatures. Second, polymer chain movements are more abundant which allow easier diffusion of the permeant. The permeation rate of gases increases at higher partial pressures. For liquids, permeation rates rise with an increase in the concentration of the permeant. Unless the permeant species are highly soluble in the polymer, the permeation rate increases linearly with pressure, concentration, and the area of permeation.

The permeation rate decreases at higher thickness, as illustrated in Fig. 3.2 for water transmission through a perfluorinated ethylene propylene copolymer (FEP). The effect of thickness is usually nonlinear. The permeation rate is very high at a low thickness and rapidly decreases with an increase in the thickness. After a critical thickness is reached, the effect of thickness is diminished and the permeation rate reaches a plateau. At lower thicknesses, the effect of surface structure begins to play a significant role in the permeation. A more oriented (ordered) surface will serve to inhibit permeation.

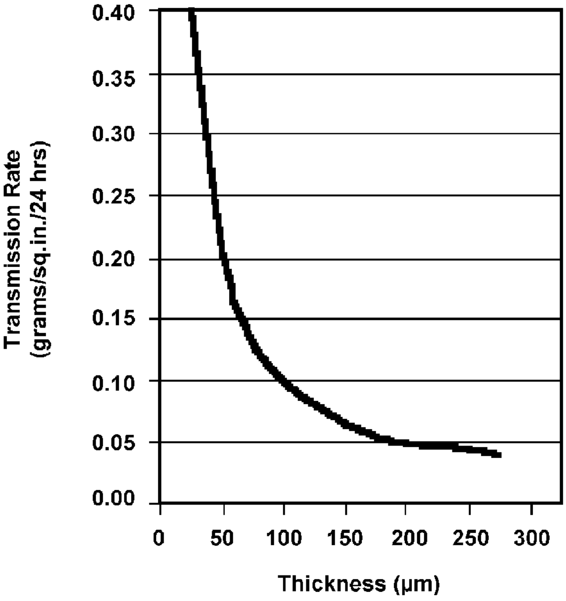

Figure 3.2 Water vapor transmission rate of Teflon® FEP resins at 40°C.[9]

Chemical and physical characteristics of the polymer have powerful effects on the rate of permeation, as much as four orders of magnitude.[10] Chemical affinity for the permeant, intermolecular forces such as van der Waals and hydrogen bonding forces, degree of crystallinity, and degree of crosslinking are the influential variables.

A similarity of chemical functional structures of the polymer and the permeant will promote solubility and permeation rate. Higher intermolecular forces of the polymer result in less permeation because of the resistance that they present to the development of space between adjacent molecules required for the passage of the permeant. Crystallinity is an important factor that can be controlled during the processing of the polymer. The crystalline phase can be considered impermeable by most species because of its orderly structure (packing) which usually minimizes its specific volume. This means that there is little or no free space among the polymer chains for the passage of a permeant. The amorphous phase has the opposite construction and is disorderly with interchain space available for permeation. The specific volumes of the crystalline (0.43 cm^3/g) and amorphous (0.5 cm^3/g) phases of PTFE provide evidence for the argument. The amorphous phase has a 13% higher specific volume, which translates into additional space for permeation. Finally, crosslinking acts somewhat similar to crystallinity, though less effective, to limit space for permeation. Crosslinking is size-dependent and smaller species may permeate.

The molecular size of the permeant, its chemical structure, and its condensation characteristics affect permeation. Diffusion of the permeant increases as its molecular size decreases, thus contributing to an increase in permeation. Molecular structure is important. A polar chemical will normally have a lower permeation rate in a nonpolar polymer than a nonpolar species would, and vice versa. This is due to the ability of chemicals with structures similar to the polymer to swell the polymer, that is, to create space between the chains for permeation. A more easily condensed chemical will also be more effective in swelling the polymer, resulting in higher rates of permeation.

3.4.1 Permeation Measurement and Data

A number of methods can be used to measure permeation rate through polymers including fluoropolymers. These methods are helpful for comparison of different materials. The extent of the information obtained is limited due to the inability of these techniques to account for real-world conditions. Typically, a film of fluoropolymer acts as a barrier to keep a gas or liquid in a reservoir (Thwing Albert cup). Permeation rate is calculated from the measured pressure or weight loss in the reservoir. Examples of techniques include ASTM D813 and F739-81. There are more complex means of measuring permeation which approach the actual applications conditions. One example is a controlled recirculation of a fluid through a closed loop system which contains commercially manufactured parts made with fluoropolymers, such as lined components. In these systems, gas chromatography and mass spectroscopy are used to analyze the permeation.

A comparison of moisture vapor permeation through various polymers can be seen in Table 3.5. Notice that PCTFE is only second to FEP and both are among the most resistant plastics to water vapor permeation. Permeability data can be found in Appendixes I through IV.

3.5 Environmental Stress Cracking

A weakness of many polymers is their tendency to fail at fairly low stress levels due to the impact of some hostile environments. This phenomenon is known as *environmental stress cracking*. Cracking occurs when the polymer is stressed for a long time under loads that are relatively small compared to the yield point of the material. A well-known example includes the failure of vulcanized natural rubber in the presence of ozone. It reacts with unsaturated hydrocarbons at the surface and, even when the elastomers are subjected to low stresses, cracks can develop and lead to failure. Another example is stress cracking of polyolefins such as high-density polyethylene in the presence of surfactants. When polyethylene is held under stress in the presence of some detergents, its behavior changes from short time ductile failure at high stresses to brittle fracture at low stresses after relatively longer times with very small break elongations.[11]

Even though environmental stress cracking must be considered in designing parts from fluoropolymers, it is not considered an extensive problem for this family of plastics. Permeation variables have a strong influence on stress cracking. Different fluoropolymers differ in their propensity to environmental stress cracking, primarily based on their degree of crystallinity. Crystallinity can be lowered by adding a comonomer and varying its concentration. A higher comonomer content decreases the crystalline phase content of the polymer. Resin processing can affect crystallinity. Fast cooling (or quenching) at the end of the fabrication process serves to reduce crystalline content and increase amorphous content. Lowering the crystalline phase content of the part tends to increase resistance to stress cracking due to the increasing break elongation. Increasing the molecular weight of the polymer reduces its crystallinity and enhances its stress crack resistance. Longer chains have higher tensile strength, i.e., load-bearing ability.

Chemicals with structures similar to the polymer tend to permeate and plasticize, thus reducing its mechanical strength. Fluoropolymers can be permeated by small halogenated molecules because of the similarity of structures (especially fluorine and chlorine). The environmental stress cracking effect of chemicals on polymers can be measured by exposing the polymer to the chemical under the desired conditions. Tensile properties of the exposed sample can then be measured. Any significant loss of elongation and tensile strength would indicate environmental stress cracking.

Processing of the fluoropolymers plays an important role in minimizing the tendency to undergo stress cracking. Reducing crystallinity as much as possible and minimizing residual stresses lowers the tendency of a part to experience environmental stress cracking. These objectives can be achieved by reducing processing times and decreasing cool-down rates, and annealing.

Another issue is the stress that a part experiences in application. Tensile loads cause less tendency for stress cracking than compressive loads. Fluoropolymer-lined equipment and parts are examples of objects which may contain residual stresses due to their design and/or fabrication.

Table 3.5. Permeation (Transmission) of Water and Gases through Polymer Films[8]

Polymer Film	**Water Vapor Transmission** gm-mil 100 in^2/24 hrs @ 100°F @ 90% RH (gm-mm/m^2/24 hrs @ 37.8°C @ 90% RH)	**Gas Transmission** cc [STP] mil/100 in^2/24 hr-ATM @ 77°F (cc [STP] mm/m^2/24 hr-ATM @ 25°C)		
	H_2O	**O_2**	**N_2**	**CO_2**
[1]ACLAR® UltRx, SupRx, Rx	0.016 (0.006)	7 (2.8)	1 (0.4)	14 (5.5)
ACLAR® 33C	0.020 (0.008)	7 (2.8)	1 (0.4)	16 (6.3)
ACLAR® 22C	0.026 (0.010)	15 (5.9)	2.5 (1.0)	40 (15.7)
ACLAR® 22A	0.027 (0.011)	12 (4.7)	2.5 (1.0)	30 (12.0)
PVC, PVDC Copolymer	0.20–0.6 (0.08–0.24)	0.8–6.9 (0.3–2.7)	0.12–1.5 (0.05–0.6)	38–44 (15–17)
Polyethylene				
Low Density	1.0–1.5 (0.39–0.59)	500 (195)	180 (71)	2700 (1060)
Medium Density	0.7 (0.28)	250–535 (100–210)	85–315 (35–125)	100–2500 (40–985)
High Density	0.3 (0.12)	185 (73)	42 (17)	580 (230)
CAPRAN® 77C (Nylon 6)	19–20 (7.5–7.9)	2.6 (1.0)	0.9 (0.35)	4.7 (1.9)
Fluorinated Ethylene Propylene	0.22 (0.008)	715 (281)	320 (125)	1670 (660)
Polyvinyl Fluoride	2.1 (0.81)	7.5 (3)	0.25 (0.10)	11 (4.3)
Polyvinylidine Fluoride	2.5 (1.0)	3.4 (1.34)	9 (3.5)	5.5 (2.2)
Polyester—PET Oriented	1.0–1.3 (0.39–0.51)	3.0–6.0 (1.2–2.4)	0.7–1.0 (0.28–0.39)	15–25 (5.9–9.8)

[1] ACLAR® is made from polychlorotrifluoroethylene.

3.6 Properties and Characteristics of PTFE

3.6.1 Introduction to Filled PTFE Compounds

Unfilled polytetrafluoroethylene is inadequate for a number of mechanically demanding engineering applications. Cold flow or creep would prevent the use of PTFE in many mechanical applications. Addition of fillers has been found to improve a number of physical properties of PTFE, particularly creep and wear rate. Filled granular resins were found to be suitable for parts such as gaskets, shaft seals, bearings, bearing pads, and piston rings. Chemical resistance, low friction, and high temperature, combined with mechanical requirements, prompt specification of filled polytetrafluoroethylene as a material of construction. Filled compounds of granular polytetrafluoroethylene are the most commercially significant commodities because of the large volume of consumption.

Compounds of fine powders of PTFE are made in-house and fabricated into articles. PTFE dispersions are formulated into coatings by incorporation of a variety of additives. Polychlorotrifluoroethylene compounds are highly specialized and not very common.

The next few sections describe the characteristics, properties, and methods of production of filled polytetrafluoroethylene powders.

3.6.1.1 Granular-based Compounds

Compounds, known as *granular powders*, are made with granular polytetrafluoroethylene resin. The choice and concentration of the filler depends on the desired properties of the final part. Glass fiber, bronze, steel, carbon, carbon fiber, and graphite are among the common filler materials. Up to 40% by volume of filler can be added to the resin without complete loss of physical properties. The impact of additives below 5% by volume of filler on the properties of compounds is insignificant. Above 40%, most physical properties of the compounds drop sharply.

Fillers. Polytetrafluoroethylene is one of the more difficult polymers to compound. This is due to the extreme neutrality of PTFE chains, which precludes any interaction with fillers. It does not have sufficiently low viscosity to flow upon melting and coat the surface of the fillers. Low coefficient of friction reduces mechanical interaction, rendering PTFE easily separable from the filler in physical mixtures. Compounding the filler with this polymer in the form of agglomerated granules is one method of locking in the filler, thus preserving the uniformity of the mixture.

The only requirement for an additive to qualify as filler for PTFE is that it should be able to withstand the sintering temperatures of polytetrafluoroethylene. Sintering involves exposure to temperatures close to 400°C for several hours, which excludes a great many materials. Characteristics of the filler such as particle size and shape and the chemical composition of the filler affect the properties of compound. A list of most common fillers and descriptions of their important characteristics can be found in Table 3.6.

Glass fiber is the most common filler with a positive impact on creep performance of PTFE by reducing it at low and high temperatures. This additive is chemically inert with the exception of its reactivity with hydrofluoric acid and strong bases. Glass filled compounds perform well in oxidizing environments. Wear characteristics of polytetrafluoroethylene are improved. Glass has little impact on the electrical properties of PTFE. Dielectric breakdown strength is somewhat adversely affected due to the increased porosity of parts. One drawback to glass is the discoloration of sintered parts, more prevalent at higher thicknesses. This problem can be solved by chemical treatment or baking of the glass fiber. In the latter case, the fiber is simply heated in an air oven for 24 hours at or above 260°C.

Typical properties of two compounds are summarized in Table 3.7. Increasing the glass fiber content of the compound reduces standard specific gravity (SSG) and shrinkage moderately, while physical properties decline more drastically.

Carbon reduces creep, increases hardness and elevates thermal conductivity of polytetrafluoroethylene. Wear resistance of carbon filled compounds improves, particularly when combined with graphite. Carbon-graphite compounds perform well in nonlubricated applications such as piston rings in compressor cylinders. Carbon-filled PTFE has some electrical conductivity. Close tolerances can be achieved

Table 3.6. Properties of Common Fillers[12]

Filler	Material Description	Particle Size (µm)	Particle Shape	Density, g/cm^3
Glass	E glass	Diameter: 13 mm Length: 0.8 mm Aspect ratio: >10	Milled fibers	2.5
Carbon	Amorphous petroleum coke	Diameter: <75 µm	Roundish	1.8
Carbon Fiber	Pitch or PAN* based		Short fibers	
Graphite	>99% C, Synthetic or natural	<75 µm	Irregular shape	2.26
Bronze	9/1 Copper to tin ratio	<60 µm	Spherical or irregular shape	
Molybdenum Disulfide	Mineral (98% pure)	<65 µm		4.9

* PAN = Polyacrylonitrile

during machining by reducing the wear rate of the tool by using a softer carbon powder.

Carbon fiber lowers creep, increases flex and compressive modulus, and raises hardness. These changes can be achieved with glass but less carbon fiber can achieve the same effects. Carbon fiber is inert to both hydrofluoric acid and strong bases which react with glass. Coefficient of thermal expansion is lowered and thermal conductivity is higher for compounds of carbon fiber PTFE. Carbon fiber parts are lubricated with water, that is, wear rate decreases, making them ideal for automotive applications in shock absorbers and water pumps.

Graphite filled polytetrafluoroethylene has an extremely low coefficient of friction due to the low friction characteristics of graphite. Graphite is chemically inert. It is also incorporated in combination with other additives such as carbon and glass. Graphite imparts excellent wear properties to PTFE, especially in contact against soft metals,[12] and high PV (pressure-velocity) values.

Bronze is the most popular metallic filler, although steel powder is occasionally used. Large quantities (40%–60% by weight) of bronze reduce deformation under load and raise thermal and electrical conductivity of PTFE compounds. These two characteristics are beneficial to applications where a part is subjected to load at extreme temperatures. Transmission and air-conditioner compressor seals are two examples of such parts. Bronze is an alloy of copper and tin and is attacked by acids and bases. It is oxidized and discolored during the sintering cycle with no impact on the quality. Nonoxidizing grades are available from suppliers such as US Bronze.

Molybdenum disulfide is an interesting additive. It increases the hardness of the surface while decreasing friction. Electrical properties of the compound are virtually unaffected. It is normally used in small proportions combined with other fillers such as glass. MoS_2 reacts with oxidizing acids and is inert towards most other chemicals.

A number of other fillers are incorporated in polytetrafluoroethylene to produce compounds for specialty applications. Calcium fluoride can replace glass in end-uses where glass is attacked by chemicals. Alumina (Al_2O_3) is an excellent electrical insulator which also improves the mechanical properties of the compound for use in high voltage components. Inorganic pigments, able to withstand sintering temperatures, are added to impart color to PTFE compounds for customization or ease of identification of parts. Mica has a platelet structure and imparts desirable properties to polytetrafluoroethylene. Mica particles orient themselves perpendicularly to the direction of pressing. This orientation results in a significant reduction in shrinkage and the coefficient of thermal expansion in the direction of orientation. Physical properties of the compounds are severely lowered, thus rendering mica compounds only useful for compressive applications.

PTFE can be compounded with polymeric fillers with adequate thermal stability. Examples of such polymers include polyarylates such as polyetherketone, polyphenylene sulfone, and polyphenylene sulfide. Surface characteristics such as wear rate, coefficient of friction, and surface tension can be modified with these additives.

Polytetrafluoroethylene selection. Polymer selection for compounding granular PTFE is relatively straightforward. Fine cut resins are used as a starting point to produce filled compounds. These powders have relatively small particle size and form the most uniform compounds. Typically, smaller particle size resins produce compounds with higher physical properties.

Filled PTFE—production techniques. Granular polytetrafluoroethylene compounds containing fillers are converted into parts by the same molding techniques as those used for neat resin. The compounding techniques aim at producing uniform blends of PTFE with fillers that can be processed in the same molding equipment. The rest of this section describes methods by which compounds can be made.

3.6.1.2 Fine Powder-based Compounds

Fine powder polytetrafluoroethylene is compounded to a much lesser extent than granular resin. It is relatively difficult to mix solids with fine powder PTFE to form a uniform blend. This is due to the large average agglomerate size (several hundred microns) of fine powders. Large concentration of filler particles serves as points of stress concentration, thus deteriorating the physical properties of the compound. Excessive shearing will lead to fibrillation of polymer particles as opposed to deagglomeration. Fibrillation of PTFE during mixing will render the mixture unusable for extrusion.

The limitation in the shear that can be applied to the resin limits the filled volume fraction. Size and shape of the filler particles impact the maximum volume fraction; more of the smaller particles can be incorporated. Incorporation of additives including fillers and pigments into fine powder polymer is usually intended to accomplish one of the following objectives:

Achieve a color

Increase electrical conductivity

Increase abrasion resistance

3.6.1.3 Compounding with Engineering Polymers

An important family of fillers is engineering polymers. These plastics are hard and, when combined with polytetrafluoroethylene, produce compounds that exhibit low coefficient of friction and a lower wear rate relative to PTFE. Flow under load or creep is also reduced. An application for such compounds is extruded tubing for push-pull cables (automotive) where low friction and wear rate is required. Examples of these polymers include polyarylene and polyamide-imide resins. Commercial polyarylene plastics include polyetheretherketone (PEEK), polyetherketone (PEK), polyetherketoneketone (PEKK), polyphenylenesulfide (PPS), polyether sulfone, and polyphenylene sulfone. A successful compound has been reported with Torlon® 400TF.[14] The powder form of these polymers is mixed with PTFE resin by briefly pre-mixing the dry powders below the transition point of polytetrafluoroethylene followed by adding lubricant and tumbling in a V-shaped mixer.

PTFE compounds may contain other additives in the form of fiber or bead, which are less expensive than engineering polymers. Some useful fillers include glass, and metals oxides[14] which also induce abrasion resistance. Abrasion resistance testing in a push-pull cable indicated that inclusion of 10 parts per hundred (phr) of polyphenylene sulfide (relative to PTFE) and 25 phr of glass beads increased the life

Table 3.7. Properties of Free Flow Glass Compound[13]

Glass Fiber, wt. %	Average Particle Size, µm	SSG	Apparent Density, g/l	Shrinkage, %	Tensile Strength, MPa	Break Elongation, %
25.2	610	2.193	877	1.33	13.8	179
38.8	670	2.174	862	0.53	8.3	79

cycle to more than 500,000 from 25,000 for an unfilled PTFE.[15] Similar results were obtained by the addition of 15 phr polyamide-imide to polytetrafluoroethylene.

3.6.1.4 Reinforced Gasketing Material

Reinforced fine powder polytetrafluoroethylene material is primarily used for application as gaskets and seals in extreme temperature, pressure, and chemical environments. A gasket in this type of application must be resilient and resistant to corrosive chemicals and also maintain a high tensile strength and dimensional stability at high temperature and pressure. PTFE has the necessary corrosion resistance to the majority of industrial chemicals up to its melting point (327°C), but in its neat (without fillers or additives) form, it is not satisfactory in many applications because of the high cold flow (creep) that is inherent to PTFE. After a short while, an unfilled PTFE gasket will begin to “creep” under the pressure exerted by bolt loads that squeeze the gasket between flanges. The net result of cold flow is loss of gasket thickness and leaks. An increase in temperature both accelerates and increases creep.

The reinforcement approach deals with the problem of cold flow by highly filling PTFE with a variety of fillers, as high as 90% by weight. Fillers are usually hard materials such as metal powders, ceramic, glass fiber, carbon, and others. The processing technique to distribute the fillers and the choice of the polymer type help retain good physical properties in the reinforced (filled) material. Fabrication of reinforced gasket material is accomplished by filling the fine powder PTFE using a somewhat unusual process which incorporates the fillers in the polymer structure. Typically, sheets of the material are made out of gaskets which can be stamped.

Examples of tensile properties of biaxially oriented sheets, unfilled and filled, are given in Table 3.8. A comparison of biaxially oriented filled fine-powder PTFE, at different temperatures, with filled granular PTFE demonstrates the advantages of the biaxial orientation process. Deformation-under-load data for biaxially oriented sheets and their comparison with filled granular PTFE are given in Table 3.9, clearly illustrating the advantage of biaxial orientation in reducing deformation-under-load.

Further reduction in deformation can be obtained by alternately inserting perforated stainless steel plates (Fig. 3.3) between the oriented sheets prior to sintering.[17] The sintering process is conducted under pressure to consolidate the composite and obtain a predetermined thickness. At the end of sintering, the composite is cooled rapidly under pressure. PTFE actually bonds to stainless steel in this process. The decrease in creep is often substantial; for example, by insertion of two steel plates, the creep relaxation of a silica-filled PTFE is decreased from 57.9% to 30.5% at 100°C.[17]

3.6.1.5 Co-Coagulated Compounds

Co-coagulation is the method by which large quantities of fillers can be incorporated in dispersion polymerized polytetrafluoroethylene. The addition of fillers takes place prior to coagulation of the resin from its dispersion state. In the process of co-coagulation, the additives are added to the polytetrafluoroethylene dispersion and mixed. This dispersion is coagulated and the compound is recovered. The smaller the filler particles, the smaller the points of stress rise in the compound will be. Significantly larger quantities of filler can be compounded in PTFE by this technique.

Coagulation is quite rapid and is completed in less than three minutes. Clear liquid on top indicates complete coagulation while the appearance of a milky layer is a sign of incomplete coagulation. Agitation of the dispersion should continue until coagulation is completed. Afterwards, minimal shear should be applied to the compound to avoid separation of the polymer and the fillers.

Co-coagulated compounds can also be molded into thick sections. In this case, the surfactant should be removed by heating the material for 4 hours at 300°C. The lumps formed during this step can be broken by chilling and pulverizing.

3.6.1.6 Fabrication of Parts from Compounds

The principles of compression molding are applicable to the molding of filled compounds of granular polytetrafluoroethylene. There are some differences in the processing conditions due to the presence of fillers. Higher molding pressure is one requirement for successful molding of parts. Preform-

Table 3.8. Tensile Properties of Biaxially Oriented Sheeting[16]

	Biaxially Oriented Unfilled Resin	Unfilled Paste-Extruded PTFE	Biaxially Oriented 40% Graphite-Filled Fine Powder PTFE	35% Graphite-Filled Granular PTFE	Biaxially Oriented 25% Glass Fiber-Filled Fine Powder PTFE	35% Glass Fiber-Filled Granular PTFE
Temperature,°C	-40	-51	-40	-54	-40	-54
Tensile Strength, MPa	56.8	39.4	32.8	8.6	32	10.9
Break Elongation, %	85	50	15	6	48	8
Temperature,°C	23	23	23	23	23	23
Tensile Strength, MPa	35.6	27.6	16.8	6.7	18.1	7.6
Break Elongation, %	450	340	130	4	280	79
Temperature,°C	100	100	100	100	100	100
Tensile Strength, MPa	19.3	–	9.8	4	9.1	3.7
Break Elongation, %	380	–	77	5	240	144
Temperature,°C	260	232	260	260	260	260
Tensile Strength, MPa	9	8	4.9	1.8	3.2	1.5
Break Elongation, %	340	320	42	11	200	108

Table 3.9. Deformation Under Load[16]

Compound	Deformation @ 23°C at 14 MPa, ASTM D621, %
Biaxially Oriented, 40% Bronze	1.9
Granular PTFE, 60% Bronze	5.8
Biaxially Oriented, 25% Glass Fiber	2.6
Granular PTFE, 25% Glass Fiber	6.4

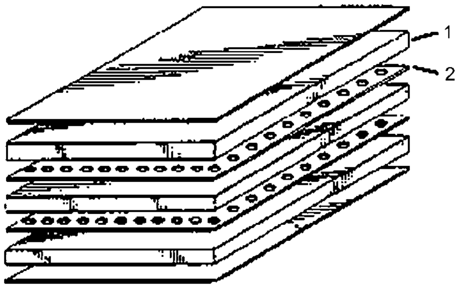

Figure 3.3 A composite of biaxially oriented sheeting with perforated steel plates.[17] *(1)* Biaxially oriented sheeting. *(2)* Perforated stainless-steel plate.

ing pressure affects the mechanical and physical properties of parts molded from compounds. Specific gravity, tensile strength, and elongation at break rise and reach plateau values with increasing preform pressure. Additional pressure has a detrimental effect on the properties.

In comparison with unfilled PTFE, compounds can be sintered by using shorter sintering cycles due to the increase in thermal conductivity of the preform by incorporation of fillers (Table 3.10).

3.6.1.7 Typical Properties of Filled Fluoropolymers

Properties of granular PTFE compounds are presented in this section. A few points should be noted about filled PTFE compounds. Shape and size of the filler and resin particles, type of molding process, and processing conditions all influence the properties of parts made from compounds. Properties of compounds made with non-spherical particles are

Table 3.10. Thermal Conductivity of PTFE Compounds[12]

Compound Type	Unfilled PTFE	15% wt. Glass Fiber	15% wt. Glass Fiber	60% wt. Bronze	23% Carbon/ 2% Graphite (wt.)	23% Carbon/ 2% Graphite (wt.)
Thermal Conductivity, W/(m·K)	0.24	0.33	0.41	0.57	0.58	0.63

usually anisotropic, i.e., they are dependent on the direction. Properties in the mold direction (MD) and perpendicularly cross direction (CD) must be measured to characterize fabricated articles. Reproducibility is only obtained by controlling all the variables.

The volume fraction of the fillers in the compound depends on its specific gravity. A higher weight fraction of heavier fillers such as bronze can be incorporated than lighter additives like glass. Physical properties of the compound deteriorate with increase in the volume fraction of the filler as illustrated in Fig. 3.4.

Mechanical properties. Polytetrafluoroethylene retains excellent properties at very low and high temperatures. Table 3.11 provides summary of some of the mechanical properties of three different compounds containing 65% bronze, 15% carbon, and 25% glass fiber at different temperatures. Properties of unfilled PTFE have been listed for comparison.

Tensile strength and break elongation at elevated temperatures are given in Table 3.12. All the listed compounds retain excellent tensile properties at above room temperature.

Deformation under load of all filled polytetrafluoroethylene compounds decreases in comparison to unfilled resin, as seen in Table 3.13. Combinations of carbon and graphite reduce deformation the most at room and at elevated temperatures. The next effective filler in reducing deformation under load is bronze at 60% by weight. Hardness is increased by the addition of additives, particularly bronze, carbon, and graphite (Table 3.14).

Compressive strength and flexural data are presented in Tables 3.15 and 3.16.

Thermal properties. Fillers reduce the linear coefficient of thermal expansion and contraction of compounds. Tables 3.17 and 3.18 provide data for several compounds at different temperatures. Aluminum reduces the coefficient of thermal contraction the most due to its flat platelet structure; mica has a similar effect.

Electrical properties. Fillers and additives significantly increase the porosity of polytetrafluoroethylene compounds. Electrical properties are affected by the void content as well as the filler characteristics. Dielectric strength drops while dielectric constant and dissipation factor rise. Metals, carbon, and graphite increase the thermal conductivity of PTFE compounds. Tables 3.19 and 3.20 present electrical properties of a few common compounds.

Chemical properties. Permeability of compounds increases due to the voids. The effect of preforming conditions on the extent of permeability increase is shown in Fig. 3.5.

Polytetrafluoroethylene has excellent chemical resistance properties. The effect of incorporation of additives on chemical properties depends on the type of the filler and the specific chemicals. In general, chemical properties of filled PTFE compounds are not as good as those of the unfilled resin. Table 3.21 shows the effect of a number of chemicals on carbon/graphite, glass, and bronze compounds.

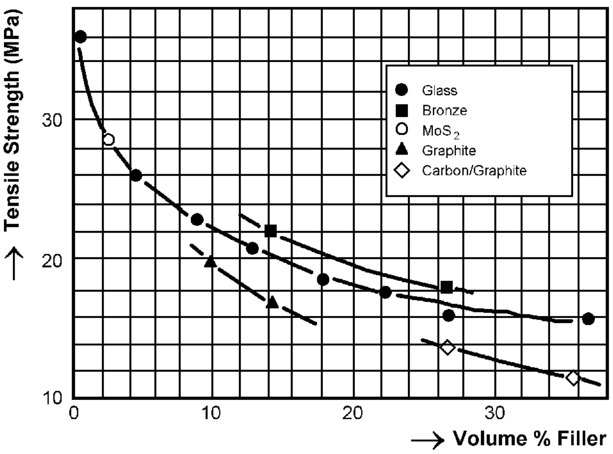

Figure 3.4 Tensile strength as a function of percent filler.[12]

Table 3.11. Mechanical Properties of Filled PTFE Compounds[12]

Property	Test Method	Units	Temperature °C	Unfilled*	Compound		
					65% Bronze	15% Carbon	25% Glass Fiber
Tensile yield strength	ASTM D1708	MPa	–253	123	—	—	30
			–196	92	47	44	24
			–183	(84)	(44)	(41)	(23)
			–129	53	(35)	(32)	(18)
			–79	36	(26)	(24)	(14)
			+23	18	12	8	10
Ultimate tensile strength	ASTM D1708	MPa	–253	124	—	—	31
			–196	103	47	47	25
			–183	(95)	(45)	(45)	(24)
			–129	63	(35)	(35)	21
			–79	42	(26)	(27)	20
			+23	36	15	16	19
Tensile modulus	ASTM D1708	MPa	–253	4300	—	—	3200
			–196	3200	—	—	2600
			–183	3100	—	—	(2500)
			–129	2100	—	—	(2000)
			–79	1400	—	—	(1600)
			+23	750	—	—	800
Elongation	ASTM D1708	%	–253	3	0	0	1
			–196	10	4	2	4
			–183	(12)	(5)	(4)	(6)
			–129	70	(34)	(23)	(35)
			–79	130	(70)	(50)	(80)
			+23	400	200	140	240
Flexural strength	ASTM D790	MPa	–253	Did not break	Did not break	Did not break	Did not break
			–196				
			–183				
			–129				
			–79				
			+23				
Flexural modulus	ASTM D790	MPa	–253	5100	—	—	2800
			–196	4700	—	—	2500
			–183	4600	—	—	2300
			–129	3200	—	—	1900
			–79	1600	—	—	1700
			+23	700	—	—	1000
Compressive strength	ASTM D695	MPa	–253	220	—	—	188
			–196	171	—	—	152
			–183	(168)	—	—	(140)
			–129	158	—	—	(109)
			–79	143	—	—	(79)
			+23	118	—	—	24

Note: Parentheses indicate values estimated by interpolation *Crystallinity: 41%–71%

(Cont'd.)

Table 3.11. ***(Cont'd.)*** **Mechanical Properties of Filled PTFE Compounds**[12]

Property	Test Method	Units	Temperature °C	Unfilled*	Compound		
					65% Bronze	15% Carbon	25% Glass Fiber
Compressive modulus	ASTM D695	MPa	–253	6200	6200	6100	6800
			–196	5500	5700	6000	5900
			–183	(5400)	(5400)	(5500)	(5600)
			–129	4100	(4100)	(4300)	(4400)
			–79	1900	(3000)	(3200)	(3200)
			+23	700	550	900	860
Torsional modulus of rigidity	ASTM D1043	MPa	–253	2200	—	—	1700
			–196	1500	—	—	720
			–183	(1400)	—	—	(690)
			–129	1000	—	—	(520)
			–79	500	—	—	(390)
			+23	160	—	—	110
Izod impact strength (notched)	ASTM D256	J/m	–253	75	67	51	53
			–196	80	70	60	59
			–183	(85)	(73)	(64)	(63)
			–129	(97)	(86)	(103)	(98)
			–79	133	(121)	(139)	(143)
			+23	160	161	169	173
Note: Parentheses indicate values estimated by interpolation					*Crystallinity: 41%–71%		

Table 3.12. Tensile Properties of Filled PTFE Compounds Measured According to ASTM D1708[12]

Temperature: 23°C	Unfilled PTFE	15% Glass	25% Glass	60% Bronze	23% Carbon, 2% Graphite	29% Carbon, 2% Graphite
Tensile strength, MPa						
MD	35.5	25.5	19.5	17.0	11.0	7.0
CD	36.5	24.5	18.5	17.0	15.0	10.0
Ultimate elongation, %						
MD	400	285	235	250	65	35
CD	450	290	250	235	105	50
Temperature: 150°C	**701-N**	**1103-N**	**1105-N**	**1146-N**	**1191-N**	**1192-N**
Tensile strength, MPa						
MD	13.5	8.6	6.3	5.4	3.8	3.0
CD	14.0	8.4	5.8	6.4	5.6	3.8
Ultimate elongation, %						
MD	440	350	305	305	120	60
CD	480	340	300	330	185	85

Table 3.13. Deformation Under Load of Filled PTFE Compounds Measured According to ASTM D621A, Molding Direction[12]

	Unfilled PTFE	15% Glass	25% Glass	60% Bronze	23% Carbon, 2% Graphite	29% Carbon, 2% Graphite
% deformation under load (1h, 23°C, 14.2 MPa)	11.8	9.8	9.0	7.8	4.8	4.7
% deformation under load (24h, 23°C, 14.2 MPa)	14.3	12.1	12.4	11.1	6.6	6.1
% permanent deformation	7.9	6.3	6.4	5.8	2.9	2.6
% deformation under load (1h, 150°C, 5 MPa)	10.0	9.8	9.2	8.2	6.6	5.6

Table 3.14. Hardness of Filled PTFE Compounds[12]

Compound	Hardness (Shore D)*	Indentation Hardness Test**
Unfilled PTFE	57	28
15% glass	62	24
25% glass	65	27
5% moly	62	30
15% graphite	63	36
60% bronze	70	39
25% carbon/graphite	68	39
32% carbon/graphite	70	—

*Measured according to ASTM D2240 at 23°C **Measured according to DIN 53456

Table 3.15. Compressive Strength of Filled PTFE Compounds Measured According to ASTM 695M, Molding Direction[12]

	15% Glass	25% Glass	60% Bronze	23% Carbon, 2% Grahpite	29% Carbon, 3% Graphite
Compressive strength, MPa (0.2% offset, 23°C)	6.8	7.2	8.2	8.8	9.0
Compressive modulus, MPa (23°C)	725	860	1050	970	815
Compressive strength, MPa (0.2% offset, 150°C)	1.6	1.8	2.1	2.3	2.8
Compressive modulus, MPa (150°C)	160	174	219	236	224

Table 3.16. Flexural Properties of Filled PTFE Compounds Measured According to ASTM D790 M1, Molding Direction[12]

	Unfilled PTFE	15% Glass	25% Glass	60% Bronze	23% Carbon, 2% Graphite	29% Carbon, 3% Graphite
Flexural yield strength, MPa (23°C, 0.2% offset)	—	6.2	5.5	8.8	10.3	8.8
Flexural modulus, MPa (23°C)	690	820	1000	1290	1090	1180

Table 3.17. Coefficient of Linear Thermal Expansion of Filled PTFE Compounds[12]

Material	Linear Thermal Contraction (% or μm/m × 10^4) from 15°C to:				
	–79°C	–129°C	–183°C	–197°C	–253°C
SAE 1020 Steel	0.1	0.1	0.1	0.2	0.2
Copper	0.2	0.2	0.3	0.3	0.3
Aluminum	0.2	0.3	0.4	0.4	0.4
PTFE, unfilled	1.5	1.9	2.0	2.1	2.1
PTFE, 60% bronze	0.8	1.0	1.2	1.2	1.4
PTFE, 25% Glass fiber (MD)	1.0	1.2	1.5	1.5	1.7
PTFE, 25% Glass fiber (CD)	0.6	0.8	0.9	0.9	0.9
PTFE, 15% Graphite	0.9	1.2	1.4	1.4	1.5

Table 3.18. Coefficient of Linear Thermal Expansion of Filled PTFE Compounds Measured According to ASTM E831[12]

Temperature Range (°C)	Unfilled PTFE		15% Glass		25% Glass		60% Bronze		23% Carbon, 2% Graphite		29% Carbon, 3% Graphite	
	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD	MD	CD
–150 to +15	103	96	88	74	83	61	70	66	79	57	67	50
–100 to +15	119	109	102	86	96	69	80	77	90	64	77	57
–50 to +15	131	117	111	93	106	74	87	84	95	67	84	61
+15 to +23	472	286	332	278	284	180	201	207	315	158	222	133
+23 to +100	125	129	135	123	109	66	117	110	114	70	108	80
+23 to +200	142	152	156	153	136	84	134	132	136	88	132	99
+23 to +250	159	176	181	179	159	102	155	152	158	107	152	115
Molded at preform pressure, N/mm^2	21		45		55		45		70		90	

Table 3.19. Electrical Properties of Filled PTFE Compounds Measured According to ASTM D149, D150[12]

	Unfilled PTFE	15% Glass	25% Glass	60% Bronze*	20% Glass, 5% Graphite	15% Glass, 5% MoS_2
Dielectric strength, kV/mm						
in air	59	17.6	12.9	x	2.48	27.2
in oil	—	36.2	34.2	x	7.36	36.7
Dielectric constant						
60 Hz	2.1	2.50	2.63	x	3.38	2.71
10^6 Hz	2.1	2.35	2.85	x	3.25	2.68
Dissipation factor						
60 Hz	<0.0003	0.0753	0.0718	x	0.0761	0.0464
10^6 Hz	<0.0003	0.0029	0.0028	x	0.0024	0.0061

*Note that bronze was too conductive to be measured.

Table 3.20. Resistivity of Filled PTFE Compounds Measured According to ASTM D257[12]

	Unfilled PTFE	15% Glass	25% Glass	60% Bronze	23% Carbon, 2% Graphite	29% Carbon, 3% Graphite
Surface resistivity (Ω)	10^{17}	$>10^{16}$	$>10^{16}$	$>10^{16}$	10^{7}	10^{7}
Volume resistivity (Ω · cm)	10^{18}	$>10^{17}$	$>10^{17}$	10^{17}	10^{5}	10^{6}

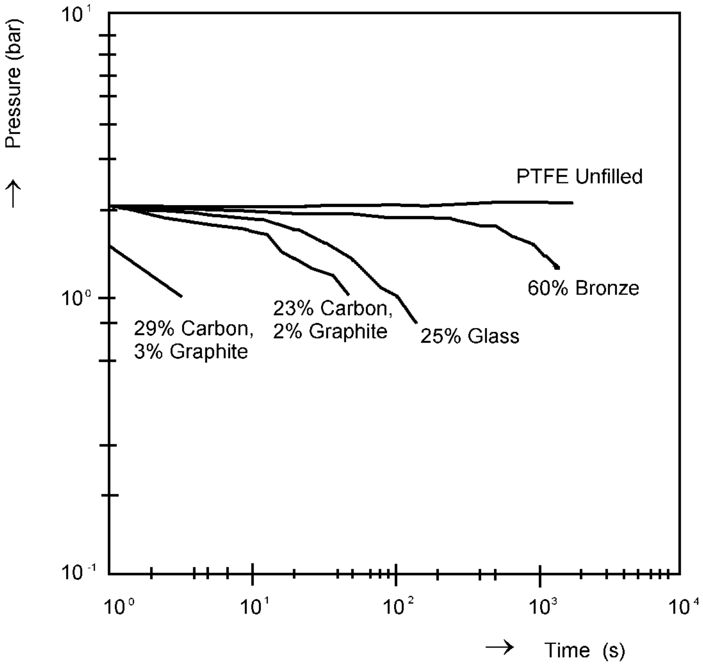

Figure 3.5 Effect of preforming conditions on the permeability of filled PTFE compounds.[12] (Nitrogen permeability of Teflon compounds measured on a membrane 50 mm diameter, 0.5 mm thickness.)

Table 3.21. Chemical Resistance of Filled PTFE Compounds[12]

Chemical	Filler		
	Carbon/Graphite	Glass	Bronze
Acetaldehyde	A	A	A
Acetone	A	A	A
Aluminium sulphate	A	A	B
Ammonium chloride	A	A	C
Ammonium hydroxide	A	B	C
Aniline	A	A	C
Benzene	A	A	A
Boric acid	A	A	A
Brine	A	A	A
Bromine (anhydrous)	C	B	C
Carbon disulphide	A	A	A
Chloroacetic acid	A	A	B
Chlorobenzene	A	A	A
Chloroform	A	A	A
Chromic acid	B	B	C
Citric acid	A	A	A
Diethyl ether	A	A	A
Ethylene glycol	A	A	A
Fatty acids	A	A	A
Ferric chloride	A	A	C
Ferric sulphate	A	A	C
Fluorosilicic acid	B	C	C
Formic acid	A	A	A
Freon* (liquid)	A	A	A
Hydroboric acid	A	B	C
Hydrochloric acid	A	B	C
Hydrocyanic acid	A	B	C
Hydrofluoric acid	A	C	C
Hydrogen sulphide (solution)	A	C	C
Lead acetate	A	A	C
Maleic acid	A	A	B
Mercury salts	A	A	C
Molasses	A	A	B
Naphtha	A	A	B
Naphthalene	A	A	B
Nickel salts	A	A	A
Nitric acid (0–50%)	C	B	C
Nitro benzene	A	A	A
Phenol	A	B	A
Phosphoric acid	A	A	C
Phthalic acid	A	A	A

A = Excellent, B = Fair, C = Unsatisfactory
*Freon is DuPont's registered trademark for its fluorocarbon solvents.

(Cont'd.)

Table 3.21. ***(Cont'd.)*** **Chemical Resistance of Filled PTFE Compounds**[12]

Chemical	Filler		
	Carbon/Graphite	Glass	Bronze
Picric acid	A	A	A
Pyridine	A	A	C
Salicyclic acid	A	A	B
Silver nitrate	A	A	C
Sodium carbonate	A	A	A
Sodium hydroxide	A	B	A
Sodium nitrite	A	A	A
Sodium peroxide	B	A	C
Sodium silicate	A	C	A
Sodium sulphide	A	A	C
Starch	A	A	A
Sulphuric acid	B	A	C
Tallow	A	A	A
Tannic acid	A	A	A
Tartaric acid	A	A	A
Trichloroethylene	A	A	B
Zinc chloride	A	A	C
A = Excellent, B = Fair, C = Unsatisfactory			

3.6.2 Mechanical Properties of PTFE

These properties are among the most important factors for the design of plastic parts and systems. In this section data for stress-strain behavior of PTFE in different modes and conditions are presented. Stress-strain curves for polytetrafluoroethylene are shown in Figs. 3.6 and 3.7 at various temperatures.

Figure 3.6 indicates that yield occurs at fairly high strain levels. The yield deformation decreases as temperature increases. The elastic modulus, defined as the slope of the linear part of the stress-strain curve, increases significantly with decreasing temperature. Figure 3.7 shows the ultimate values of stress before failure by fracture occurs. Tensile strength decreases while break elongation increases with increasing temperature. Figures 3.8 through 3.11 provide stress-strain data for tension, compression, and shear modes. Yield stress in the compressive mode has a similar value to that in the tensile mode.

Poisson's ratio is defined as the ratio of the change in the width per unit width of a material, to the change in its length per unit length, as a result of strain.[19] Poisson's ratio for PTFE is about 0.5 at above room temperature. At 23°C, it has a value of 0.46.

3.6.2.1 Deformation Under Load (Creep) and Cold Flow

This property is an important consideration in the design of parts from polytetrafluoroethylene. PTFE deforms substantially over time when it is subjected to load. Metals similarly deform at elevated temperatures. *Creep* is defined as the total deformation under stress after a period of time, beyond the instantaneous deformation upon load application. Significant variables that affect creep are load, time under load, and temperature. Creep data under various conditions in tensile, compressive, and torsional modes can be found in Figs. 3.12 through 3.19.

Resin manufacturers have long recognized the excessive deformation of polytetrafluoroethylene in applications where parts such as gaskets and seals experience high pressures. Copolymers of tetrafluoroethylene with small amounts of other fluorinated monomer are known as *Modified PTFE* resins and have been reported to exhibit reduced deformation under load. Examples of the properties of some of the commercial products can be seen in Tables 3.22–3.24 and Figs. 3.20 and 3.21. Significant reduction in deformation under load can be achieved, particularly at elevated temperatures and pressures.

Stress relaxation is important in applications where PTFE is subjected to a compressive load. For example, a gasket under bolt pressure will creep, resulting in a reduced bolt pressure. This reduction in load may lead to leakage at the joint. Tightening the flange after 24 hours will prevent leakage. Thereafter, stress relaxation will be negligible. Plots of tensile stress relaxation can be used (Figs. 3.22 and 3.23) to illustrate the decay rate at constant strain.

Alternative compressive loading and load removal indicates nearly complete recovery from strain, as long as the original strain is below the yield strain elastic range. PTFE does not experience work hardening.[18]

3.6.2.2 Fatigue Properties

Flexibility characteristics are of paramount importance in many applications involving motion. A valve diaphragm is a good example of a part where a polymer membrane experiences repeated movement. *Flex life* is defined as the number of cycles that a part can endure before catastrophic fatigue occurs; the higher the molecular weight, the higher the flex life. Crystallinity has a detrimental effect on flex life; the higher the crystallinity, the lower the flex life. Figure 3.24 illustrates the flex life of PTFE as a function of molecular weight and crystallinity. Voids should be eliminated from any part expected to perform in demanding flex applications. Each void becomes the nucleus of failure after the part has been subjected to repeated movement.

3.6.2.3 Impact Strength

Impact strength of a part depends on its ability to develop an internal force multiplied by the deformation of the part as a result of impact. The shape of a part, such as a metal spring as opposed to a flat metal plate, can enhance its ability to absorb impact. PTFE resins have excellent impact strength in a broad temperature range. Table 3.25 summarizes the results of tensile and Izod impact strength for polytetrafluoroethylene (Izod, according to ASTM D256). Even at extremely low temperatures, PTFE retains a great deal of its impact toughness.

3.6.2.4 Hardness

Hardness of PTFE is determined by a number of methods, such as ASTM D758 or D2240 (Rockwell R Scale), or by Durameter scales. The numbers reported are Rockwell R Scale of 58, Durameter A Scale of 98,[18] and Durameter D Scale of 50–65.[24] Figure 3.25 illustrates the variation of hardness of PTFE and nylon as a function of temperatures. Both plastics become softer with increasing temperature but, in all temperatures, nylon is harder than PTFE.

Fillers improve the hardness of PTFE by 10%–15%, which is preserved over a wide range of temperatures. Increasing the filler content, in general, elevates the hardness of the compound.

3.6.2.5 Friction

Polytetrafluoroethylene is a slippery material with a smooth surface due to its low coefficient of friction. Numerous mechanical applications have been developed for PTFE with slight or without lubrication, particularly at low velocities and pressures above 35 kPa. Table 3.26 contains values for coefficient of friction as a function of velocity. Dynamic coefficient of friction of PTFE is larger than its static coefficient of friction and grows with increasing speed until the motion is destabilized. Static coefficient of friction remains unchanged in the temperature range of 27°C–327°C which is important in applications where a polytetrafluoroethylene part may experience heat buildup and temperature increase.

Polytetrafluoroethylene’s coefficient of friction rises quickly with sliding speed (below 30 m/min, Fig. 3.26), which prevents “slipstick” behavior. No noise takes place even at slow speeds. Above 45 m/min, sliding velocity has little effect at combinations of pressure and velocity before the PV limit of PTFE is reached.[18] Figure 3.27 indicates that static coefficient of friction decreases with increase in pressure.

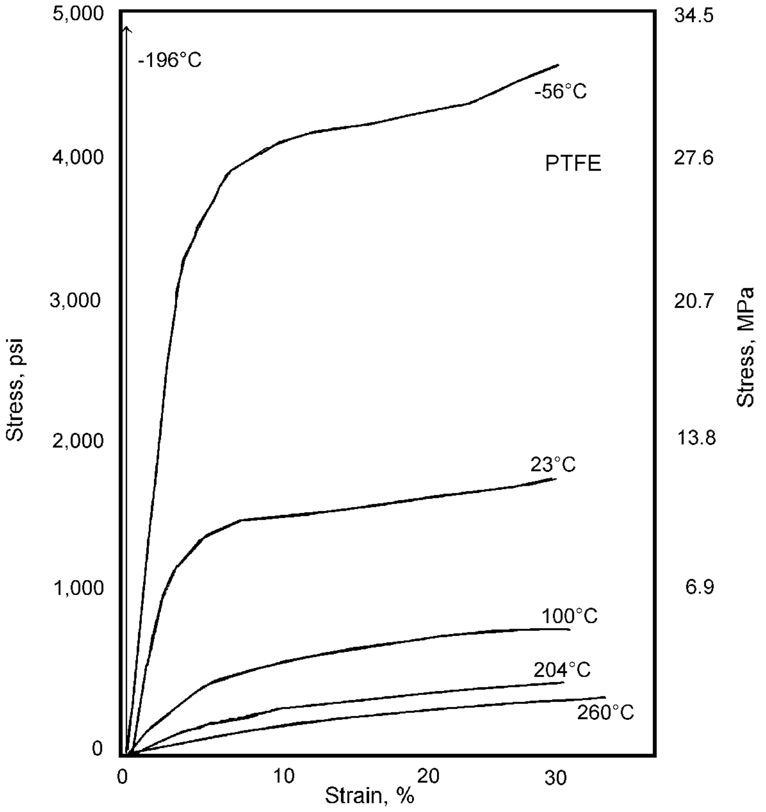

Figure 3.6 Tensile stress, based on original cross section.[3]

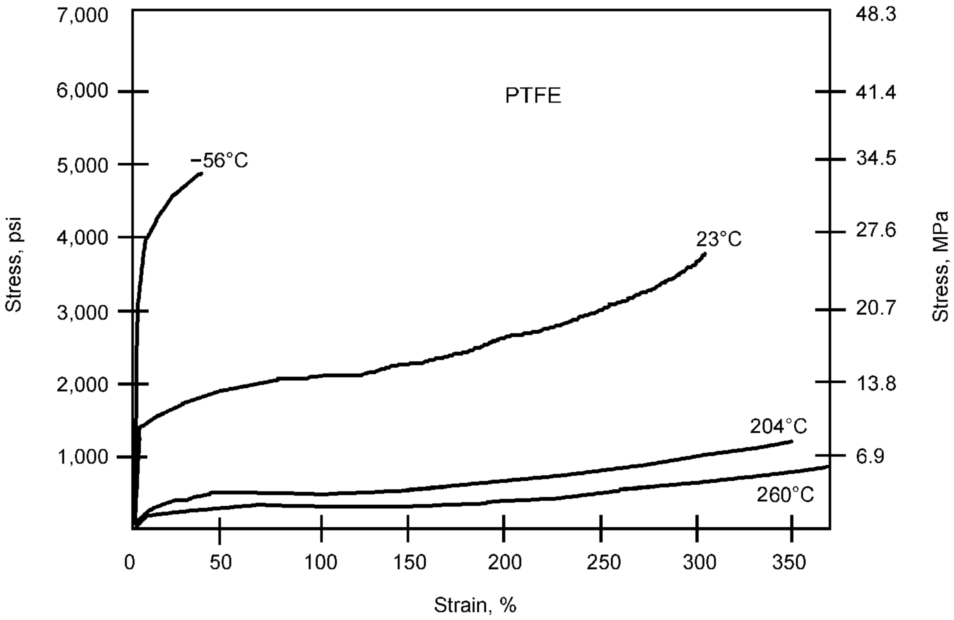

Figure 3.7 Stress vs strain in tension.[18]

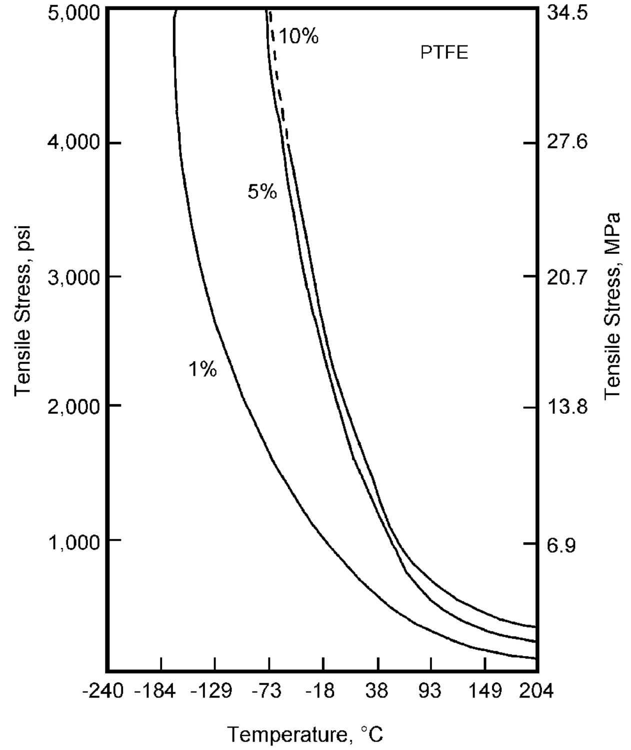

Figure 3.8 Tensile stress vs temperature at constant strain.[18]

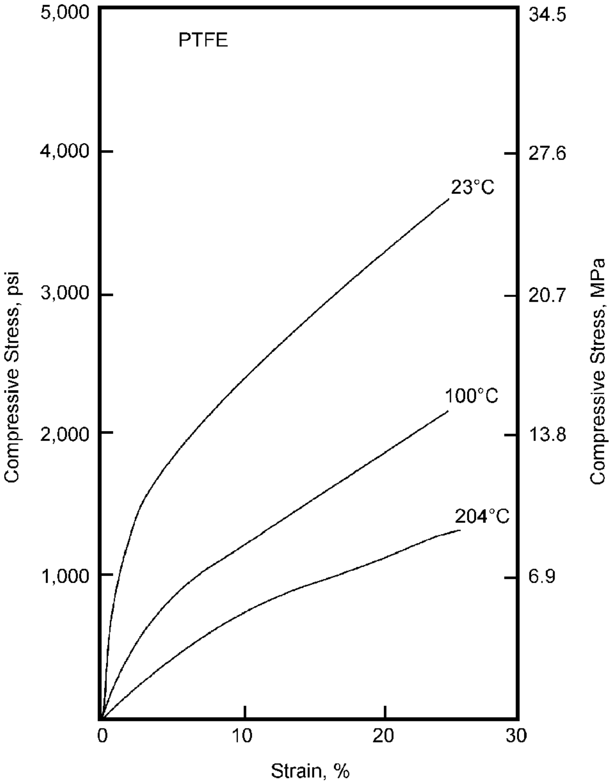

Figure 3.9 Stress vs strain in compression (ASTM D695).[18]

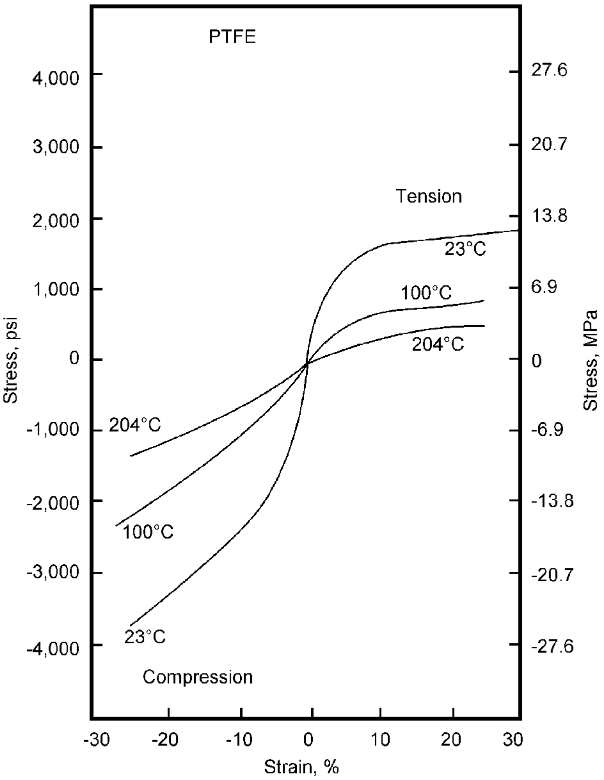

Figure 3.10 Stress vs strain in tension and compression (ASTM D695).[18]

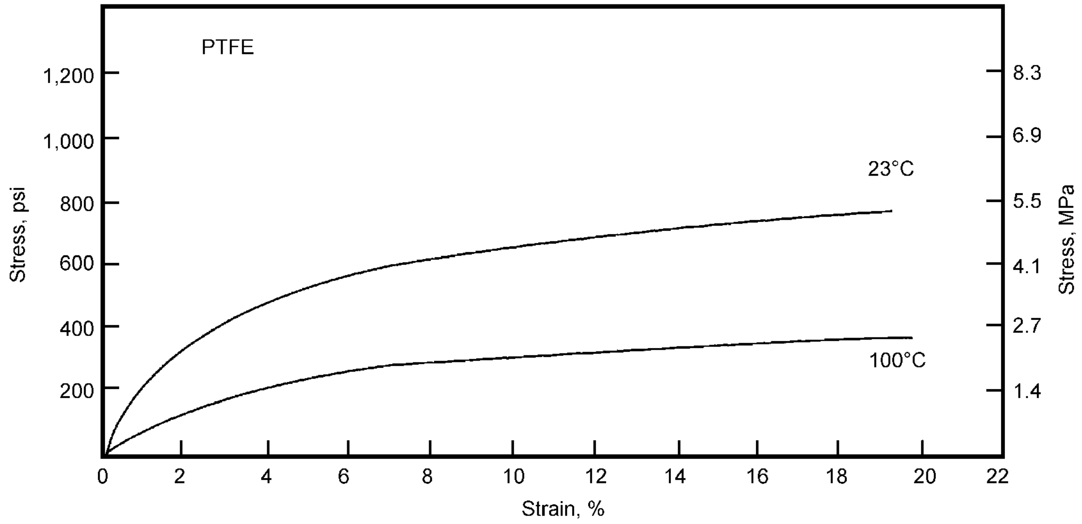

Figure 3.11 Stress vs strain in shear to 20%.[18]

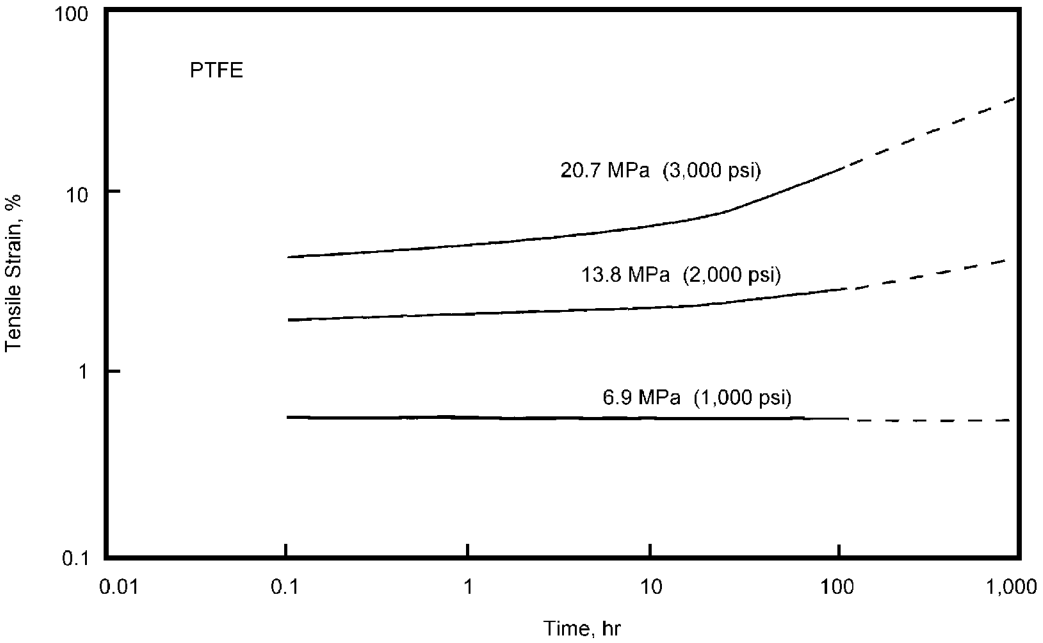

Figure 3.12 Total deformation vs time under load at -54°C (-65°F).[18]

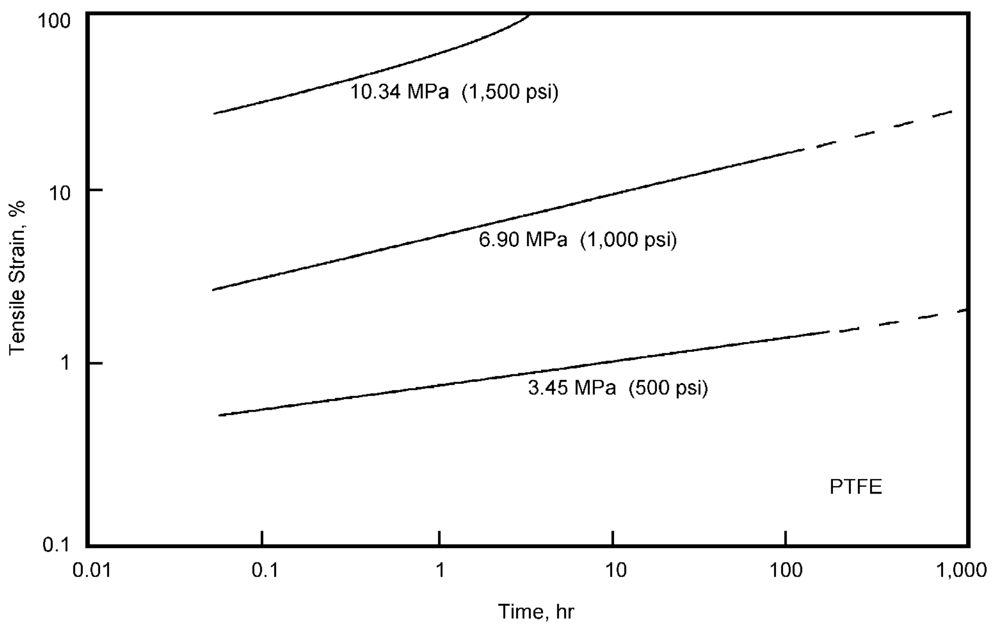

Figure 3.13 Total deformation vs time under load at 23°C (73°F).[18]

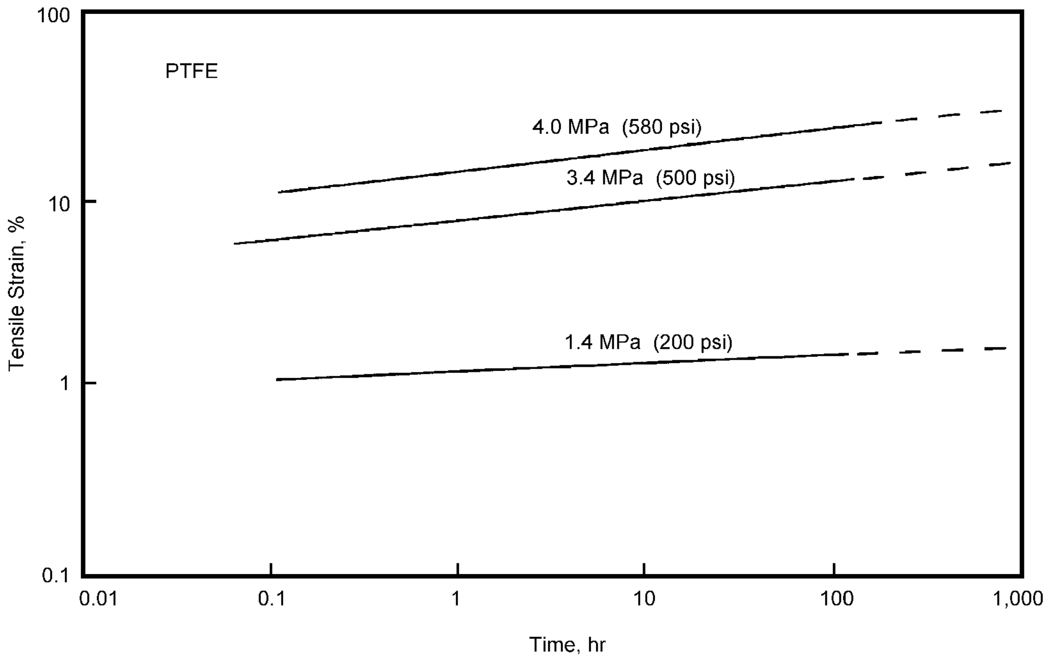

Figure 3.14 Total deformation vs time under tensile load at 100°C.[18]

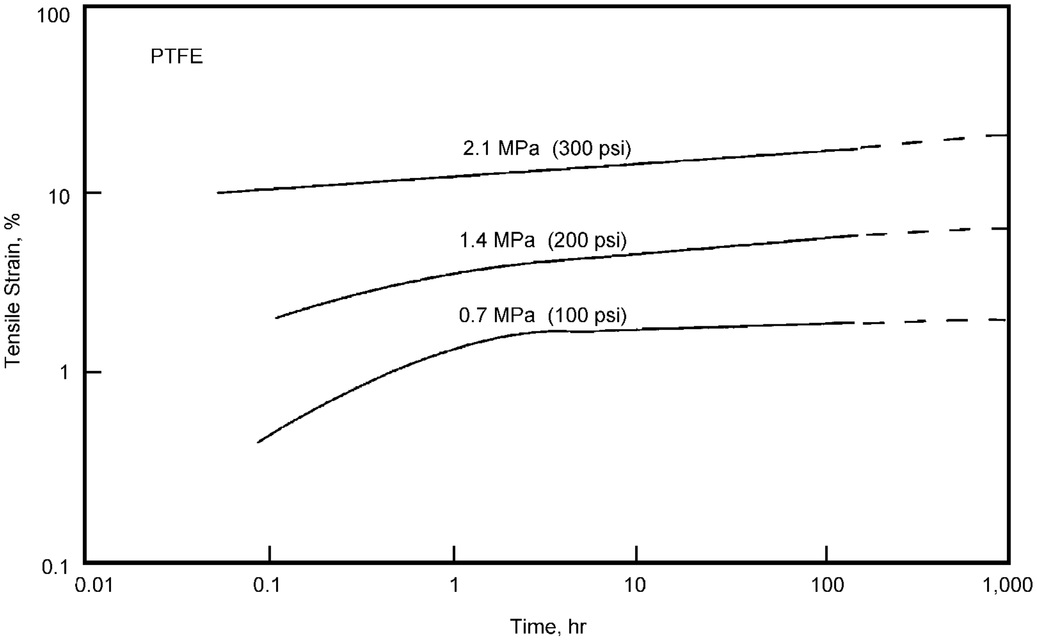

Figure 3.15 Total deformation vs time under tensile load at 200°C.[18]

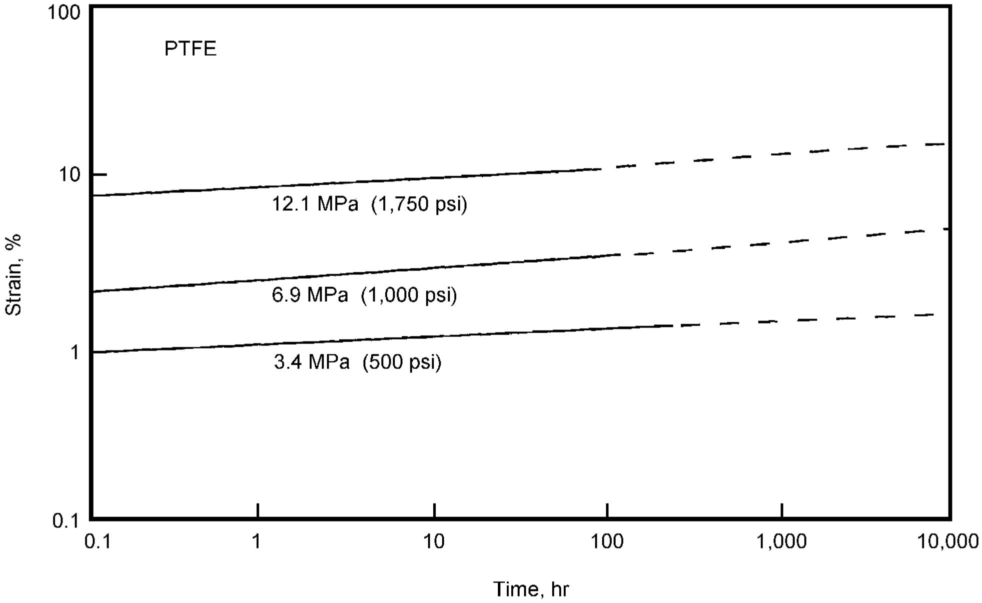

Figure 3.16 Total deformation vs time under compressive load at 23°C.[18]

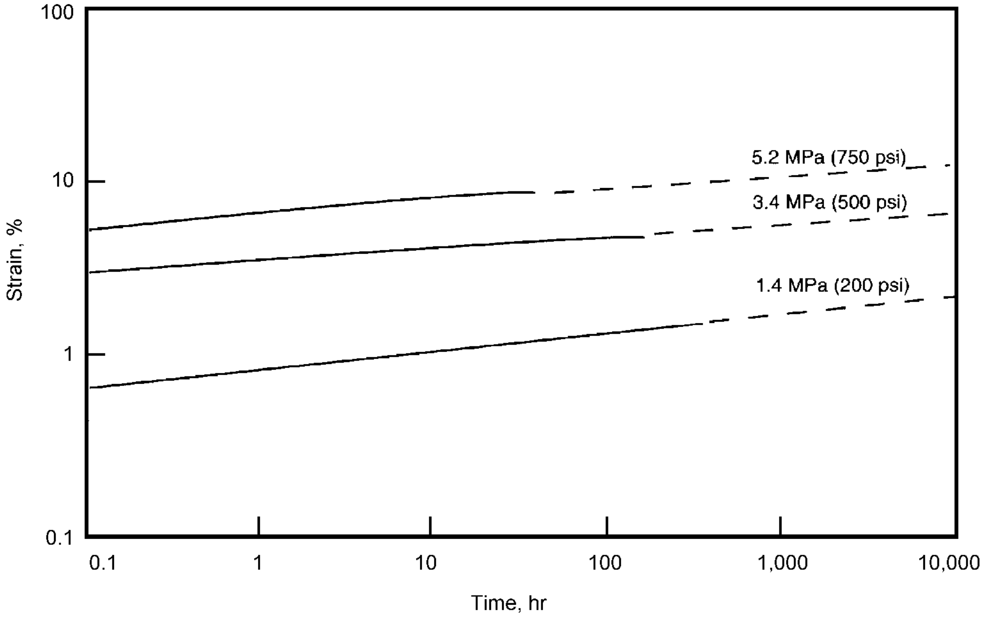

Figure 3.17 Total deformation vs time under compressive load at 100°C.[18]

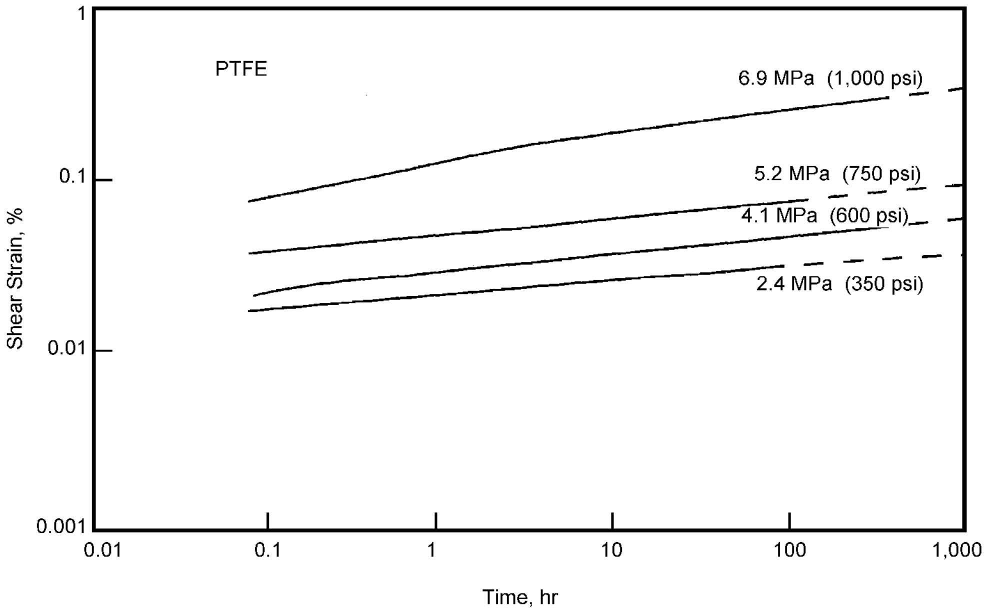

Figure 3.18 Total deformation vs time under torsional load at 23°C.[18]

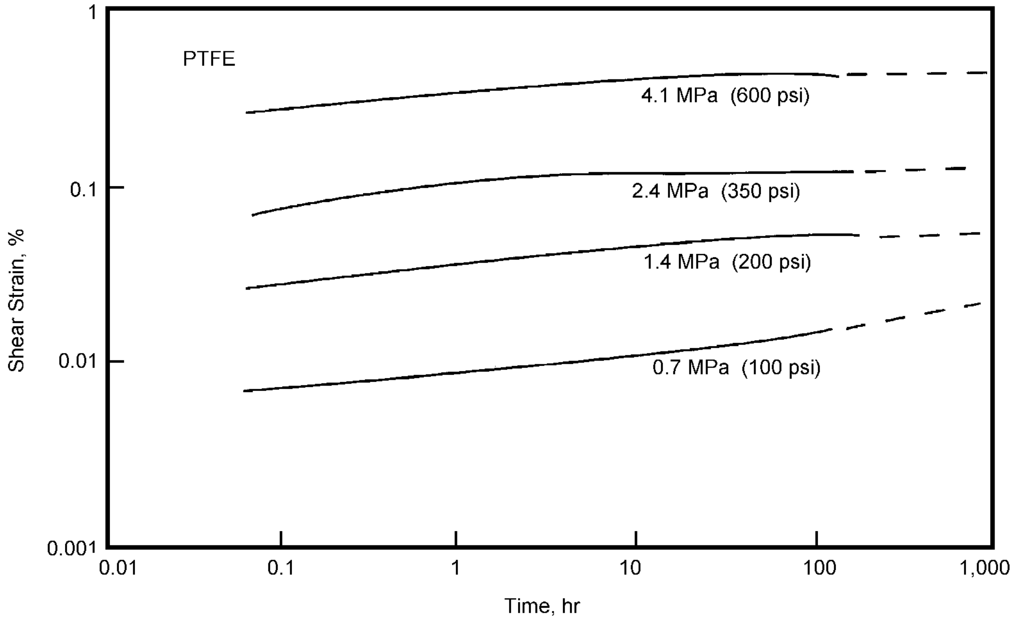

Figure 3.19 Total deformation vs time under torsional load at 100°C.[18]

Table 3.22. Deformation Under Load Data for Commercial Standard and Modified PTFE Resins[20]

Resin Type	Test	Test Conditions Temperature,°C/Pressure, MPa after 24 hours		
		23°C/3.4 MPa	23°C/6.9 MPa	23°C/14 MPa
Teflon® NXT 70	ASTM D621	0.2	0.4	3.2
Teflon® 7A	ASTM D621	0.7	1.0	8.2

Table 3.23. Deformation Under Load Data for Commercial Standard and Modified PTFE Resins[20]

Resin Type	Test	Test Conditions Temperature,°C/Pressure, MPa after 24 hours		
		25°C/6.9 MPa	100°C/3.4 MPa	200°C/1.4 MPa
Teflon® NXT 70	Dynamic Mechanical Analyzer (DMA)	5.3	5.4	3.6
Teflon® 7A	Dynamic Mechanical Analyzer (DMA)	6.7	8.5	6.4

Table 3.24. Deformation under Load Data for Commercial Standard and Modified PTFE Resins[21]

Resin Type	Test	Test Conditions Temperature,°C/Pressure, MPa after 100 hours		
		23°C/6 MPa	23°C/8 MPa	23°C/14 MPa
Hostaflon®1700	ASTM D621	2	2.5	8
Hostaflon®1750	ASTM D621	3	4	14.5

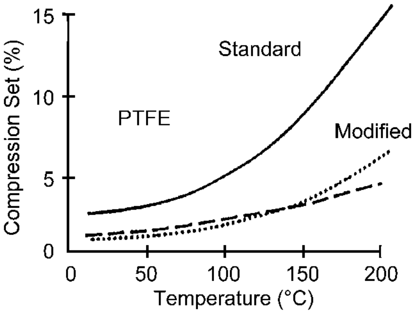

Figure 3.20 Conditions: based on ASTM D621 (load 6.9 MPa).[22]

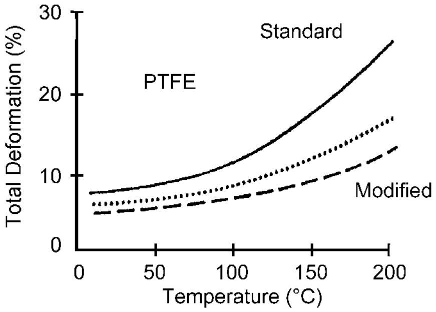

Figure 3.21 Conditions: based on ASTM D621 (load 6.9 MPa).[22]

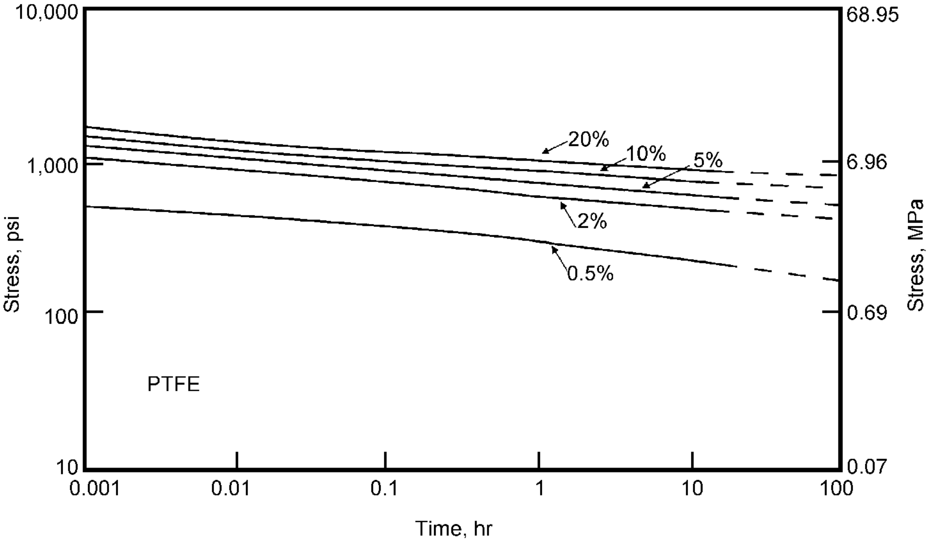

Figure 3.22 Tensile strength relaxation at 23°C.[18]

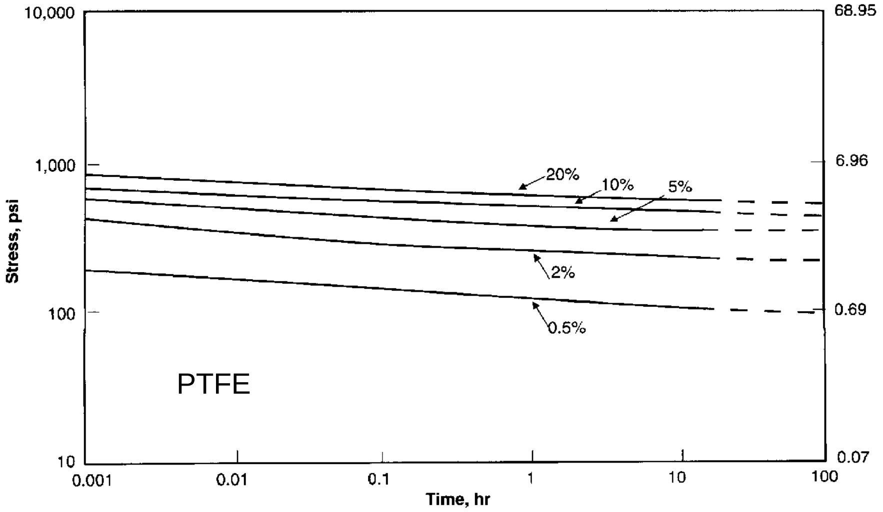

Figure 3.23 Tensile strength relaxation at 100°C.[18]

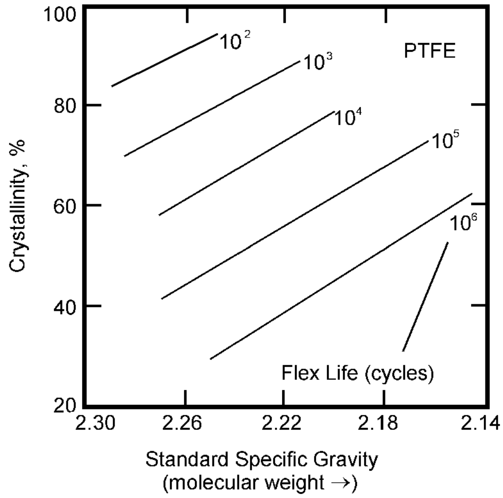

Figure 3.24 How crystallinity and molecular weight affect flex life (nonstandard test, 45 cycles per minute, 180-degree bend).[23]

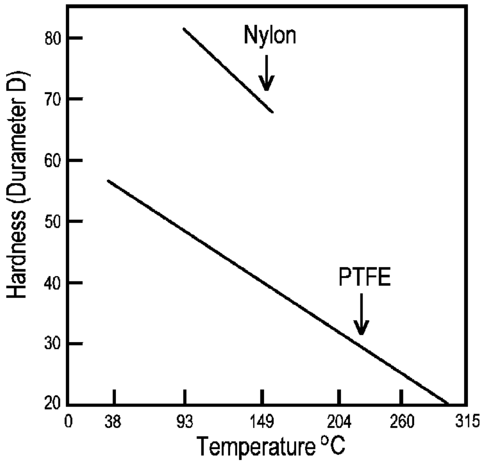

Figure 3.25 Hardness vs temperature.[23]

Table 3.25. Tensile and Izod Impact Strength of Polytetrafluoroethylene[18]

Temp., °C	Tensile Impact Strength, joules/cm^2	Izod Impact Strength, joules/cm^2
23	67	0.61
-54	22	0.48

Table 3.26. Coefficient of Friction[18]

Type of Coefficient	Condition	Value of Coefficient
Static	3.4 MPa Static Load	0.05-0.08
Dynamic	Velocity (m/min)	
(PV = 285-357 kg/cm^2.cm/sec.)	3	0.10
	30	0.13
	300	Unstable Operation

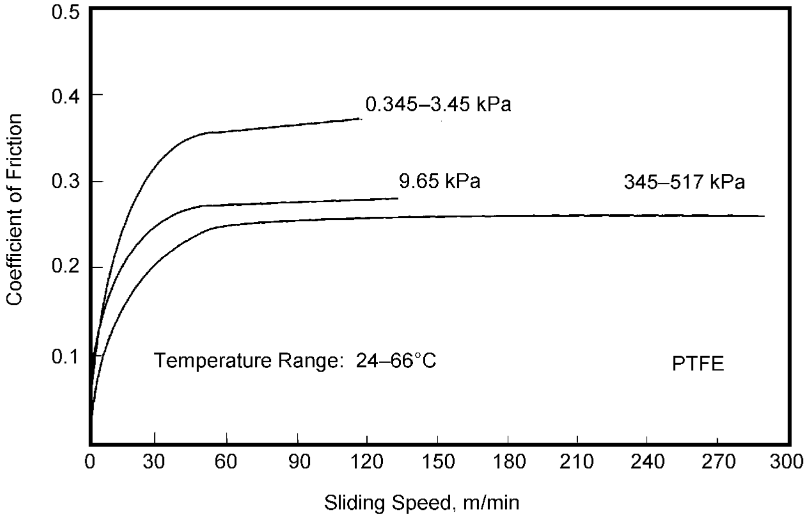

Figure 3.26 Coefficient of friction vs sliding speed.[18]

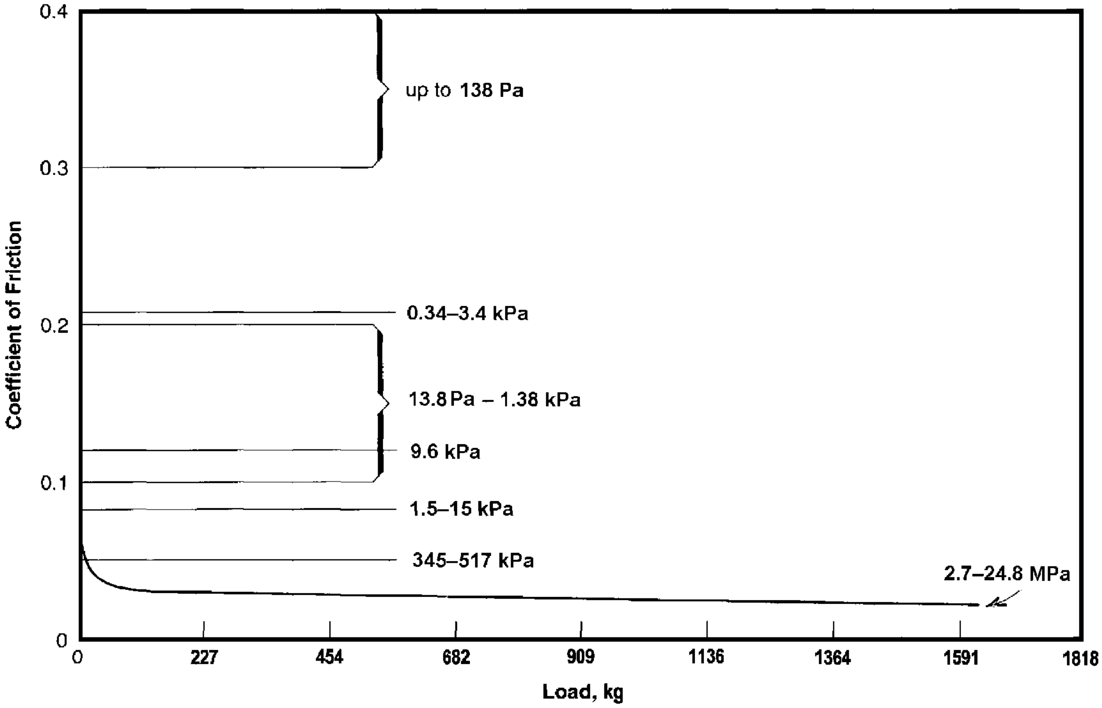

Figure 3.27 Coefficient of friction vs load (at 0.6 m/min and room temperature).[18]

3.6.2.6 PV Limit

The PV (pressure × velocity) convention is utilized to define the maximum combinations of pressure and velocity at which a given material will operate continuously without lubrication. The values are usually given for operation in air at temperatures of 21°C–27°C. PV limits do not always define the actual combinations of pressure and velocity where the material can be practically used, because wear is not considered in the determination of PV values. In other words, the application must not exceed PV limit and wear limits of a material. Such a limit can be determined by finding the pressure and velocity combination at which wear rate accelerates or exceeds the expected life of a part.

PV limits of polytetrafluoroethylene are given in Table 3.27. All PTFE reaches a PV value of zero at above 288°C, no matter whether the temperature is reached thermally or mechanically. Reducing the temperature below 21°C increases the limiting PV.

3.6.2.7 Abrasion and Wear

Polytetrafluoroethylene parts have good wear properties, as seen from the data in Table 3.27. The resistance of unfilled PTFE to wear is less than that of filled compositions. Data from tests measuring wear rate are presented in Tables 3.28–3.30. They should be viewed with an understanding that none of the techniques represent an actual wear situation. In all three methods, a new surface is exposed to abrasion during the repeated motion of the abrading surface.

3.6.3 Electrical Properties of PTFE

Electrical stability of polytetrafluoroethylene is outstanding over a wide range of frequency and environmental conditions. This plastic makes an excellent electrical insulator at normal operating temperatures. Dissipation factor and dielectric constant values are virtually constant up to 10 MHz. Dielectric strength of PTFE drops off with increasing frequency slower than most other material.

PTFE dielectric constant and dissipation factors remain constant over a broad temperature range (-40 to 240°C) as seen in Fig. 3.28.[25] They are not affected by exposure to high frequency (>1 MHz) and high temperature. The value of dielectric constant is 2.1 essentially over the entire spectrum of frequency. The dissipation factor of PTFE resins remains <0.0004 up to 100 MHz. It reaches a peak value at 1 GHz. The peak value occurs at higher frequencies with increasing temperature.

The dielectric strength of polytetrafluoroethylene is quite high and remains fairly constant with temperature and heat aging. The short-term dielectric strength decreases slightly, up to 300°C (Fig. 3.29). Short-term dielectric strength is 24 kV/mm (for 1.5 mm thick film) according to ASTM D149. Like all plastic material, dielectric strength decreases as thickness increases. Durability of insulation at high voltage is dependent on corona discharge.[18] In special wire constructions, absence of corona allows high voltages without any harm to the PTFE insulation.

The stability of PTFE is evidenced by a lack of change in its dielectric constant after aging at 300°C for a period of nine months (Table 3.31). There are no other plastics known to exhibit these properties. Exposure to weather has no effect on the dielectric constant and dissipation factor. Figure 3.30 summarizes the results of a ten-year study in south Florida where representative samples were exposed to the climatic elements. No change in dielectric constant or dissipation is detected as a result of weathering.

3.6.4 Thermal Behavior of PTFE

In this section, heat and temperature related or dependent properties of polytetrafluoroethylene resins are discussed. These include thermal stability, thermal expansion, thermal conductivity, and specific heat (heat capacity). These characteristics are important to both design and use of PTFE parts.

3.6.4.1 Thermal Stability

Polytetrafluoroethylene resins are very stable at their normal use temperature range (<260°C). They exhibit a small degree of degradation at higher temperatures. The rate of decomposition is a function of the specific polymer, temperature, time at temperature, and, to some extent, on the pressure and nature of decomposition environment. In actual processing, degradation is tracked by indirect measurement of molecular weight. Thermal exposure leads to a reduction in the molecular weight, which can be quantified by an increase in the specific gravity and heat of fusion of PTFE, in controlled measurements.

Degradation is usually measured and characterized by weight loss using thermogravimetric analysis (TGA) technique while degradation products are identified by gas chromatography, infrared spectroscopy and mass spectroscopy. Initial rates of decomposition have been summarized in Table 3.32. This data is particularly helpful for the estimation of outgassing in applications where PTFE parts are under vacuum exposure. It can clearly be seen that decomposition rates of PTFE are quite low at fairly high temperatures. The small amount of degradation requires TGA experiments to be conducted for several hours to allow accurate detection of weight loss.

Figure 3.31 and Table 3.33 provides a summary of degradation-rate studies by Baker and Kasprzak.[26] In this figure, weight loss rate in air is plotted against temperature. It can be seen that polytetrafluoroethylene, disregarding its type, is the most thermally stable of the perfluorinated fluoropolymers. As a matter of fact, very few organic materials approach the thermal stability of PTFE. Degradation is accelerated in air compared to vacuum decomposition.

In vacuum, polytetrafluoroethylene degrades into nearly pure monomer. Products of PTFE degradation in air include carbonyl fluoride (COF_2), tetrafluoroethylene (TFE), and small amounts of perfluoroisobutylene (PFIB).[27]–[29] PFIB and COF_2 are highly toxic if they are inhaled.

Table 3.27. PV and Wear Performance[18]

Velocity, m/min	PV Limit at 21°C–27°C, MPa·m/min
3	2.52
30	3.78
300	5.25

Table 3.28. Weight Loss Caused by Sliding Tape[18]

Resin	Average Weight Loss*, g/mm^2
PTFE	5.22×10^{-4}

*Armstrong Abrasion Test (ASTM D1242): This test measures abrasion resistance of flat surfaces by drawing abrasive tape, under load, over test specimens at a slip rate of 15.75 g/cm^2. With No. 320 abrasive under a 6.8 kg load, weight loss was measured after 200 revolutions (1 hr, 40 min.).

Table 3.29. Weight Lost from Revolving Disk[18]

Resin	Test Cycles*					
	10	50	100	500	1000	2000
PTFE	0.35	1.65	2.2	5.7	8.9	13.4
	Cumulative weight loss in milligrams					

*Armstrong Abrasion Test: This test measures abrasion resistance of a flat surface by rotating a 10 cm diameter specimen disk beneath an abrasive under load. A 1,000 g load was used on a Calibrase wheel No. CS-17F.

Table 3.30. Tape Length Required to Abrade Through Wire Coating[3]

Resin	Heat Aging			
	None	96 hr at 150°C	500 hr at 150°C	96 hr at 200°C
PTFE	191.5	196.6	247	211.7
	Average tape length in centimeters*			

*Armstrong Abrasion Test (MIL-T-5438): This test measures abrasion resistance of wire coating by drawing, under load, a clean abrasive cloth tape of continuous length across the test wire until the coating is worn through. A 0.45 load on No. 400 grit tape was used on a coating thickness of 0.038 cm.

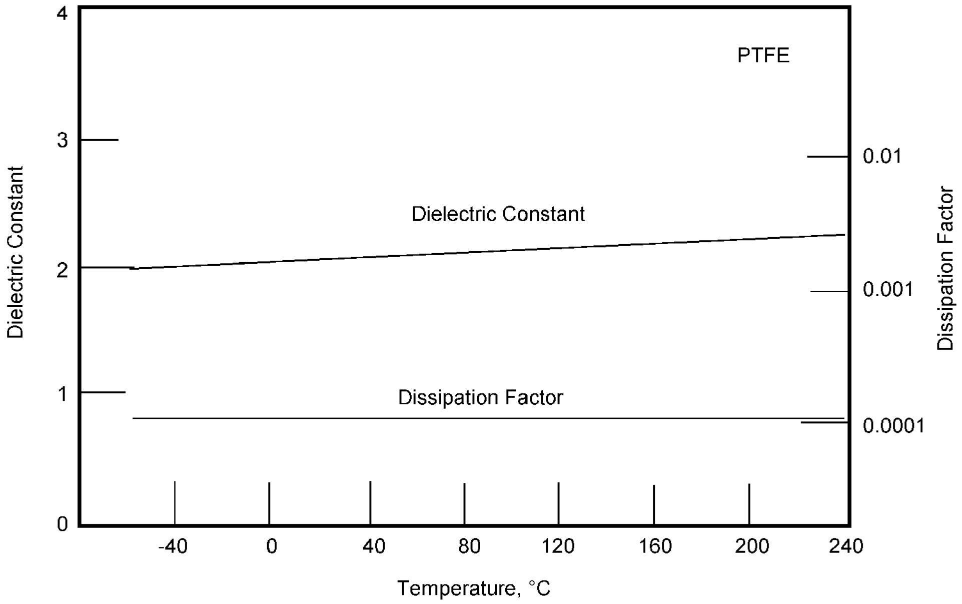

Figure 3.28 Dielectric constant, dissipation factor vs temperature.[25]

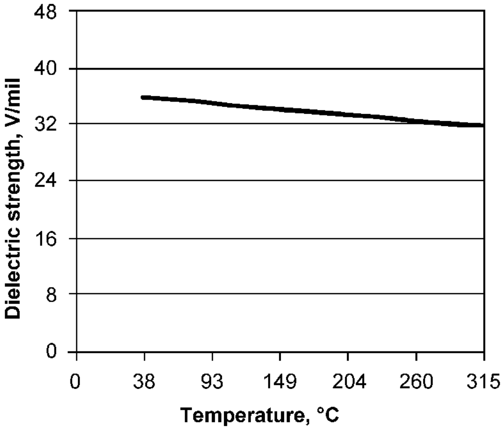

Figure 3.29 Dielectric strength (short-time) vs temperature (1.1 mm thick molded sheet).[25]

Table 3.31. Effects of Oven-Aging at 300°C on the Electrical Properties of PTFE Resins[25]

Sample	Exposure Time at 300°C	Dissipation Factor	Dielectric Constant	Dielectric Strength, kV/mm (ASTM D149)
125-µm extruded PTFE film	As received	0.0001	2.1	117.1
	1 month	0.0001	2.1	
	3 months	0.0001	2.1	115.6
	6 months	0.0001	2.1	
	9 months			118

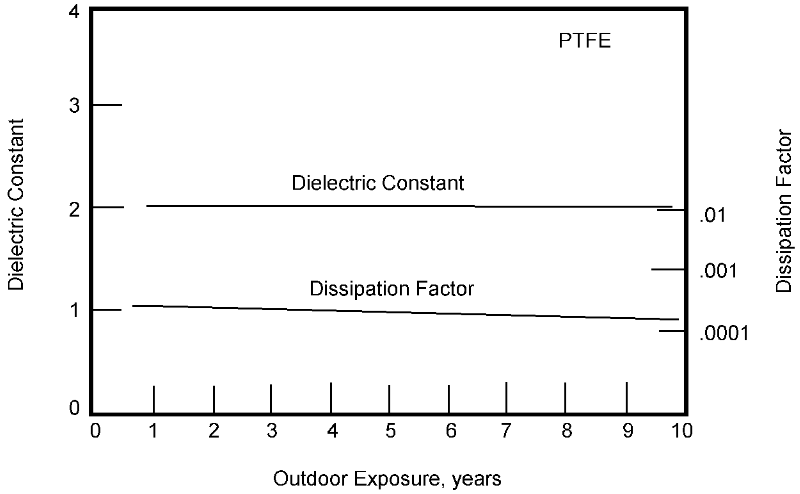

Figure 3.30 Dielectric constant, dissipation factor vs exposure.[25]

Table 3.32. Decomposition Rates of PTFE at Elevated Temperatures[18]

Temperature, °C	Rate of Decomposition, %/hr		
	Fine Powder	Granular Resin	
	Initial	Initial	Steady State
232	0.0001–0.0002	0.00001–0.00005	1×10^{-11}
260	0.0006	0.0001–0.0002	100×10^{11}
316	0.005	0.0005	0.000002
371	0.03	0.004	0.0009

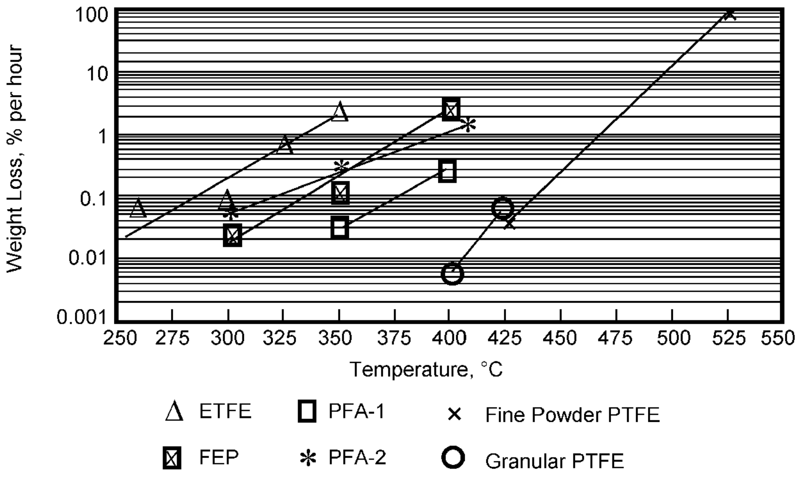

Figure 3.31 Percent weight loss on heating in air.[26]

Table 3.33. Fluoropolymer Weight Loss Data[26]

PTFE Resin	Temp., °C	% Weight Loss/hr	
		Thermal equilibrium to 15 min.	Thermal equilibrium + 60 min.
Fine Powder	400		~0.06
	425		0.15
	425		0.04[b]
	525	255[a]	95.0
Granular	350		0.02
	350		0.005[c]
	400		0.03
	400		0.006[c]
	425		0.06
	425		0.06[b]

[a] Gross decomposition in one hour. Initial rate 255% per hour.

[b] Hourly rate from 8 to 11.8 hours after beginning run.

[c] Hourly rate from 3.3 to 6.6 hours after beginning run.

3.6.4.2 Thermal Expansion

A polytetrafluoroethylene part contracts 2% when it is cooled from 23°C to -196°C and expands 4% upon heating from 23°C to 249°C. These dimensional changes are significant to the design, fabrication, and use of PTFE parts. Tables 3.34 and 3.35 and Fig. 3.32 provide data for linear thermal expansion and volumetric coefficients of expansion. An abruptly large expansion occurs at the transition temperature (19°C) of polytetrafluoroethylene. It is important to keep this dimensional change in mind in the design, measurement of size, and machining of PTFE parts. The best approach is to work at a consistent temperature (23°C–25°C) safely above the transition temperature.

Polytetrafluoroethylene has a somewhat higher coefficient of expansion than other plastics. This differential expansion can result in leaking of joints when PTFE is combined with other materials. Addition of fillers such as glass, fiber, graphite, bronze, and molybdenum disulfide alters the coefficient of expansion of polytetrafluoroethylene compounds (Table 3.36). A compound containing 25% filler has a coefficient of expansion about half that of the unmodified resin.

3.6.4.3 Thermal Conductivity and Heat Capacity

Polytetrafluoroethylene resins have very low thermal conductivity and are considered good insulators. The values of thermal conductivity are given in Table 3.37.

Fillers usually increase the thermal conductivity of polytetrafluoroethylene as with other plastics (Table 3.38). Specific heat of PTFE at various temperatures is given in Table 3.39. Enthalpy of molded PTFE is given in Fig. 3.33.

3.6.4.4 Heat Deflection Temperature

Heat deflection temperature of polytetrafluoroethylene is given in Table 3.40.

3.6.5 Irradiation Resistance of PTFE

Polytetrafluoroethylene and other perfluorinated fluoropolymers are quite susceptible to radiation. Exposure to high energy radiation such as x-rays, gamma rays, and electron beams, degrades PTFE by breaking down the molecules and reducing its molecular weight. As in thermal degradation, radiation stability of PTFE is much better under vacuum compared to air. For example, exposure of PTFE film to a dose of one megarad of gamma rays from a Co^{60} in air resulted in 87% loss of initial elongation and 54% loss of tensile strength. Significantly less loss of tensile properties occurs when PTFE is exposed to the same radiation dose in vacuum. (See Table 3.41.)

Table 3.34. PTFE Resins Linear Coefficients of Expansion[18]

Temperature Range, °C	Linear Coefficient of Expansion, 10^{-5} mm/mm · °C
25 to –190	8.6
25 to –150	9.6
25 to –100	11.2
25 to –50	13.5
25 to 0	20
10 to 20	16
20 to 25	79
25 to 30	16
25 to 50	12.4
25 to 100	12.4
25 to 150	13.5
25 to 200	15.1
25 to 250	17.5
25 to 300	22

3.6.6 Standard Measurement Methods for PTFE

Table 3.42 summarizes the standard test methods for characterization of polytetrafluoroethylene parts. These tests are often specified by the customer, and suppliers of parts are expected to meet them consistently.

Table 3.35. PTFE Resins Cubical Coefficients of Expansion[18]

Temperature Range, °C	Cubical Coefficients of Expansion cm^3/cm^3 · °C
-40 to 15	2.6×10^{-4}
15 to 35*	1.7%
35 to 140	3.1×10^{-4}
140 to 200	6.3×10^{-4}
200 to 250	8.0×10^{-4}
250 to 300	1.0×10^{-3}

* Quinn, et al., *J. Applied Phys.* 22, 1085 (1951)

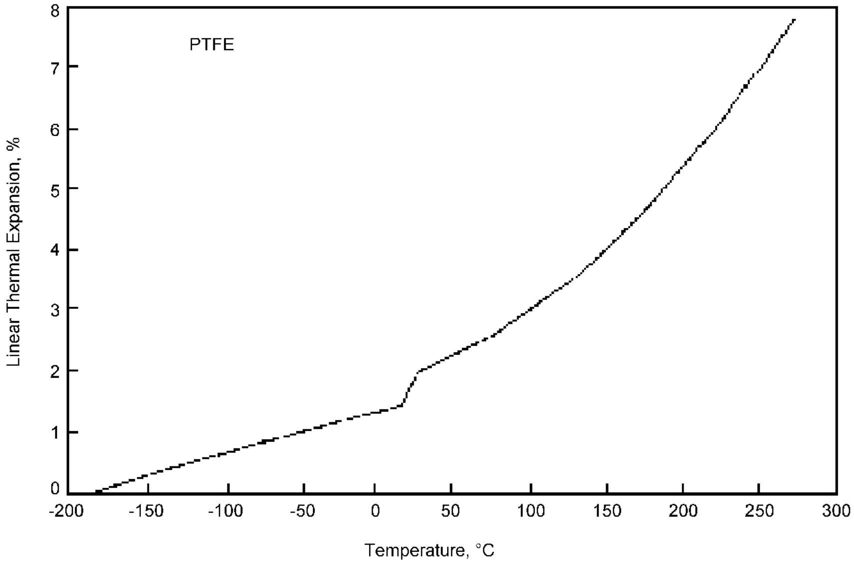

Figure 3.32 Linear thermal expansion vs temperature.[18]

Table 3.36. The Effect of Fillers on the Linear Thermal Expansion of TFE Resins[23]

Property	Test	Unfilled TFE	15% Glass Fiber	25% Glass Fiber	15% Graphite	60% Bronze	20% Glass, 5% Graphite	15% Glass, 5% MoS^2
Filler loading vol.%			13.3	22.2	14.6	27.1	17.6, 5.0	13.3, 2.4
Bulk density, lb/cu.in.		0.0129	0.0103	0.0107	0.0087	0.0103	0.0104	0.0107
Specific gravity:	ASTM D1457-66T							
Theoretical		2.18	2.22	2.26	2.19	3.97	2.25	2.28
Measured			2.20	2.22	2.12	3.85	2.18	2.27
Coeff. of linear therm. exp. (×10^{-5}), m/in/°F	ASTM D696-44							
78°F–200°F	MD		8.02	6.97	6.97	5.40	7.73	8.33
	CD	6.81	2.94	4.19	4.38	4.38	2.61	3.51
78°F–300°F	MD		8.40	7.33	7.46	5.72	7.73	8.77
	CD	7.04	2.96	4.19	4.67	4.37	3.01	3.55
78°F–400°F	MD		9.05	8.00	8.14	6.35	8.12	9.61
	CD	7.60	3.42	4.72	5.12	4.99	3.22	3.85
78°F–500°F	MD		10.31	9.35	9.50	7.82	9.24	11.11
	CD	9.12	4.15	5.55	5.97	5.75	3.88	4.45
MD = Parallel to molding direction; CD = Cross section perpendicular to molding direction.								

Table 3.37. Thermal Conductivity of PTFE[23]

Temperature, °C	Thermal Conductivity, W/mK
-253	0.13
-128 to 182	0.25

Table 3.38. Thermal Conductivity of PTFE Compounds[23]

Filler Type	Filler Concentration, weight %	Thermal Conductivity, W/mK
Unfilled	0	0.25
Glass Fiber	15	0.37
Glass Fiber	25	0.46
Graphite	15	0.46
Bronze	60	0.48
Glass Graphite	20 5	0.37
Glass Molybdenum Disulfide	15 5	0.33

Table 3.39. Specific Heat of PTFE[18]

Temperature, °C	Specific Heat, kJ/kg·K
20	1.4
40	1.2
150	1.3
260	1.5

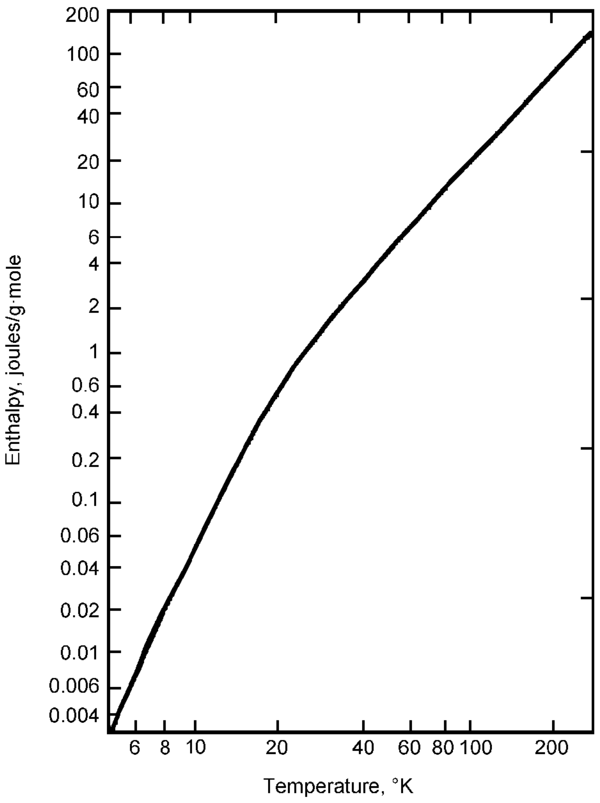

Figure 3.33 Enthalpy of molded PTFE.[23]

Table 3.40. Heat Deflection Temperature of PTFE[23] (ASTM D648)

Pressure, kPa	Temperature, °C
450	73
1800	45

Table 3.41. Heat Deflection Temperature of PTFE[23]

Environment	Elongation Loss, %	Tensile Strength Loss, %
Air	87	54
Vacuum	44	17

Table 3.42. ASTM Tests Applicable to Fabricated PTFE Parts[18]

Property	Extruded Rod	Molded Sheet	Molded Parts	Films and Tapes	Extruded Tubing
Tensile Strength	D1710	D3293	D3294	D3308 D3369	D3295
Ultimate Elongation	D1710	D3293	D3294	D3308 D3369	D3295
Measured Specific Gravity	D1710	D3293	D3294	D3308	D3295
Dielectric Strength	D1710	D3293	D3294	D3308 D3369	D3295
X-Ray Inspection	D1710		D3294		
Melting Point	D4894	D3293	D3294	D3308 D3369	D3295
Dye Penetrant		D3293	D3294		
Dimensional Stability	D1710	D3293	D3294		D3295
Pinhole Count				D3308 D3369	
Central section of test specimens machined to 60% of nominal diameter. Tested at 5 cm/min cross-head speed.					

3.7 Properties and Characteristics of Melt-processible Fluoroplastics

3.7.1 Mechanical and Dynamic Properties

These properties are among the most important factors for the design of plastic parts and systems. Mechanical properties of fluoroplastics, similar to other semicrystalline polymers, are strongly influenced by the degree of crystallinity of the part. Crystallinity, in turn, is determined by the cooling rate of the part from molten state to below the melting point of the plastic. In this section, data for tensile strength, elongation, moduli, impact strength, and deformation under load (creep) of fluoroplastics, under different conditions, are presented.

3.7.1.1 Tensile Properties

Figures 3.34 and 3.35 show the relationship of tensile strength and ultimate (break) elongation with temperature for perfluoroalkyl vinyl ether modified perfluoroalkoxy polymer (PFA). Figures 3.36 through 3.38 show a comparison of the properties of PFA with MFA, which is perfluoromethyl vinyl ether (PMVE). The common measurement technique for tensile properties of fluoroplastics is ASTM D1708.

FEP is a copolymer of tetrafluoroethylene and hexafluoropropylene; a third monomer is sometimes incorporated to modify the FEP properties. Stress-strain behavior of FEP in tensile and compressive modes is shown in Figs. 3.39 and 3.40 as a function of temperature. Figures 3.41 through 3.44 provide comparisons of stress-strain behavior of FEP with different melt flow rate (MFR) values at temperatures of -52°C to 200°C. Figures 3.45 and 3.46 illustrate the relationship of tensile strength and ultimate elongation with temperature in the -40° to 200°C range for different FEP grades.

Polyvinylidene fluoride is a homopolymer or copolymer of vinylidene fluoride. Figures 3.47 through 3.49 present the tensile strength and elongation at break of PVDF as a function of temperature. The effect of temperature on both tensile strength and elongation at break is quite drastic as can be seen from these figures.

ETFE is usually an alternating copolymer of ethylene and tetrafluoroethylene; a third comonomer is incorporated to reduce the crystallinity of the copolymer. Figures 3.50–3.52 illustrate the tensile and compressive stress-strain for different grades of ETFE at room temperature. Figures 3.53 and 3.54 present the tensile strength and ultimate elongation of different grades of ETFE versus temperature. Tensile strength decreases and elongation increases with increasing temperature.

ECTFE is usually an alternating copolymer of ethylene and chlorotrifluoroethylene; a third comonomer is incorporated to reduce the crystallinity of the copolymer. Figures 3.55 and 3.56 present the yield and tensile strength and yield and ultimate elongation of ECTFE versus temperature. Yield and tensile strength decrease with increasing temperature.

3.7.1.2 Moduli

The moduli of fluoropolymers are a function of a number of variables, most important of which is the composition of the polymer and, more specifically, the presence or absence of hydrogen in the polymer. Other variables are those affecting the other mechanical properties of these plastics. They include testing temperature, molecular weight, and crystallinity, which affect the modulus of these plastics independently of the regime/type of measurements. Perfluoropolymers have lower moduli than partially fluorinated fluoroplastics. An increase in the fluorine content of the fluoroplastic increases the modulus.

Figures 3.57 through 3.61 give data for flex modulus as a function of temperature for PFA, FEP, PVDF, ETFE, and ECTFE. Table 3.43 gives flexural modulus of PFA as a function of temperature and MFR (molecular weight). Table 3.44 presents data for flexural modulus of homo/copolymers of PVDF at -40°C. The most common technique for measuring flexural modulus is ASTM D790. Figure 3.57 shows the effect of crystallinity as represented by two different values of specific gravity (SG). PFA specimens were cooled at different rates; the larger SG belongs to the specimen with the higher crystallinity (cooled more slowly). It can be seen that higher crystallinity results in a higher modulus.

Figures 3.62 and 3.63 illustrate the behavior of tensile moduli of PFA, MFA, and ETFE as a function of temperature and resin grade. Figure 3.64 shows apparent flex modulus of ETFE in creep mode as a function of temperature, time, and resin grade.

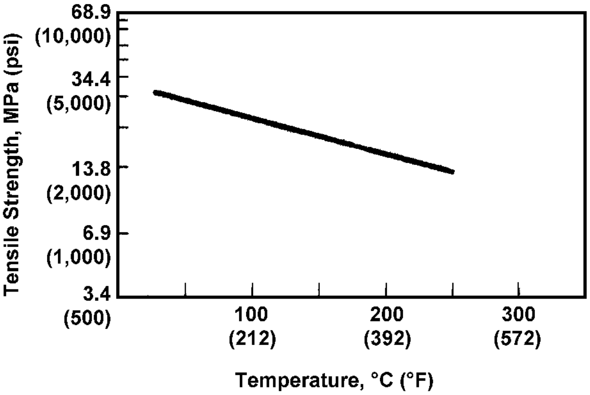

Figure 3.34 Tensile strength of PFA as a function of temperature.[32]

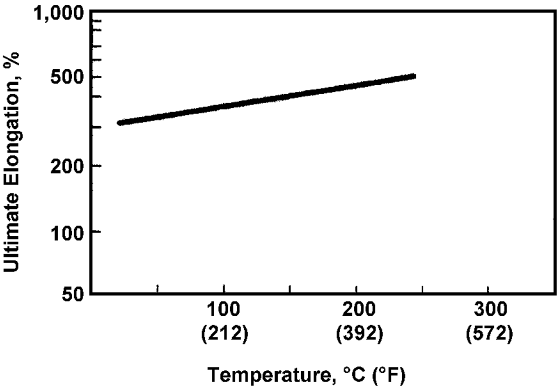

Figure 3.35 Ultimate (break) elongation of PFA as a function of temperature.[32]

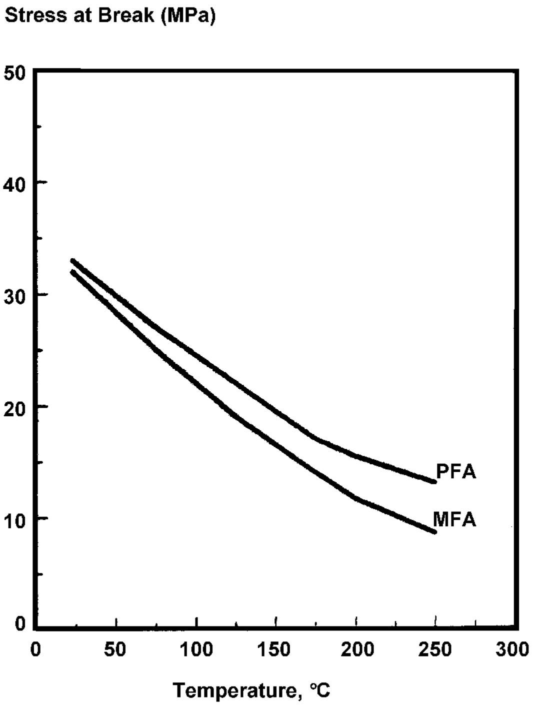

Figure 3.36 A comparison of tensile strength of PFA and MFA as a function of temperature.[33]

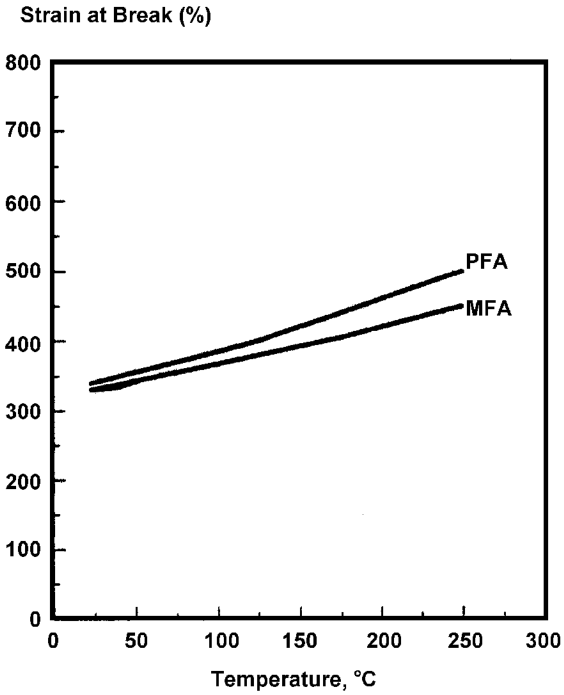

Figure 3.37 A comparison of ultimate elongation of PFA and MFA as a function of temperature.[33]

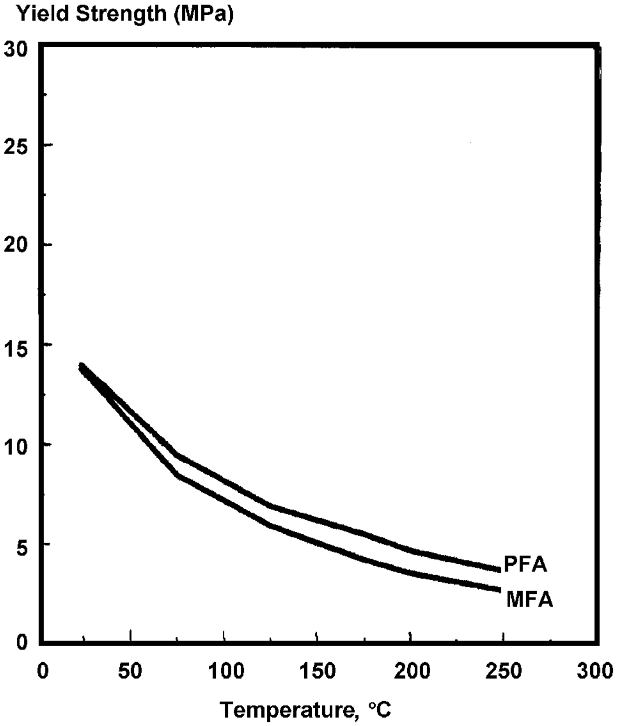

Figure 3.38 A comparison of yield strength of PFA and MFA as a function of temperature.[33]

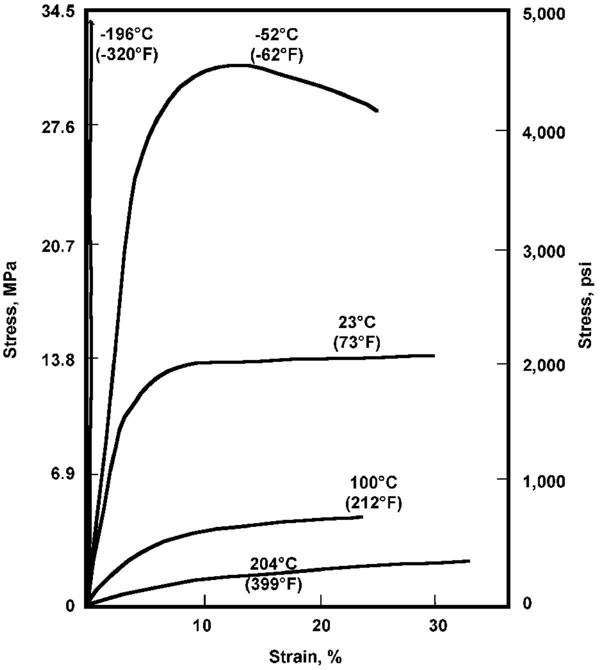

Figure 3.39 Tensile stress-strain behavior of FEP (MFR = 7) as a function of temperature.[34]

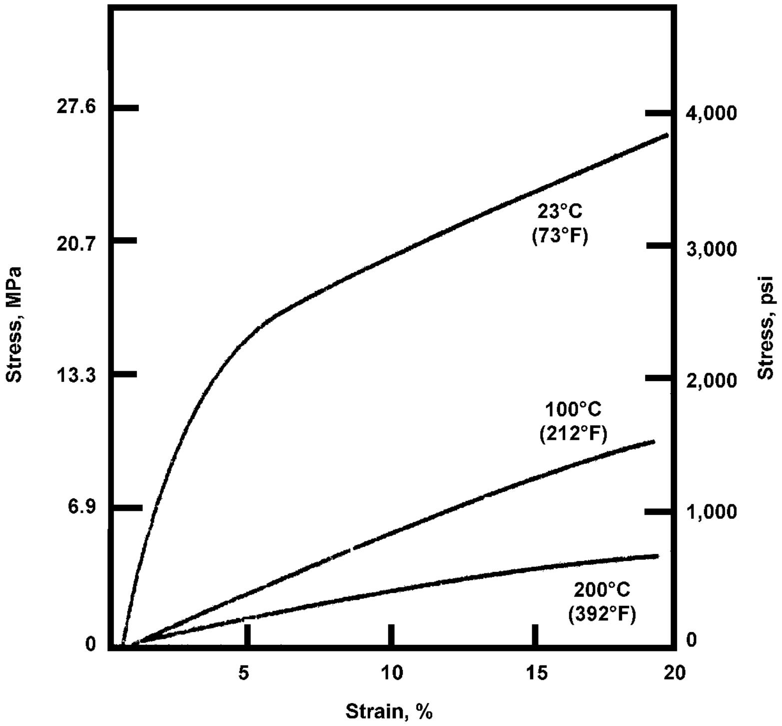

Figure 3.40 Compression stress-strain behavior of FEP (MFR = 7) as a function of temperature.[34]

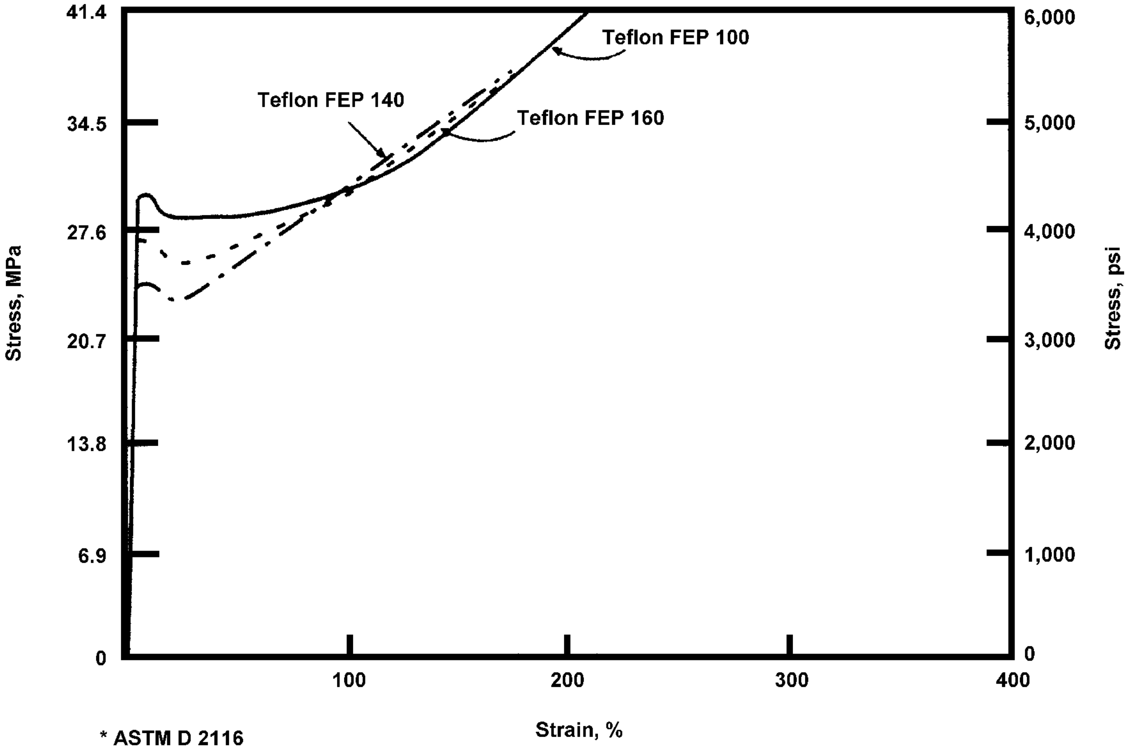

Figure 3.41 Stress-strain behavior of various grades of FEP at -52°C.[34]

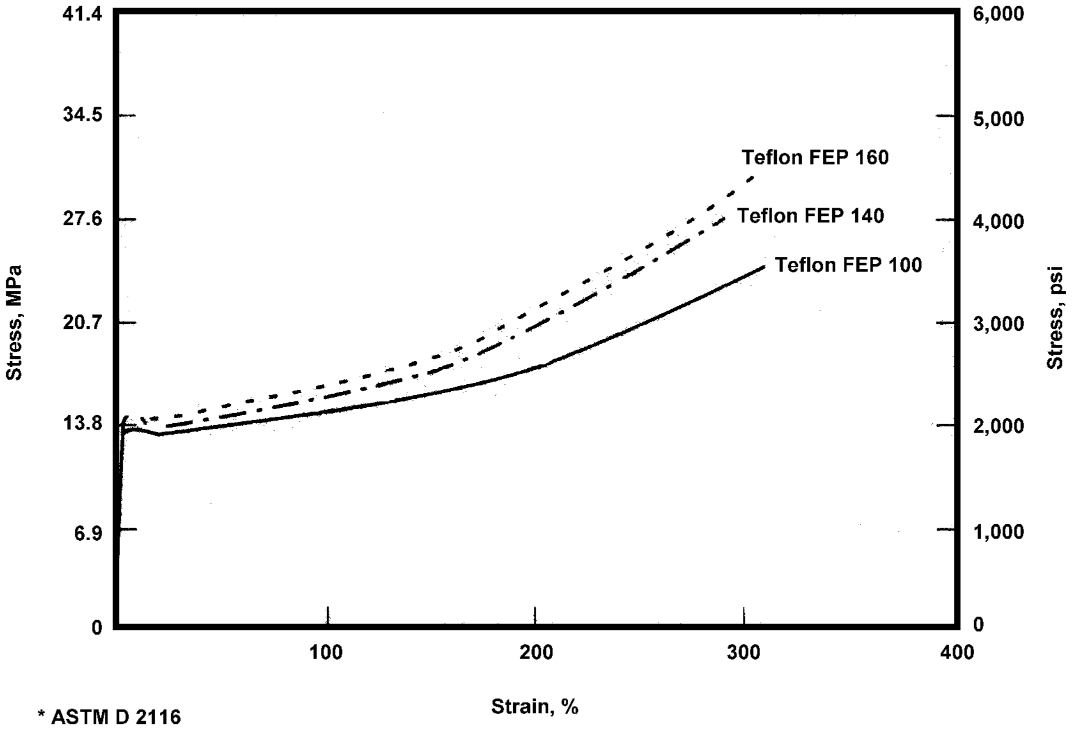

Figure 3.42 Stress-strain behavior of various grades of FEP at 23°C.[34]

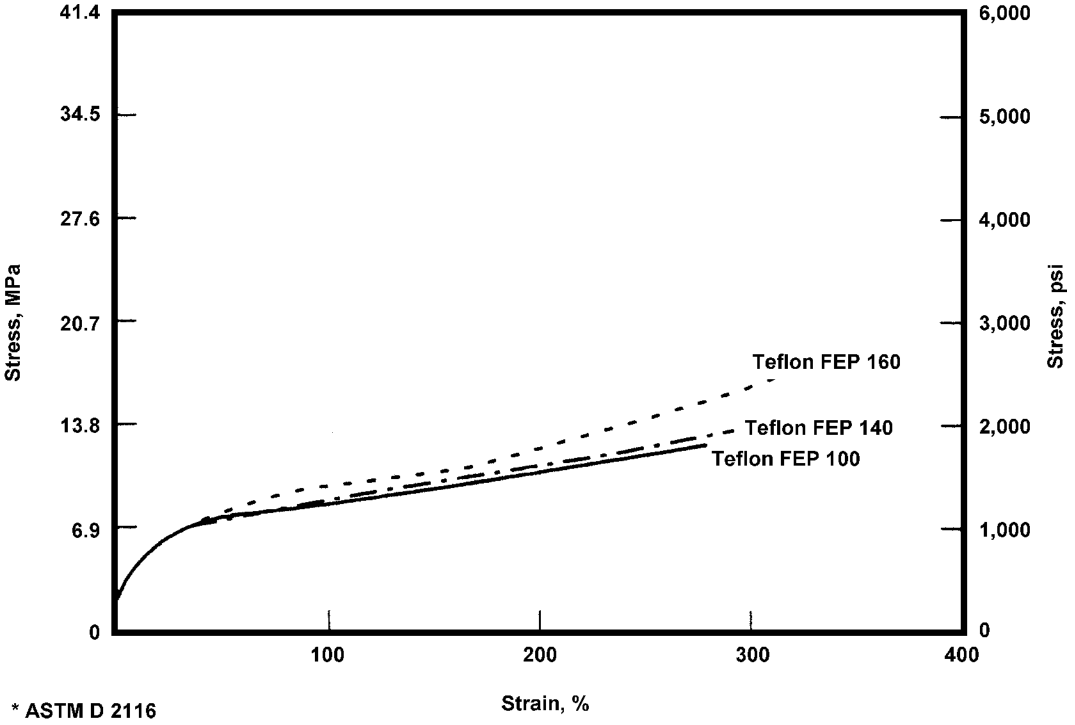

Figure 3.43 Stress-strain behavior of various grades of FEP at 100°C.[34]

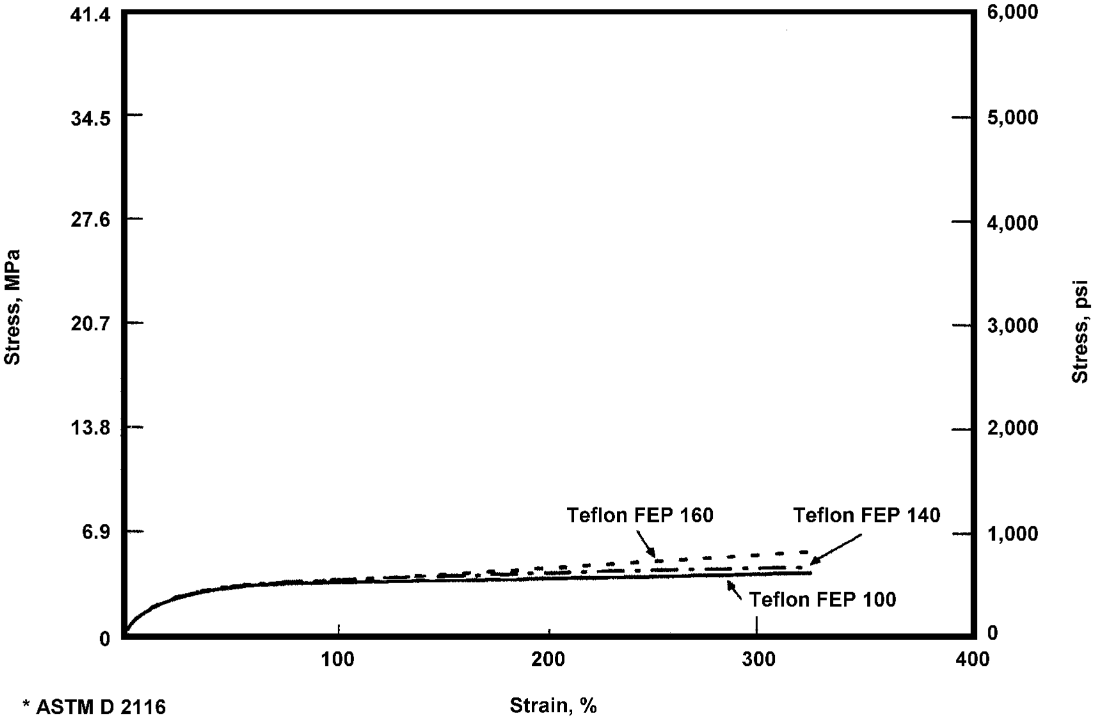

Figure 3.44 Stress-strain behavior of various grades of FEP at 200°C.[34]

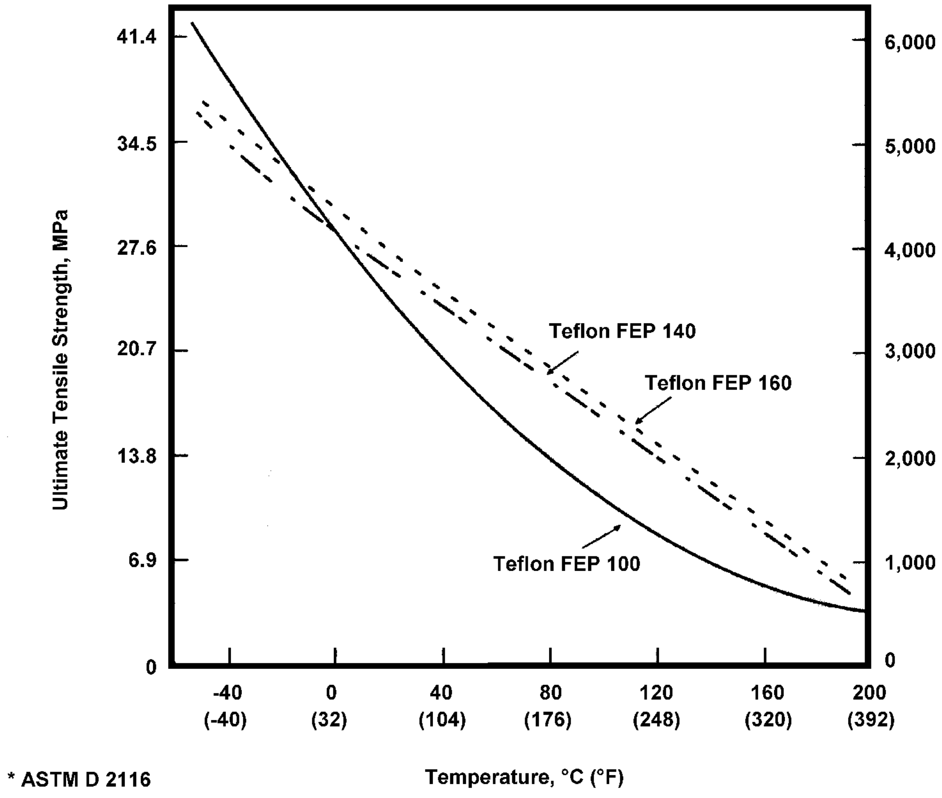

Figure 3.45 Tensile strength of FEP as a function of temperature and grade.[34]

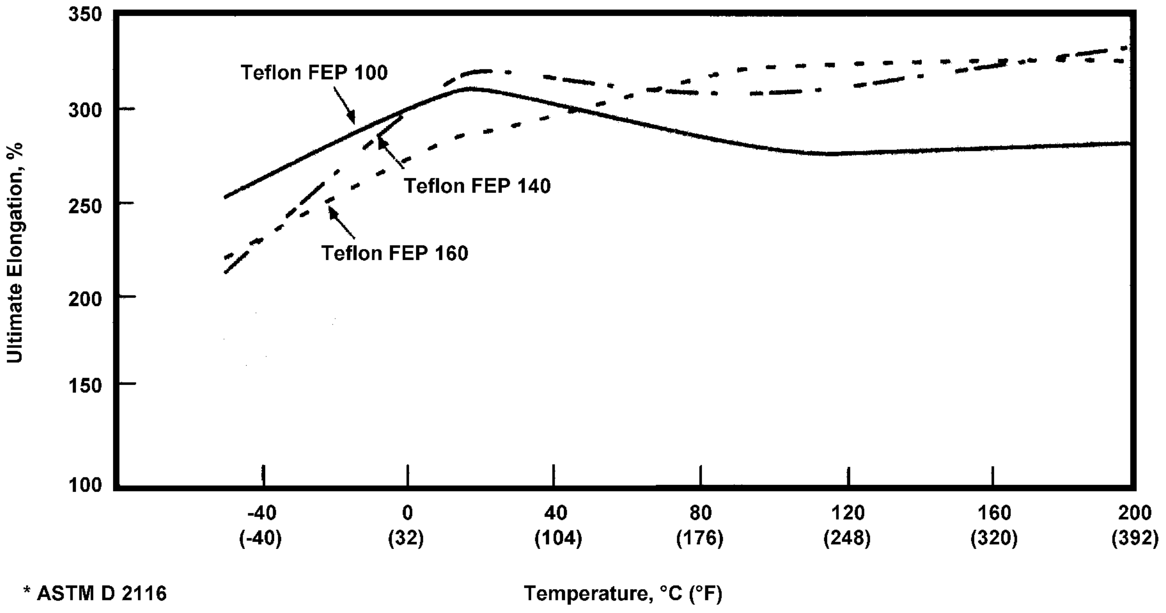

Figure 3.46 Ultimate (break) elongation of FEP as a function of temperature and grade.[34]

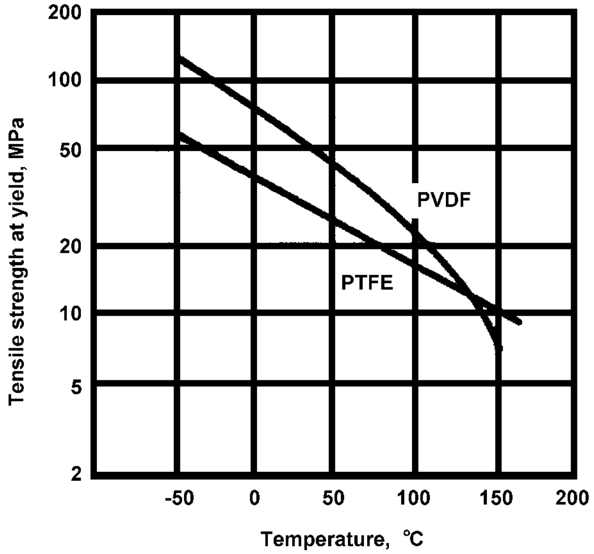

Figure 3.47 Tensile strength of PVDF as a function of temperature.[35]

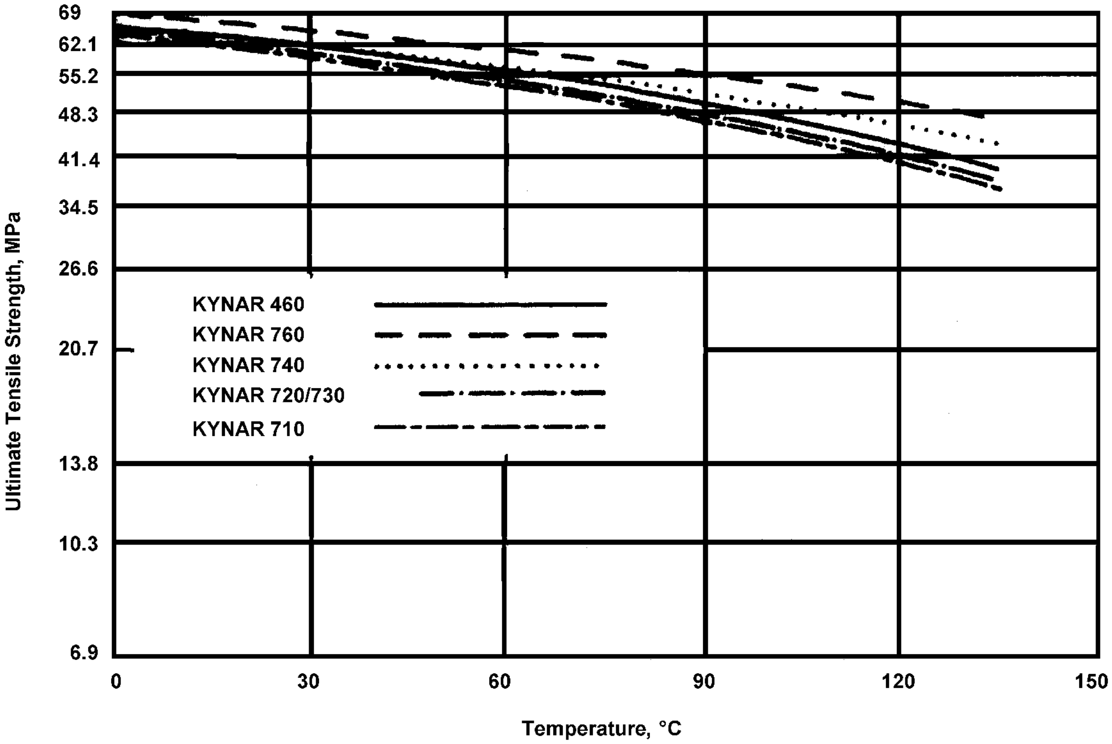

Figure 3.48 Tensile strength of PVDF as a function of temperature and grade.[36]

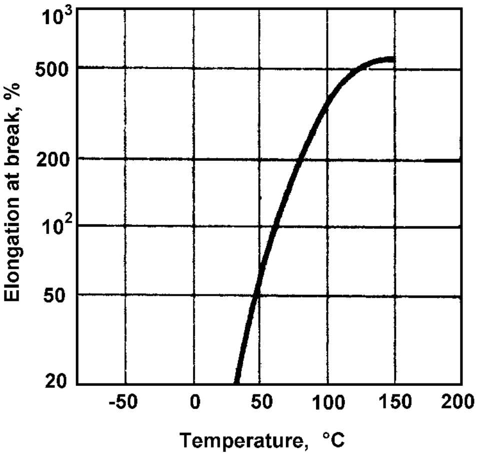

Figure 3.49 Ultimate (break) elongation of PVDF as a function of temperature.[35]

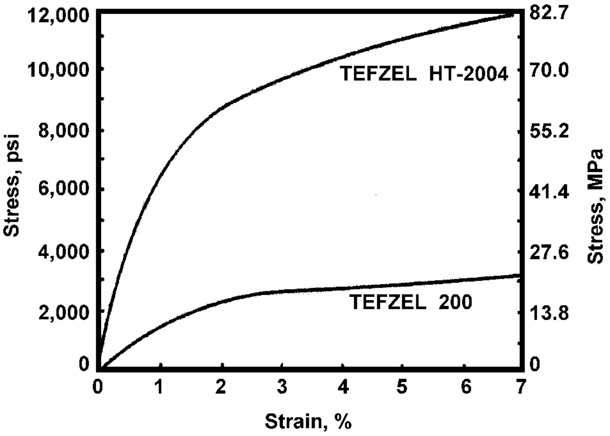

Figure 3.50 Tensile stress-strain behavior of various grades (MFRs) of ETFE at room temperature.[37]

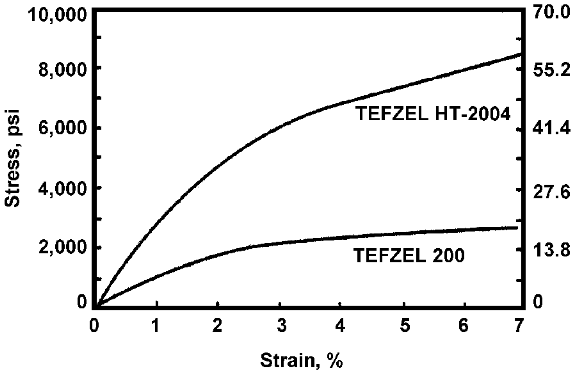

Figure 3.51 Compressive stress-strain behavior of various grades (MFRs) of ETFE at room temperature.[37]

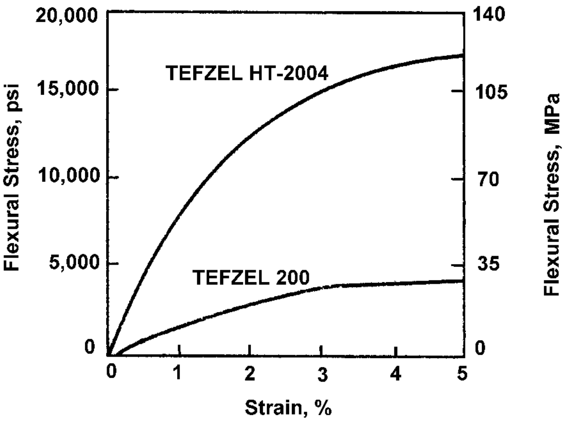

Figure 3.52 Flexural stress-strain behavior of two grades (MFRs) of ETFE at room temperature.[37]

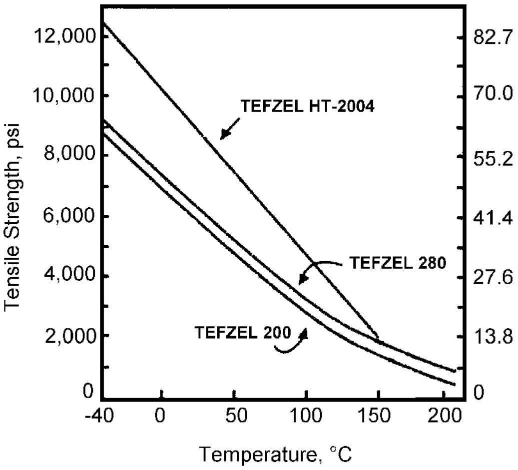

Figure 3.53 Tensile strength of ETFE as a function of temperature and grade.[37]

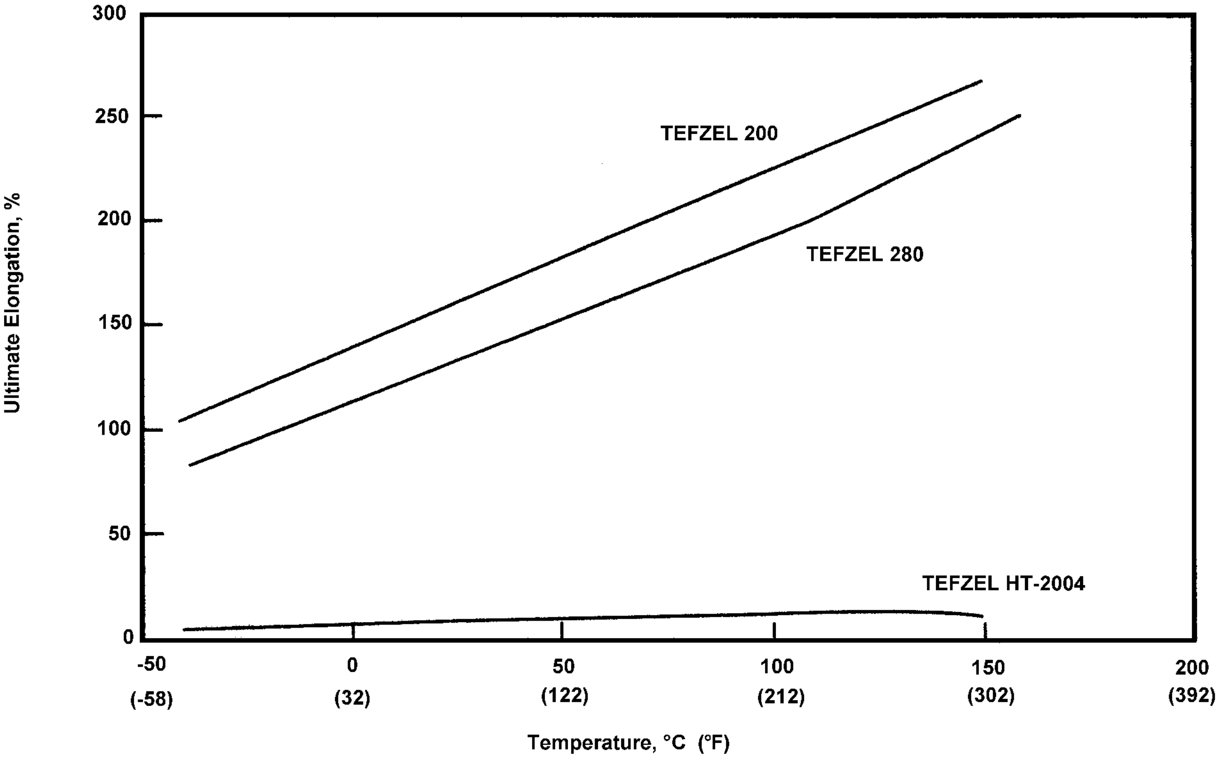

Figure 3.54 Ultimate (break) elongation of ETFE as a function of temperature.[37]

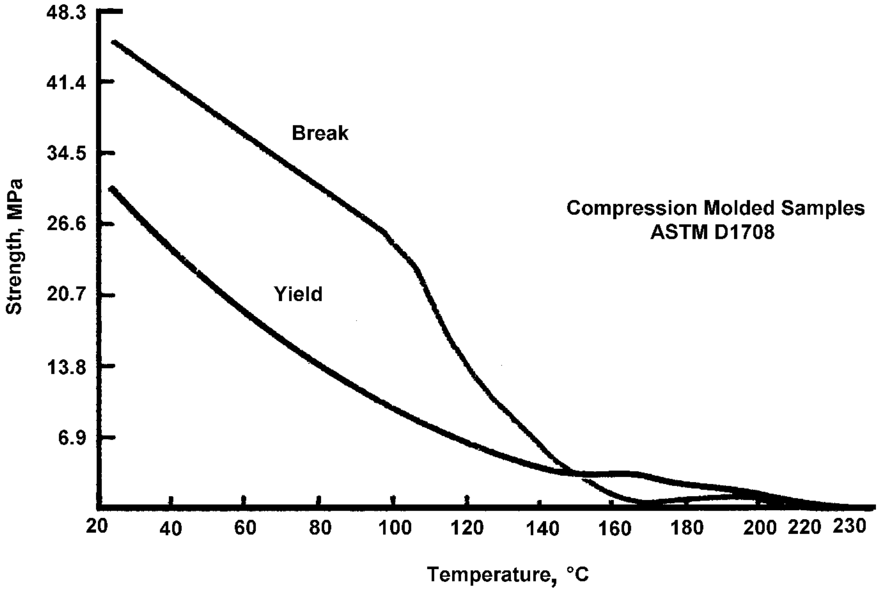

Figure 3.55 Yield strength and tensile (break) strength of ECTFE as a function of temperature.[38]

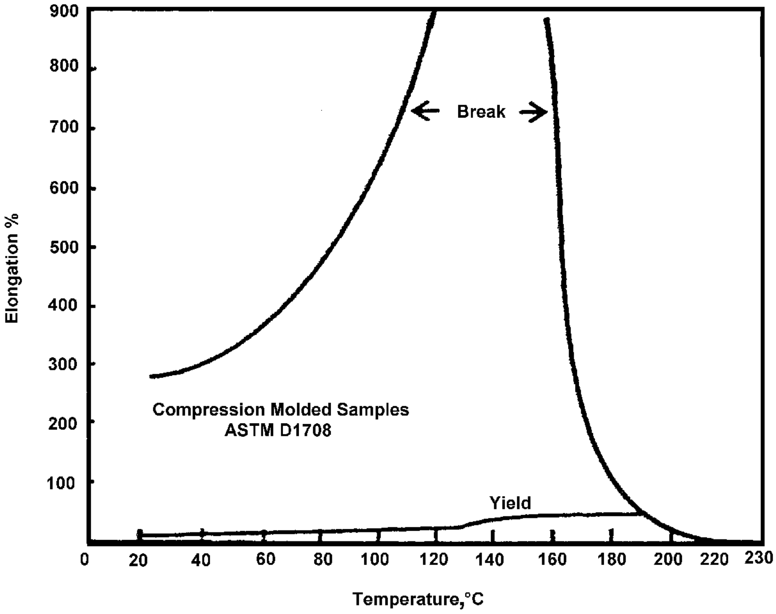

Figure 3.56 Yield elongation and ultimate (break) elongation of ECTFE as a function of temperature.[38]

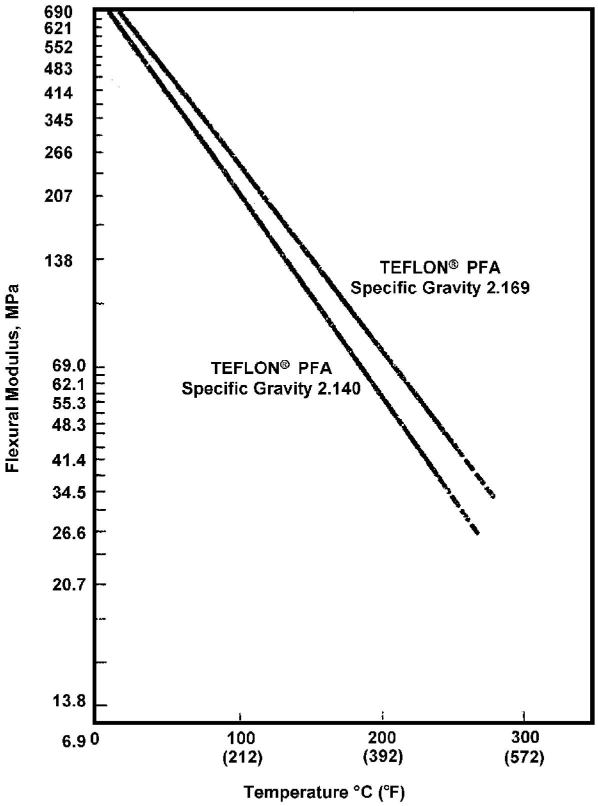

Figure 3.57 Flexural modulus of PFA as a function of temperature and crystallinity.[32] (Note: higher crystallinity results in higher specific gravity.)

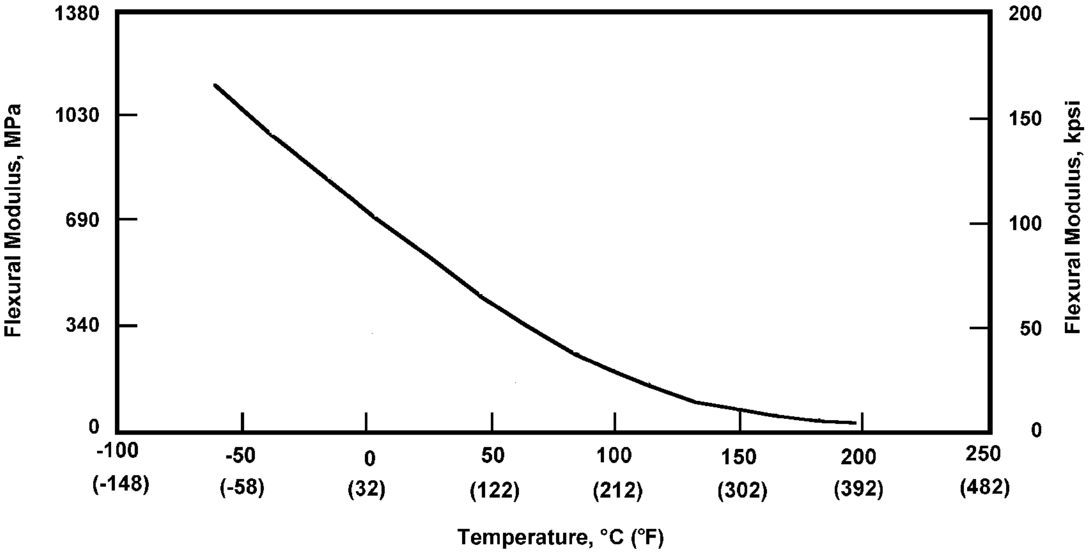

Figure 3.58 Flexural modulus of FEP as a function of temperature.[34]

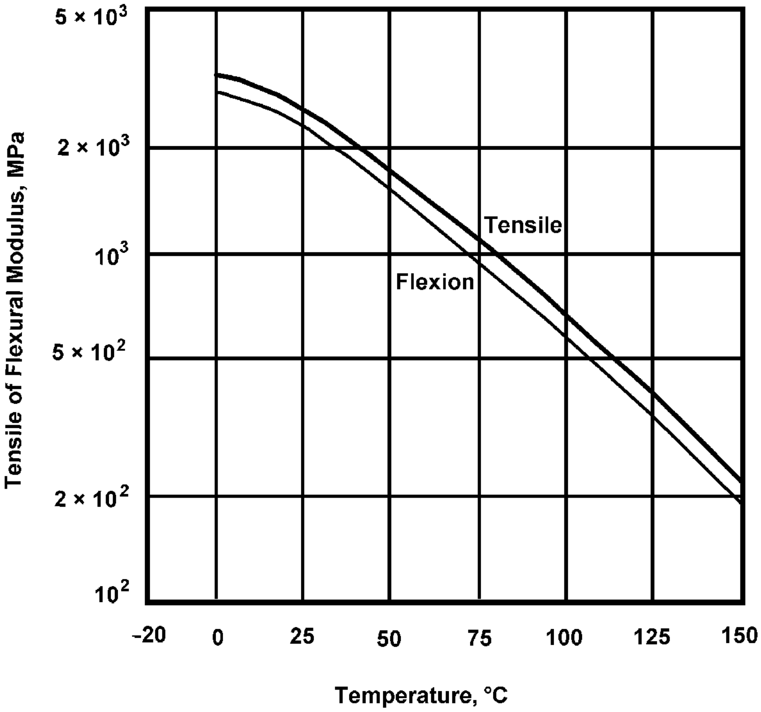

Figure 3.59 Flexural and tensile modulus of PVDF as a function of temperature.[35]

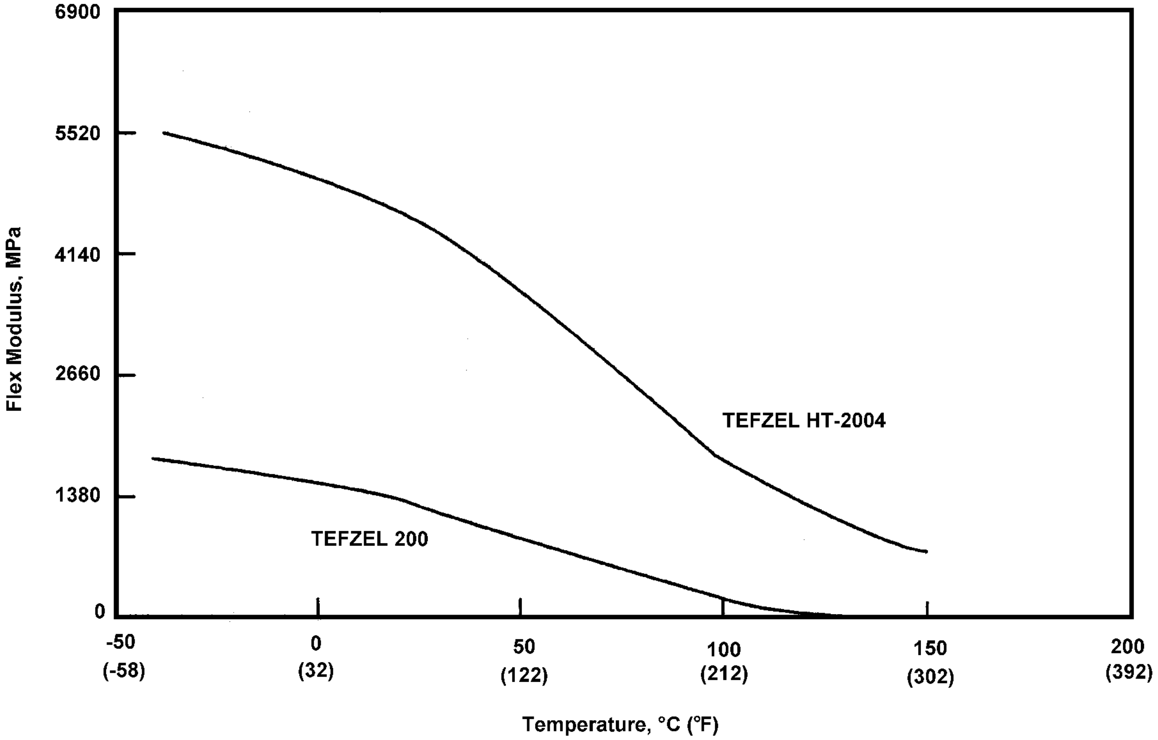

Figure 3.60 Flexural modulus of ETFE as a function of temperature.[37]

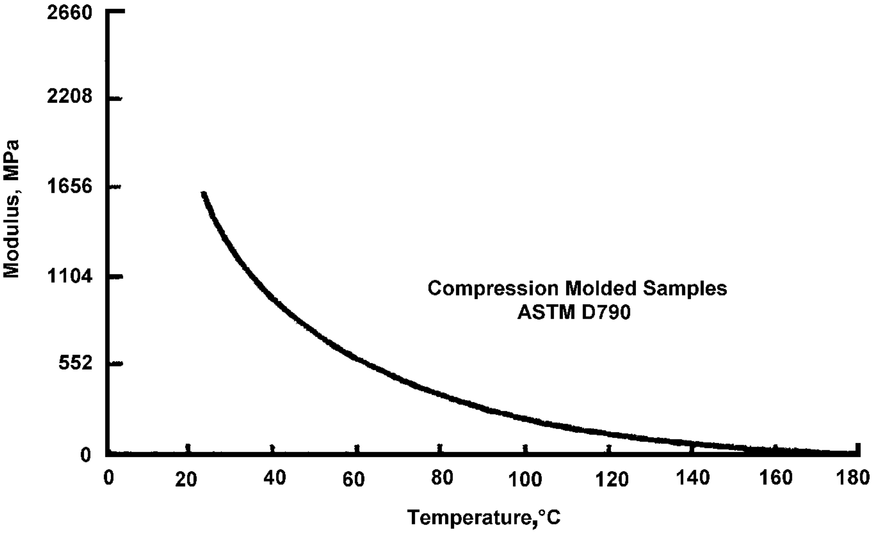

Figure 3.61 Flexural modulus of ECTFE as a function of temperature.[38]

Table 3.43. Flexural Modulus of PFA vs MFR and Temperature[32]

Temperature, °C	Flexural Modulus, MPa	
	MFR = 13 g/ 10 min	MFR = 2 g/ 10 min
23	590	625
250	55	69

Table 3.44. Flexural Modulus of PVDF at -40°C[35]

PVDF Polymer	Maximum Load, MPa	Modulus, MPa
Homopolymer	149	3,800
Homopolymer	151	3,700
Copolymer	112	3,000

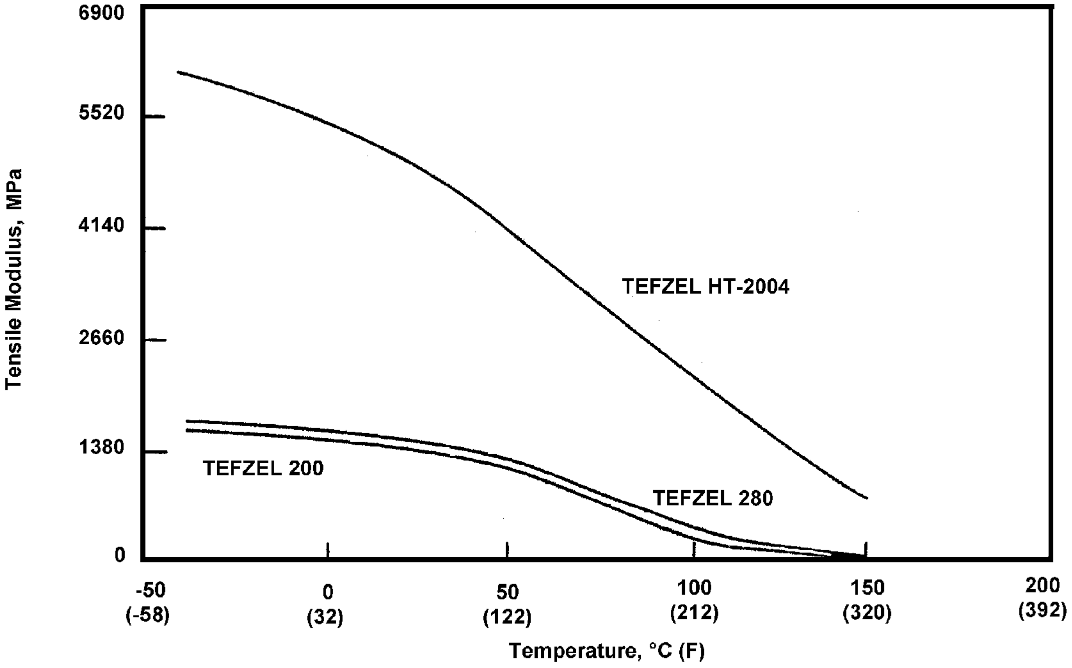

Figure 3.62 Tensile modulus of ETFE as a function of temperature.[37]

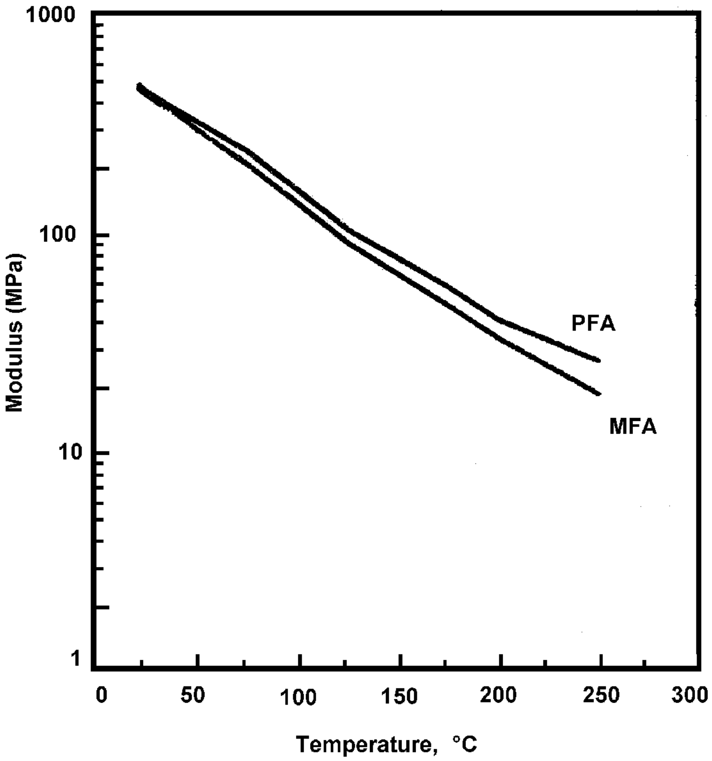

Figure 3.63 Tensile modulus of PFA and MFA as a function of temperature.[33]

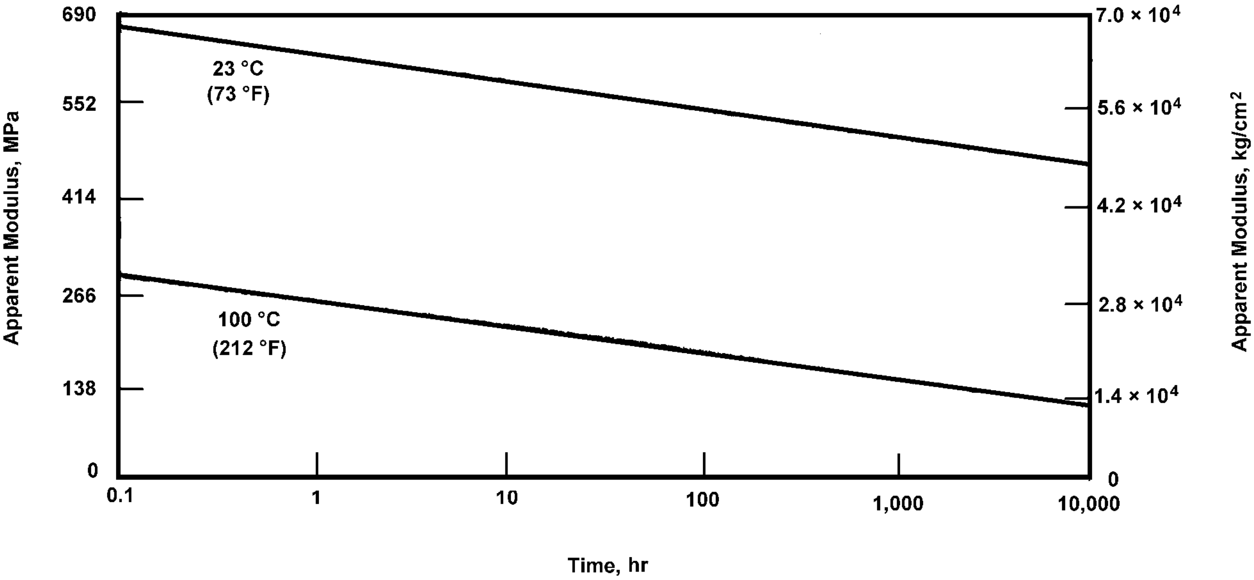

Figure 3.64 Apparent flexural modulus of ETFE in creep mode as a function of temperature, time, and resin grade.[37]

3.7.1.3 Deformation Under Load (Creep)

This property is an important consideration in the design of parts from fluoroplastics because they deform substantially over time when subjected to load. Metals similarly deform at elevated temperatures. *Creep* (also called cold flow) is defined as the total deformation under stress after a period of time, beyond the instantaneous deformation upon the application of load. Significant variables that affect creep are chemical structure of resin, load, time under load, and temperature. Creep is measured under various conditions: tensile, compressive, and torsional.

Perfluorinated fluoroplastics have higher creep tendency than partially fluorinated fluoropolymers. Polytetrafluoroethylene, comprised of 100% tetrafluoroethylene monomer, has the highest tendency to exhibit cold flow. Copolymers of tetrafluoroethylene containing small amounts (0.1% by weight) of certain other fluorinated monomers, also referred to as *modifiers,* have significantly lower creep. These modifiers form pendent groups in the polymer chain.

FEP and PFA are examples of perfluorinated interpolymers (one or more comonomers) of tetrafluoroethylene that contain much higher quantities of comonomers than modified PTFE's. The higher content of comonomer significantly alters the properties of perfluoroplastics, one of which is a reduction in their tendency to deform under load. Figures 3.65 through 3.75 illustrate the deformation under load of PFA and FEP in tensile and compressive modes as a function of time, stress, and temperature. Creep behavior and resistance of PVDF polymers is shown in Figs. 3.76 through 3.81. Figures 3.82 and 3.83 show flexural creep behavior of ETFE while Figs. 3.84 and 3.85 demonstrate tensile creep behavior of ECTFE.

Stress relaxation is important in applications where the part is subjected to compressive load in contrast to tensile stress. For example, a gasket under the pressure of flange bolts will creep, resulting in a reduced bolt pressure. This reduction in load often leads to leakage at the joint. Tightening the flange after 24 hours will prevent leakage. Thereafter, stress relaxation will be negligible. Plots of tensile stress relaxation (Figs. 3.86 and 3.87) illustrate the decay rate at constant strain. Alternative compressive loading and load removal indicates nearly complete recovery from strain as long as the original strain is below the yield strain. FEP does not experience work hardening.

3.7.1.4 Poisson's Ratio

Poisson's ratio is defined as the ratio of the change in a sample's width per unit width to the change in the length per unit length, as a result of straining a plastic sample.[39] Examples of Poisson's ratios of fluoropolymers are illustrated in Table 3.45.

3.7.1.5 Flex Fatigue Properties

Flexural characteristics are of paramount importance in applications involving movement or vibration of parts. Valve diaphragms are an example of a part in which the membrane experiences repetitive movement. *Flexural* or *flex life* is defined as the number of cycles that a part can endure before catastrophic fatigue occurs; the higher the molecular weight, the higher the flex life. Increased crystallinity has a detrimental effect on the flex life; the higher the crystallinity, the lower the flex life. Bubbles, voids, and contamination should be eliminated from any part expected to perform in demanding flex applications. Each of these defects can become the nucleus of failure after the part has been subjected to flexing action. The geometry and design of a part also influence its flexural endurance.

There are a number of different techniques for measuring flex life; the most common of them is the MIT Folding Endurance test according to ASTM D2176. Tables 3.46 and 3.47 contain flex life data for perfluoroalkoxy polymers. The effect of molecular weight on flex life is drastic; increasing molecular weight decreases the MFR. Table 3.48 provides fatigue resistance data for FEP (MFR = 7 g per 10 minutes) as a function of stress as determined using a Sonntag-Universal machine.

Figure 3.88 shows the relationship between stress and flex life (cycles to failure) for ETFE at 23°C. In this figure, flex fatigue characteristics of an unfilled resin (MFR = 7) and a filled resin (25% by weight glass) has been plotted. Testing was conducted according to ASTM D671 at a rate of 1,800 cycles per minute, alternating the specimen between tension and compression.

3.7.1.6 *Impact Strength*

Impact strength, or ability of a part to absorb energy, translates into its ability to develop an internal force multiplied by the deformation of the part without failure. This is difficult to predict because the design characteristics of a part, such as a metal spring as opposed to a flat metal plate, have a major effect on its ability to absorb impact.

Designing flexibility into the part to increase the length over which energy is distributed reduces the internal force required to resist impact.

Generally, fluoropolymers have excellent impact strength in a broad temperature range. They can withstand significant impact force at cryogenic temperatures. Tables 3.49 and 3.50 present examples of impact strength of different fluoroplastics.

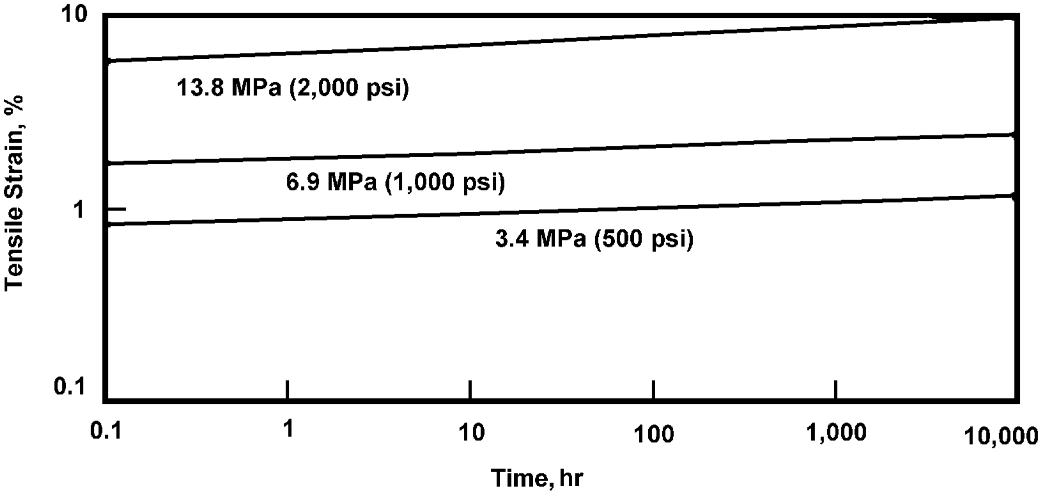

Figure 3.65 Deformation under load of PFA in tensile mode at 23°C.[32]

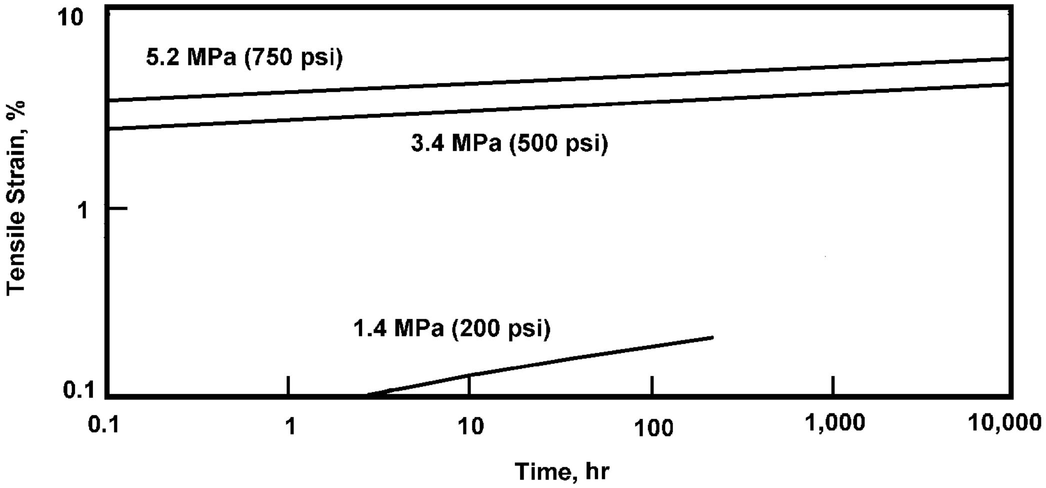

Figure 3.66 Deformation under load of PFA in tensile mode at 100°C.[32]

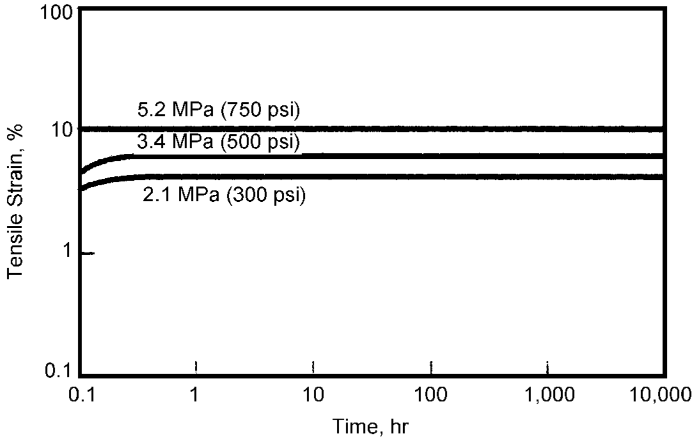

Figure 3.67 Deformation under load of PFA in tensile mode at 200°C.[32]

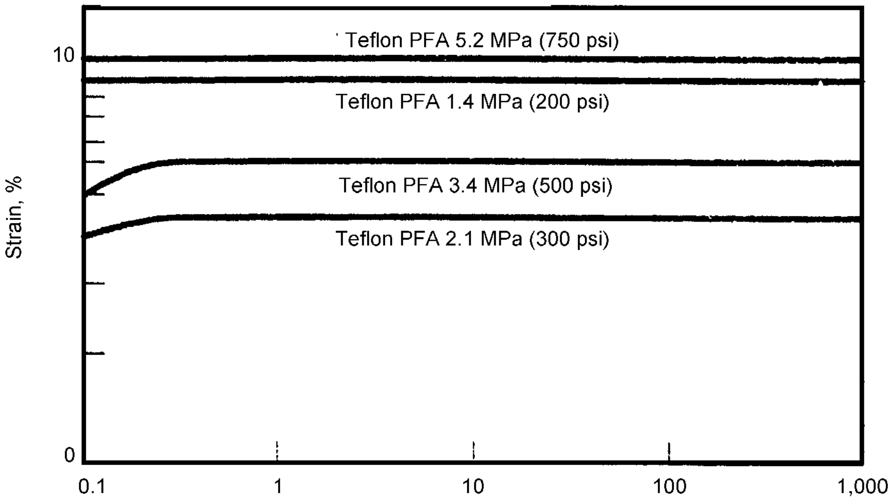

Figure 3.68 Deformation under load of PFA in compressive mode at 200°C.[32]

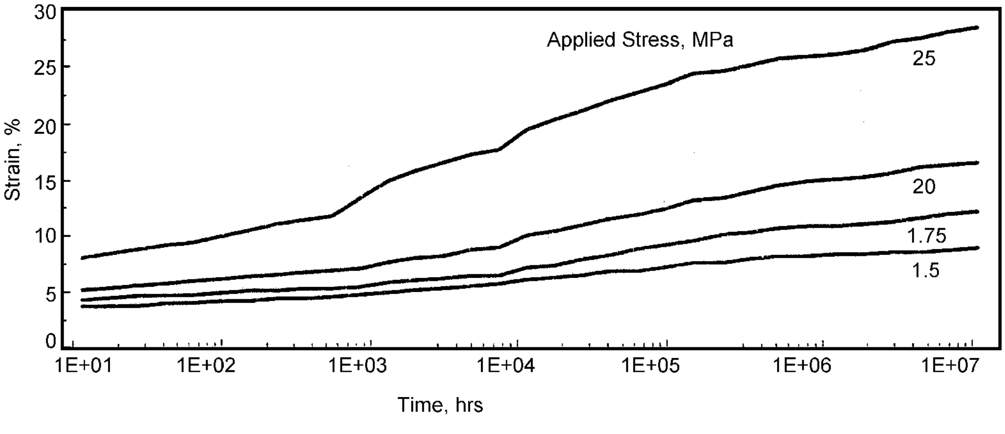

Figure 3.69 Deformation under load of PFA (MFA, modified by perfluoromethyl vinyl ether) in tensile mode at 200°C.[33]

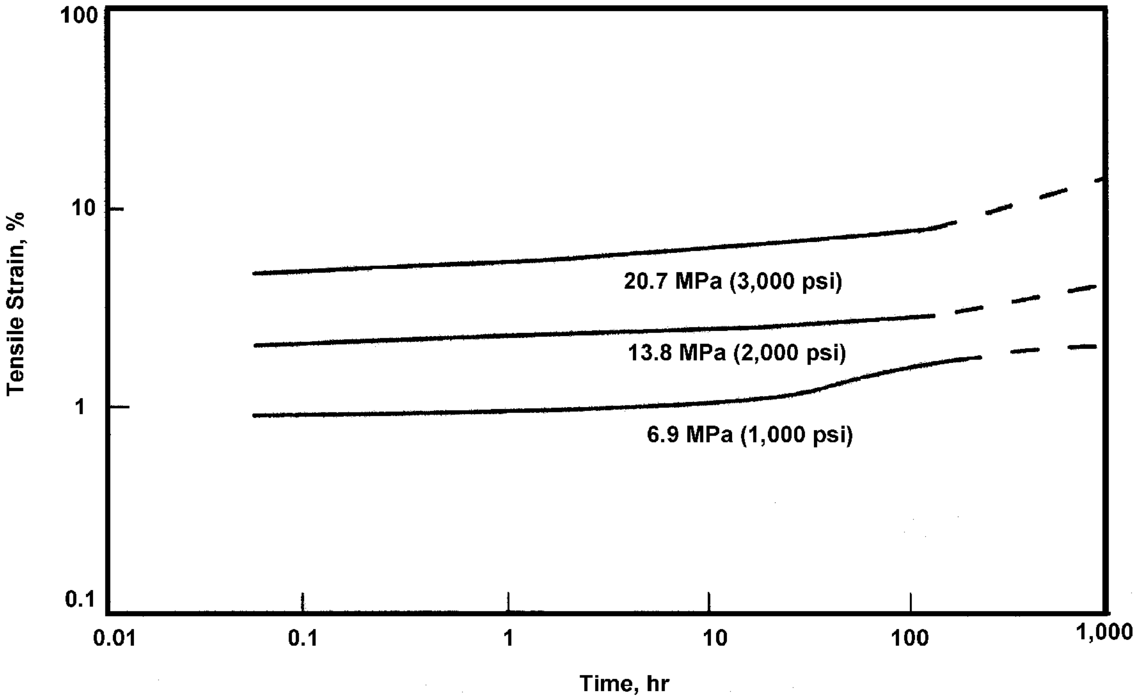

Figure 3.70 Deformation under load of FEP in tensile mode at -54°C.[34]

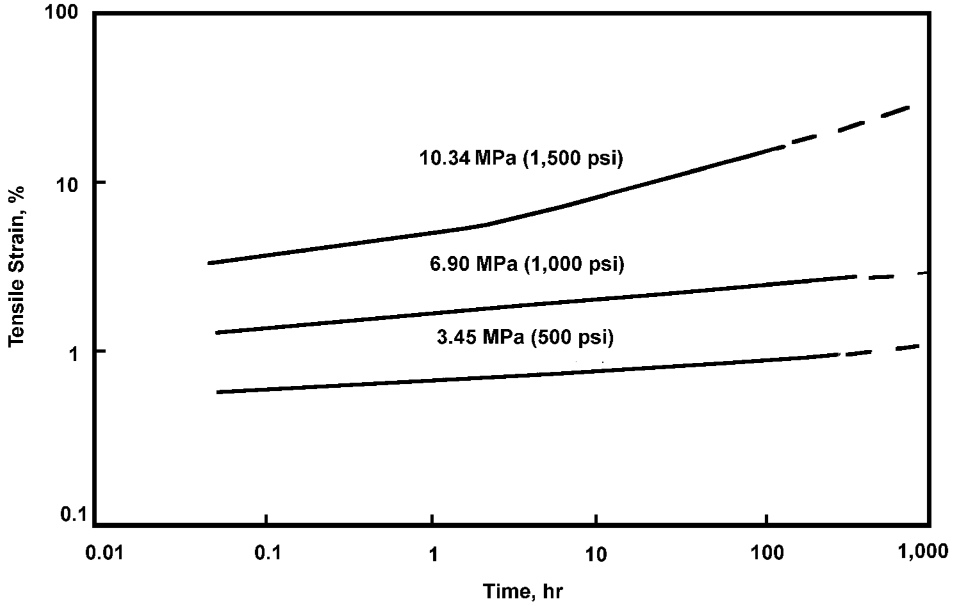

Figure 3.71 Deformation under load of FEP in tensile mode at 23°C.[34]

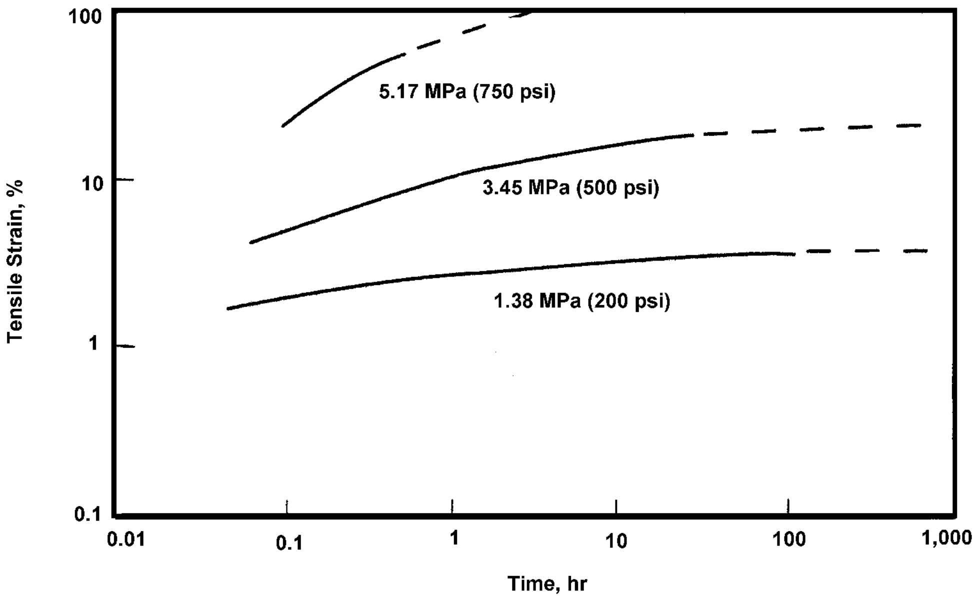

Figure 3.72 Deformation under load of FEP in tensile mode at 100°C.[34]

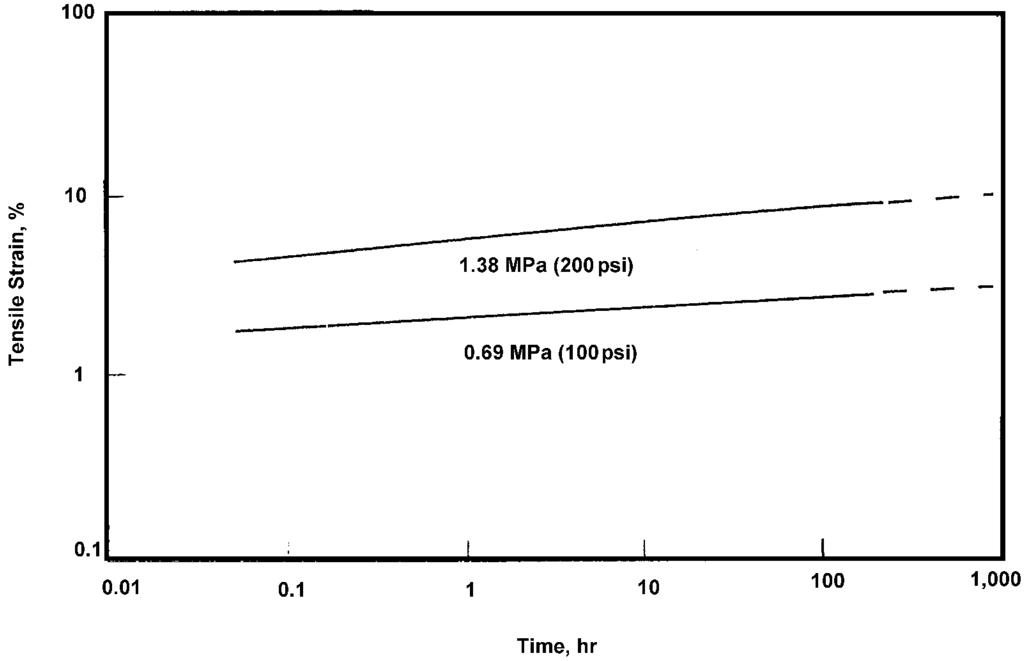

Figure 3.73 Deformation under load of FEP in tensile mode at 175°C.[34]

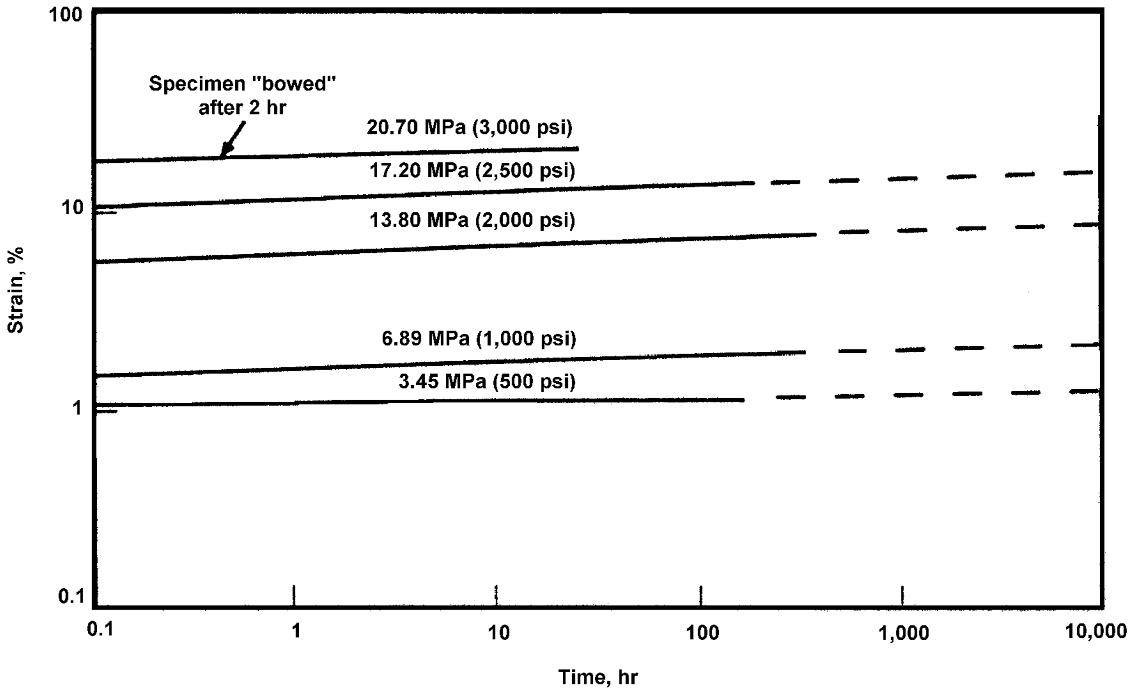

Figure 3.74 Deformation under load of FEP in compressive mode at 23°C.[34]

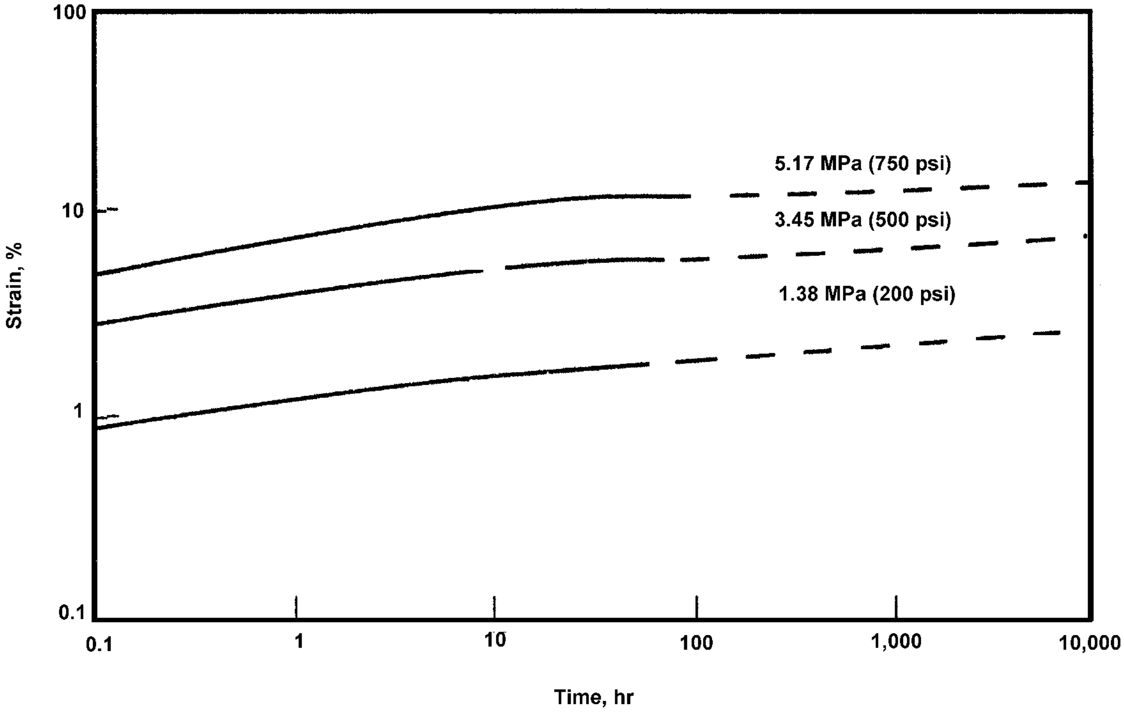

Figure 3.75 Deformation under load of FEP in compressive mode at 100°C.[34]

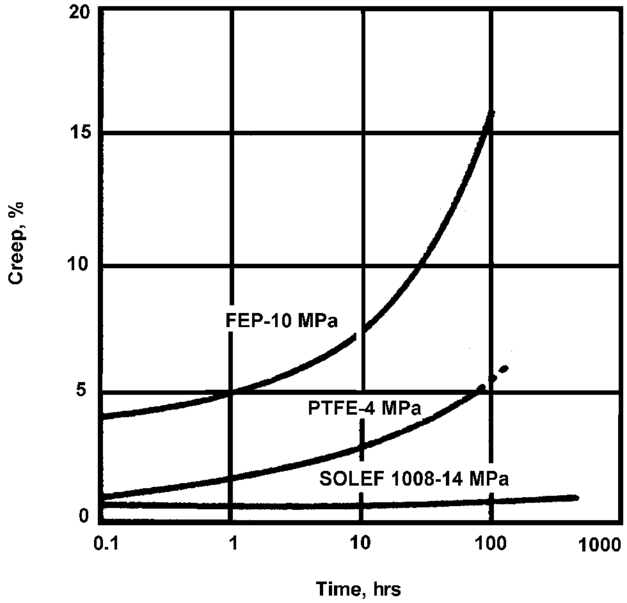

Figure 3.76 Creep behavior of PVDF, FEP, and PTFE in tensile mode at 23°C.[35]

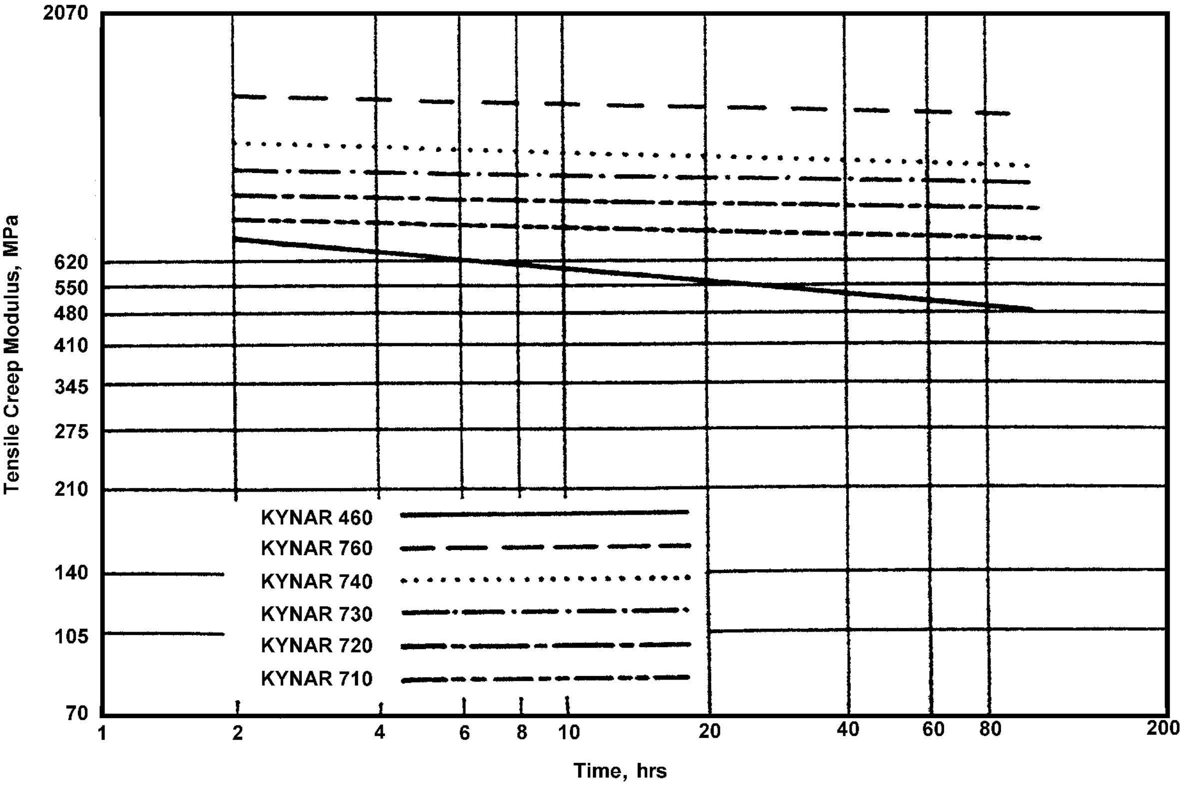

Figure 3.77 Tensile creep resistance of various grades of PVDF at 0.7 MPa and 140°C.[36]

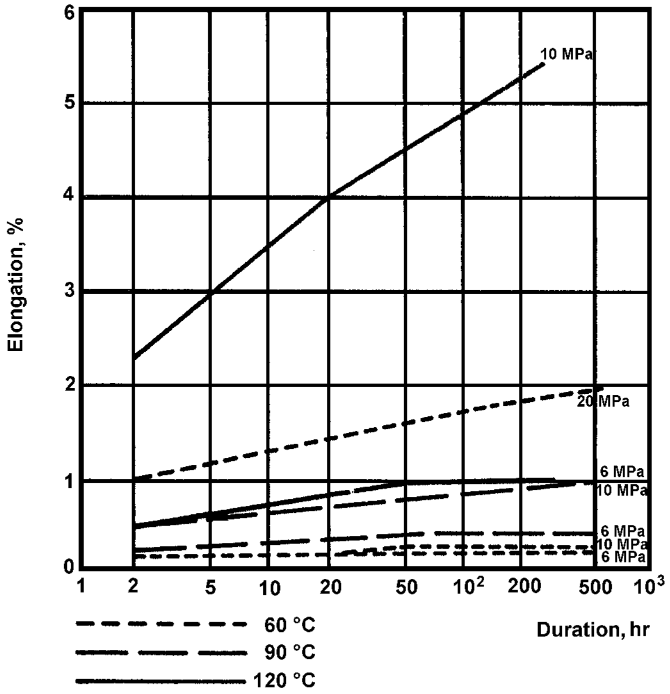

Figure 3.78 Tensile creep of PVDF (MFR = 18 g/10 min) as a function of stress, time, and temperature.[35]

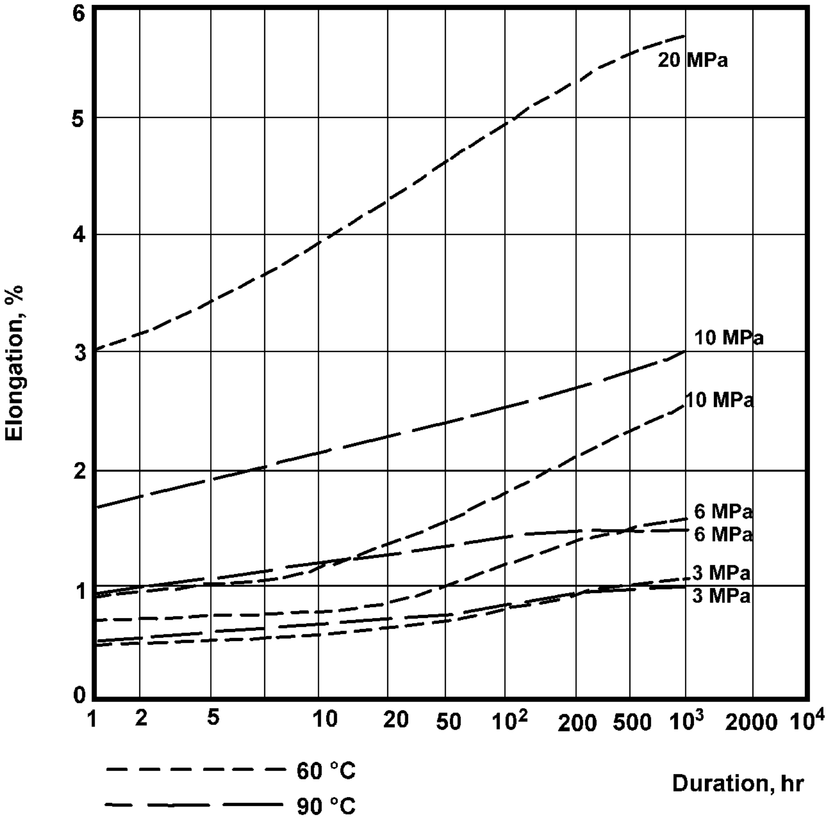

Figure 3.79 Tensile creep of PVDF (MFR = 4 g/10 min) as a function of stress, time, and temperature.[35]

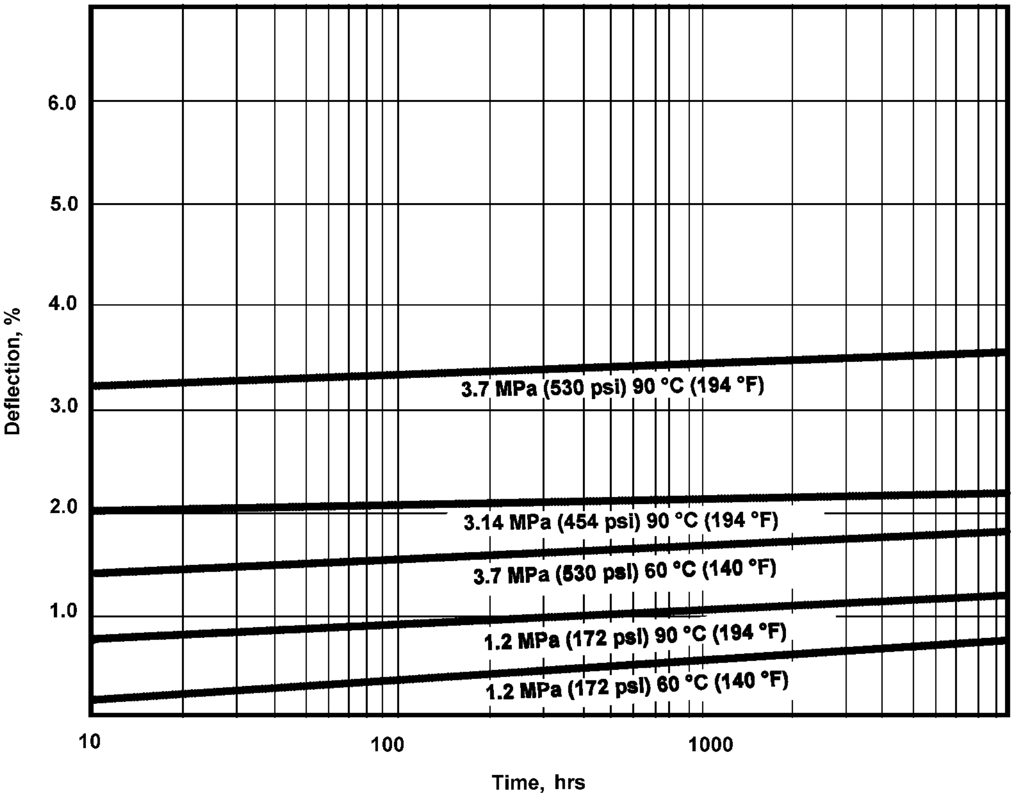

Figure 3.80 Flexural creep of various grades of PVDF as a function of stress, time, and temperature.[36]

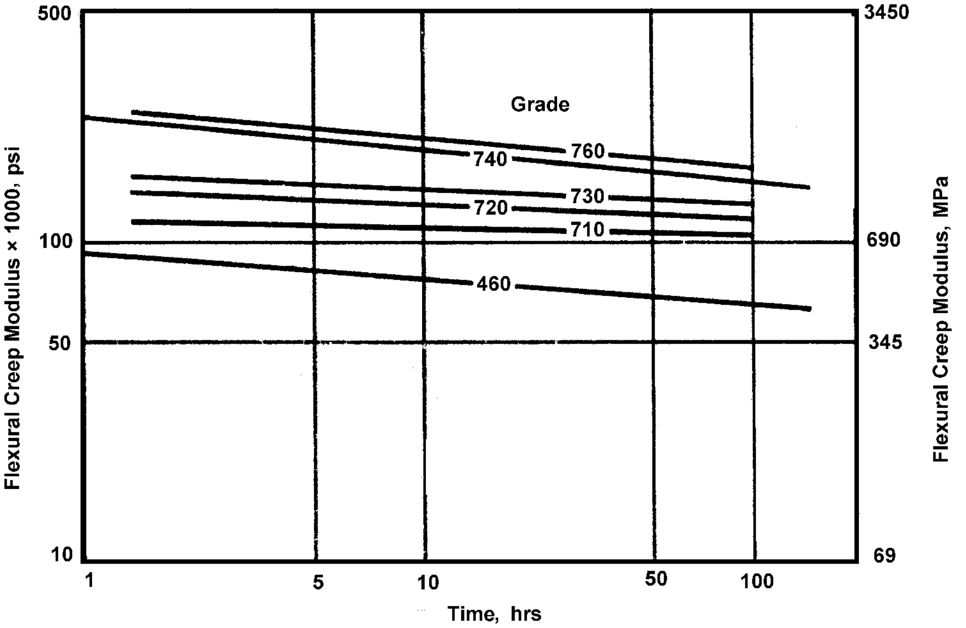

Figure 3.81 Flexural creep resistance of various grades of PVDF at 0.7 MPa and 140°C.[36]

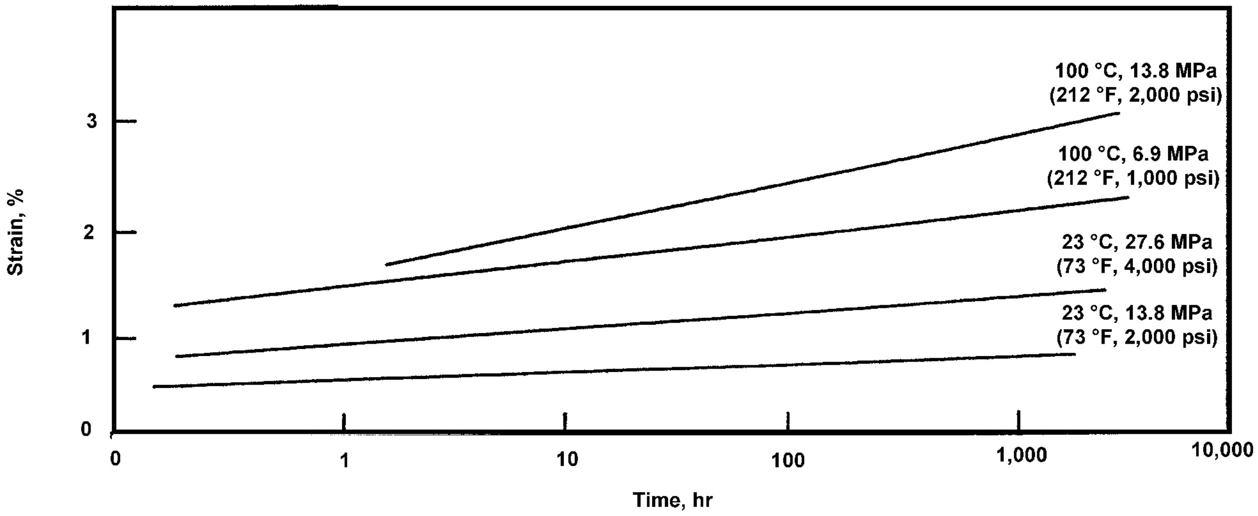

Figure 3.82 Flexural creep behavior of 25% by weight glass-filled ETFE as a function of stress, time, and temperature.[37]

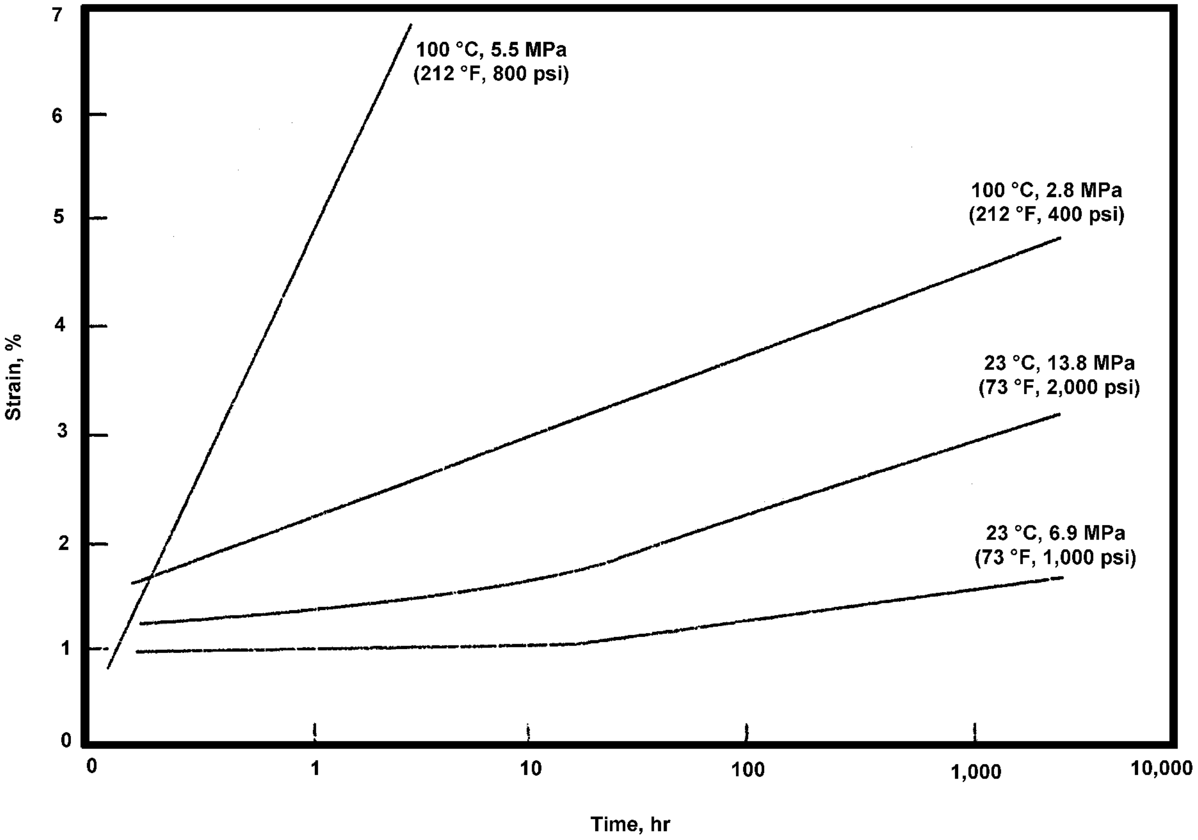

Figure 3.83 Flexural creep behavior of unfilled ETFE (MFR = 7) as a function of stress, time, and temperature.[37]

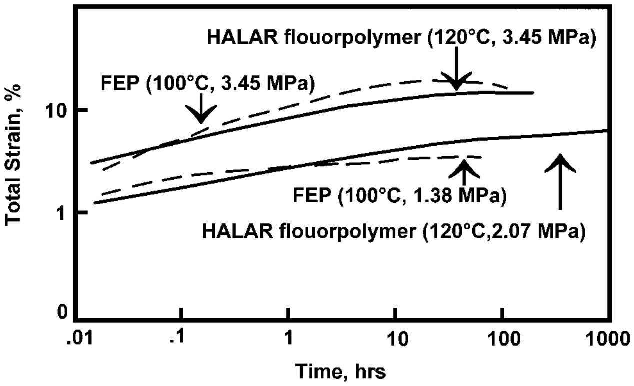

Figure 3.84 Tensile creep resistance of ECTFE (Halar®) and FEP as a function of stress, time, and temperature.[38]

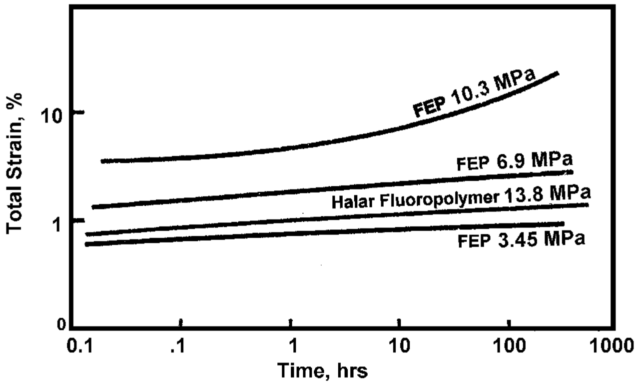

Figure 3.85 Tensile creep resistance of ECTFE (Halar®) and FEP as a function of stress and time at 23°C.[38]

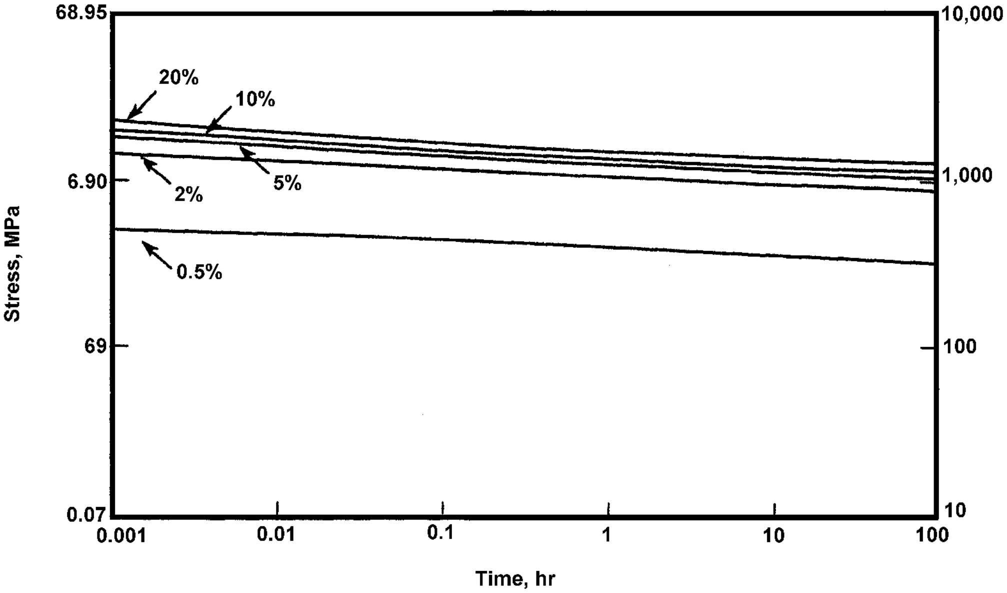

Figure 3.86 Tensile stress relaxation of FEP (MFR = 7) at constant strain at 23°C.[34]

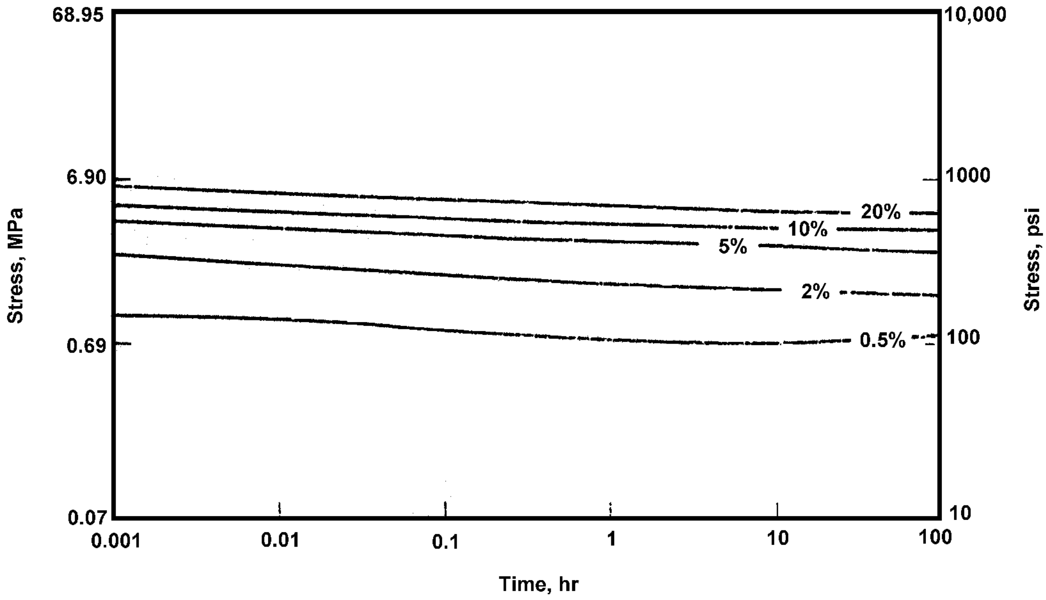

Figure 3.87 Tensile stress relaxation of FEP (MFR = 7) at constant strain at 100°C.[34]

Table 3.45. Poisson's Ratio of Fluoropolymers[34][40][41]

Fluoropolymer	Temperature, °C	Poisson's Ratio
FEP	23	0.48
	100	0.36
PTFE	23	0.46
	>23	approaches 0.50
PVDF	30	0.383

Table 3.46. MIT Flex Life of PFA According to ASTM D2176[42]–[45]

Molecular Weight (MW)	MFR, g/10 min	Flex Life, cycles to failure (0.19 mm thickness specimen)
Increase in MW	14	15,000
	6.5	100,000
	2.0	500,000
	1.7	1,800,000

Table 3.47. MIT Flex Life of MFA According to ASTM D2176[33]

Molecular Weight (MW)	MFR, g/10 min	Flex Life, cycles to failure
Increase in MW	10–17	4,000–7,000
	2–5	70,000–100,000

Table 3.48. Flex Fatigue Resistance of FEP (MFR = 7) Measured by Sonntag-Universal Machine[34]

Stress, MPa	Flex Life, cycles to failure
6.9	>7,000,000
9.65	>7,200,000
10.0	1,300
10.3	960

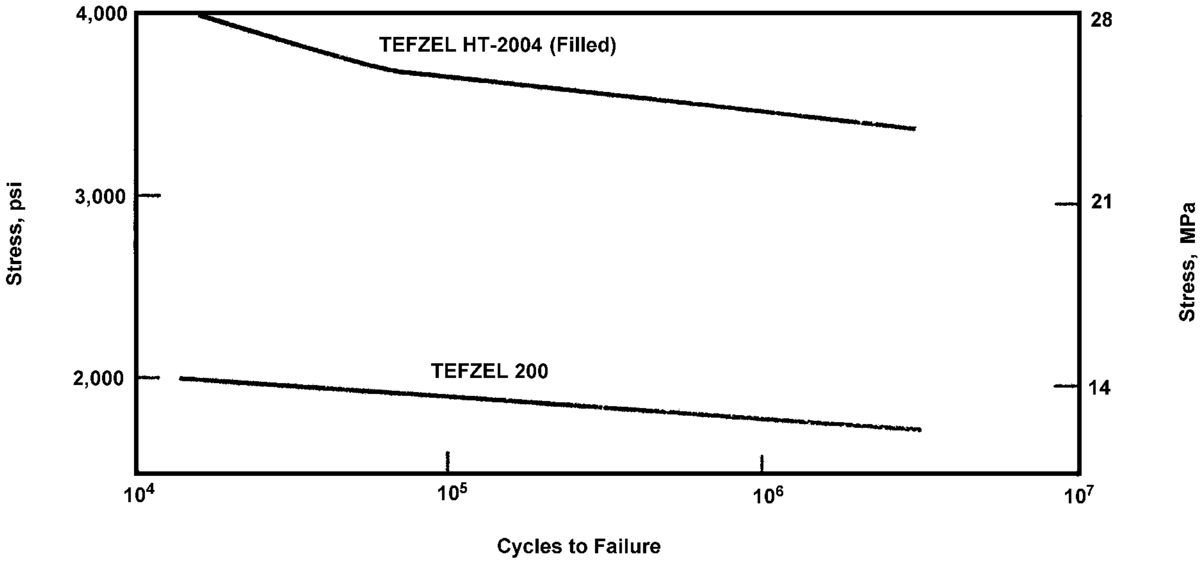

Figure 3.88 Flex fatigue behavior of filled and unfilled ETFE vs stress.[37]

Table 3.49. Impact Strength (J/m) of Perfluoroplastics Measured by Notched Izod ASTM D256[32]–[34]

Polymer	Temperature, °C			
	-196	-60	-40	23
PFA	-64	—	—	No Break
MFA	—	—	No Break	—
FEP (MFR = 1.5–22 g/10 min)		No Break	No Break	No Break

Table 3.50. Impact Strength (J/m) of Partially Fluorinated Fluoroplastics Measured by Notched Izod ASTM D256[36]–[38]

Polymer	MFR (g/10 min)	Temperature, °C	
		23	40
PVDF	2 7–190	107–214 160–427	—
ETFE	4–23	No Break	—
ECTFE	1–18	No Break	48–122

3.7.1.7 Hardness

Fluoroplastics are soft plastics relative to engineering polymers such as nylons and polycarbonates. Increased fluorine content decreases the hardness of the fluoropolymer, thus perfluoropolymers are the softest fluoroplastics. Hardness is measured by a number of methods such as ASTM D758 or D2240 (Rockwell R Scale) or by Durameter scales. Table 3.51 gives typical values for hardness of fluoroplastics. Plastics become softer with increasing temperature and fluoroplastics behave similarly. Adding fillers improves the hardness of these plastics incrementally, which is preserved over a wide range of temperatures. Increasing the filler content, in general, elevates the hardness of the compound as well as reducing creep. Other mechanical properties such as tensile and flex fatigue resistance deteriorate by the addition of fillers.

3.7.1.8 Friction, Wear, and Abrasion

Coefficient of friction is inversely proportional to pressure and proportional to velocity. Wear rate of fluoropolymers is proportional to load (P) and velocity (V). Combinations of pressure and velocity are defined where the material can be used, thus a *PV limit* is defined. Above this PV limit, the wear increases exponentially because of the heat that is generated as a result of motion. Generally, a polymer or its compounds can be characterized by PV limit, deformation under load, and wear factor. *Wear factor* or *specific wear rate* is defined as the volume of material worn away per unit of sliding distance and per unit of load.

Wear and friction are two independent and mutually exclusive variables, that is, they are independent of each other. Unfilled perfluoropolymers have low coefficients of friction and high wear rates. The incorporation of fillers does not affect the coefficient of friction while the wear rate of the compound is reduced. The wear rate of the mating surface may be high as a result of abrasion. Abrasion is a strong function of the type, morphology, and concentration of filler. Wear, friction, and abrasion are, in general, a function of many variables including load, velocity, type of movement, degree of coverage, temperature, filler, finishing of the part, break-in conditions, material surface, lubrication, environment, and the presence of wear debris.

The characteristics of the filler and its content impact the wear behavior of compounds. Particle size, shape, and structure are the key contributing filler variables. The coefficient of friction of the compound is only mildly affected by the filler while wear factor is a strong function of the filler. It is difficult to draw general conclusions from the performance of a filler under one set of conditions. For example, under moderate wear conditions, bronze does not perform as well as glass fiber. Under severe wear conditions (high velocity and load), bronze- or graphite-filled compounds perform better due to their ability to remove the excessive heat from the surface. Fibrous fillers such as glass fiber wear less rapidly than spherical ones such as glass beads.

Fluoroplastics are, generally, slippery materials with smooth surfaces due to their low coefficients of friction. The coefficient of friction decreases with an increase in fluorine content. Numerous mechanical applications depend on low friction of these plastics with little or no lubrication. In the case of perfluoroplastics, such as PFA, FEP, and PTFE, dynamic coefficient of friction is larger than static coefficient of friction. It increases with increasing sliding speed regardless of pressure. This behavior prevents the tendency for “stick-slip” and no squeaking occurs even at low speeds. Static coefficient of friction of perfluoropolymers decreases with increasing pressure.

Table 3.52 presents friction and wear data for samples of PFA molded into thrust bearings.[32] Testing took place in ambient air at room temperature with no lubrication against a mating surface specified as an AISI 1018, R_c20, 16AA steel. A PV limit of 5,000 (psi·ft/min) was found which was less limiting than the wear rate of the bearing. For example, at a PV value of 1,000 psi·ft/min*, the wear rate was 0.005 mm/hr. Wear factor declined from $1{,}840 \times 10^{-10}$ to 700×10^{-10} in the PV range of 1,000 to 5,000 psi·ft/min*.

Wear factor is a proportionality parameter related to the wear of a non-lubricating surface against a mating surface below the PV limit of the material. Equation (3.2) shows the calculation of wear rate of a material.

Eq. (3.2) $t = K\,P\,V\,T$

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* To convert from psi·ft/min to (kg/m^2)(m/min), multiply by 214.3.

where t = wear (in), K = wear factor (in^3·min/ft.lb·hr), P = pressure (psi), V = velocity (ft/min), and T = time (hr).

Like PFA, FEP forms a smooth and slippery surface that has many practical applications because of its low coefficient of friction. Coefficient of friction changes little with the incorporation of fillers in FEP. Wear rate and abrasion of FEP behave quite similarly to PFA. Coefficient of friction of FEP increases rapidly with sliding speeds up to 30 m/min independent of pressure that prevents stick-slip from occurring. Figure 3.89 indicates that the static coefficient of friction of FEP decreases with an increase in pressure. Figure 3.90 shows the coefficient of friction versus load and pressure at low speeds. At above 45 m/min, sliding speed has little effect on PV, as long as PV does not exceed the material limit. Table 3.53 gives PV and wear data for unfilled and filled FEP.

Abrasion resistance is usually measured by the Taber Test procedure described by ASTM D1044. Abrasion resistance of unfilled semicrystalline polymers is linked to the degree of crystallinity that is itself related to the molecular structure and weight of the resin and its processing. Table 3.54 includes the results of testing two types of perfluoroalkoxy polymers, PFA and MFA, and ECTFE. Notice the large difference between wear index (weight loss by abrasion in 1000 cycles) of ECTFE which is a partially fluorinated fluoroplastic and those of PFA and MFA. ECTFE and ETFE are significantly "harder" than perfluoropolymers. More abrasion resistance data can be found in Table 3.55.

It is clear from the data (Table 3.55) that while partially fluorinated fluoroplastics are more abrasion resistant than perfluoropolymers, they are softer than engineering polymers such as polyamides and polycarbonates. This deficiency could be overcome by incorporating fillers such as the addition of glass fibers to ETFE. Table 3.56 contains the static coefficient of friction of an ETFE resin containing 25% by weight of glass fiber, showing that it increases with pressure. The addition of glass fiber decreases the wear factor and reduces creep of filled ETFE, rendering it suitable for bearing applications.

Dynamic coefficient of friction depends on pressure and velocity (*PV*). Figure 3.91 is a plot of dynamic coefficient of friction of 25% glass-filled ETFE, rubbing on a mating surface of steel, as a function of PV. Heat buildup becomes significant at a PV of 10,000 psi·ft/min and thermal runaway occurs at a PV around 20,000 psi·ft/min. The equilibrium temperature of the bearing as a function of PV is shown in Fig. 3.91. Table 3.57 gives the wear factors of glass-filled ETFE and the mating surfaces as a function of pressure and velocity for steel and aluminum.

Table 3.51. Hardness of Fluoroplastics[32]–[34][36]–[38]

Polymer	MFR (g/10 min)	Shore D	Rockwell R
PFA	2–13	55–57	—
MFA	2–17	59	—
FEP	7	56	25
PVDF	2 7–190	74–80 76–80	77–83 79–83
ETFE	4–23	63–72	
ECTFE	1–18	75	90

Table 3.52. Results of Wear and Friction Data for a PFA Thrust Bearing[32]

Velocity, ft/min	Wear Factor, $[(\text{cm}^3\cdot\text{min})/(\text{N}\cdot\text{m}\cdot\text{min})] \times 10^{-6}$	Dynamic Coefficient of Friction	Duration, hr
3	1.92	0.210	103
10	2.22	0.214	103
30	1.19	0.229	103
50	0.83	0.289	103

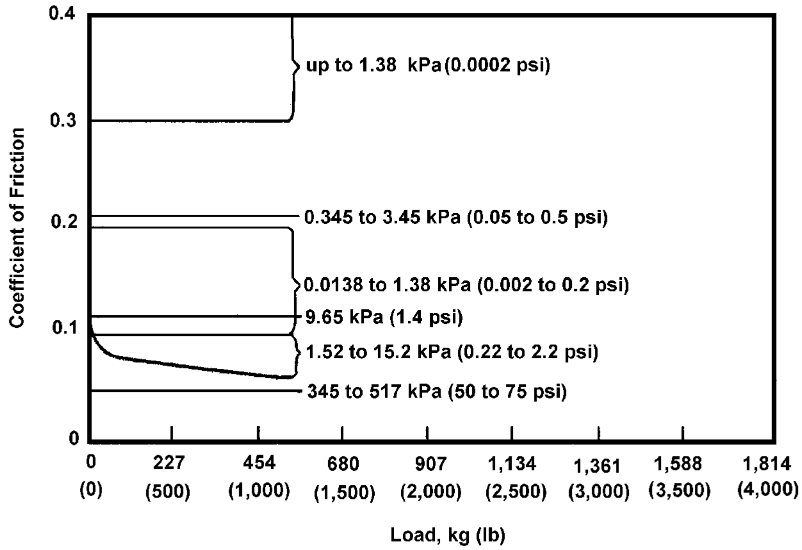

Figure 3.89 Coefficient of friction of FEP vs load at low speeds (<2 ft/min) and room temperature.[34]

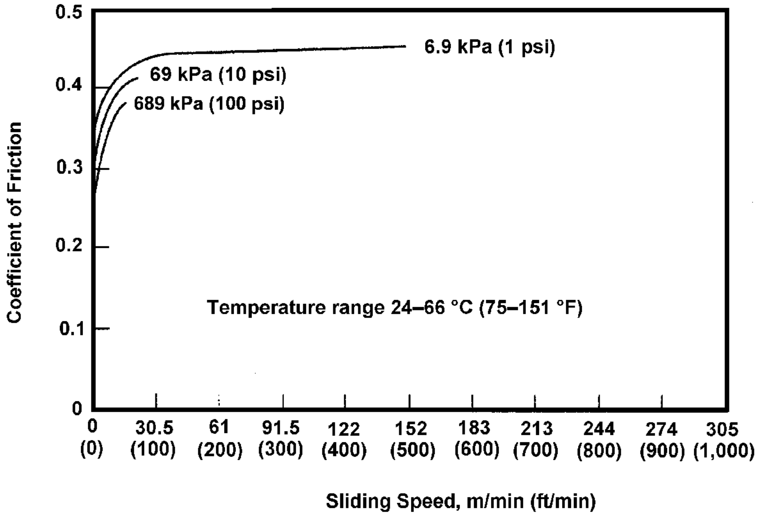

Figure 3.90 Coefficient of friction of FEP vs sliding speed and pressure.[34]

Table 3.53. Wear and *PV* Data for Unfilled and Filled FEP[34]

Resin	PV Limit, psi · ft/min			PV for 0.005 in radial wear in 1,000 hr	Wear Factor, 10^{-10} in^3 · min/ft.lb.hr
	at 10 ft/min	at 100 ft/min	at 1,000 ft/min		
Unfilled FEP	600	800	1,000	0.210	> 5,000
15% by volume glass-filled FEP	4,500	10,000	8,000	0.214	30
10% by volume bronze-filled FEP	9,000	12,000	10,000	0.229	10

Table 3.54. Abrasion Resistance of Fluoroplastics Measured by Taber Test[33]

Resin	MFR, g/10 min	Wear Index, mg/1,000 cycles
PFA	2–3	9–10.5
MFA	2–3	10–11.5
PFA	12–15	15.5–17
MFA	12–15	15.5–17
ECTFE	—	0.005

Table 3.56. Static Coefficient of Friction of 25% Glass-filled ETFE vs Pressure[37]

Pressure, MPa	Coefficient of Friction
0.069	0.51
0.345	0.38
0.69	0.31
3.45	0.34

Table 3.55. Abrasion Resistance of Thermoplastics Measured by Taber Test[35]

Resin	Wear Index, mg/1,000 cycles
Elastomers	1–2
Polyamides	4–7
Ultrahigh molecular weight polyethylene	4–7
PVDF	7–10
PVC	12
PCTFE	25
High density polyethylene	25
Polypropylene	18–28

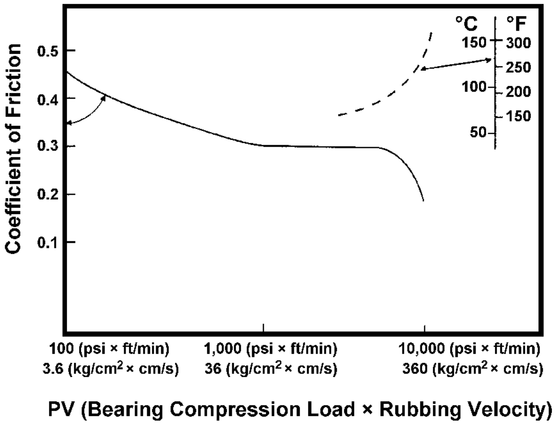

Figure 3.91 Dynamic coefficient of friction of 25% glass-filled ETFE against a steel surface.[37]

Table 3.57. Wear Factor of 25% Glass-filled ETFE Bearing[37]

Mating Surface (Finish of 406 nonometers)	Pressure, MPa	Velocity, cm/sec	Wear Factor, 10^{-10} $in^3 \cdot min/ft.lb.hr$	
			ETFE	Metal
Steel	6.9	2.5	16	4
Steel	6.9	5.1	14	6
Steel	6.9	7.6	19	13
Steel	6.9	8.9	30	16
Steel	6.9	10.2	Fail	—
Aluminum	2.07	5.1	1,220	1,220
Aluminum	0.69	25.4	480	390

3.7.2 Thermal Properties of Melt-processible Fluoropolymers

This section presents information and data related to thermal stability of resins and basic properties as a function of temperature. Thermal stability of fluoropolymers has special importance because of the high processing temperatures required by these thermoplastics and the toxic and corrosive nature of their degradation products. Fluoroplastics have useful properties at temperature extremes above and below ambient conditions.

3.7.2.1 Thermal Stability

Fluoropolymers are, generally, very stable at or below their specified maximum use temperatures. The rate of degradation of these plastics at higher temperatures is a function of their chemical structures in addition to temperature, time at temperature, and, to some extent, on the pressure and the atmosphere of decomposition. In actual processing, degradation is tracked by indirect measurement of molecular weight. Thermal exposure leads to a reduction in the molecular weight, which can be quantified by an increase in the MFR, heat of fusion of polymer, and in specific controlled measurements.

Perfluoropolymers are more thermally stable than partially fluorinated resins. Thermal stability usually increases with the fluorine content, as do other basic properties of fluoroplastics like chemical resistance. Figure 3.92 shows a comparison of degradation rate (weight percent per hour) as a function of temperature by thermogravimetric analysis (TGA). It can be seen that for a given rate of degradation, say 0.1%, perfluoropolymers, that is PTFE, PFA, and FEP, require higher temperatures than ETFE. Among the perfluoropolymers, PTFE, which has a linear unbranched structure, is more stable than PFA and FEP. The degradation rates of specific fluoropolymers have been listed in Table 3.58.

Degradation is usually measured and characterized by weight loss using TGA techniques while degradation products are identified by gas chromatography, infrared spectroscopy, and mass spectroscopy. The small amount of degradation requires TGA experiments to be conducted for several hours to allow accurate detection of weight loss. Table 3.59 gives a comparison of the composition products of the degradation of ETFE, FEP, and PFA. The most toxic compounds are perfluoroisobutylene (PFIB) and carbonyl fluoride (COF_2). Results of thermogravimetric analysis of PVDF are illustrated in Table 3.60.

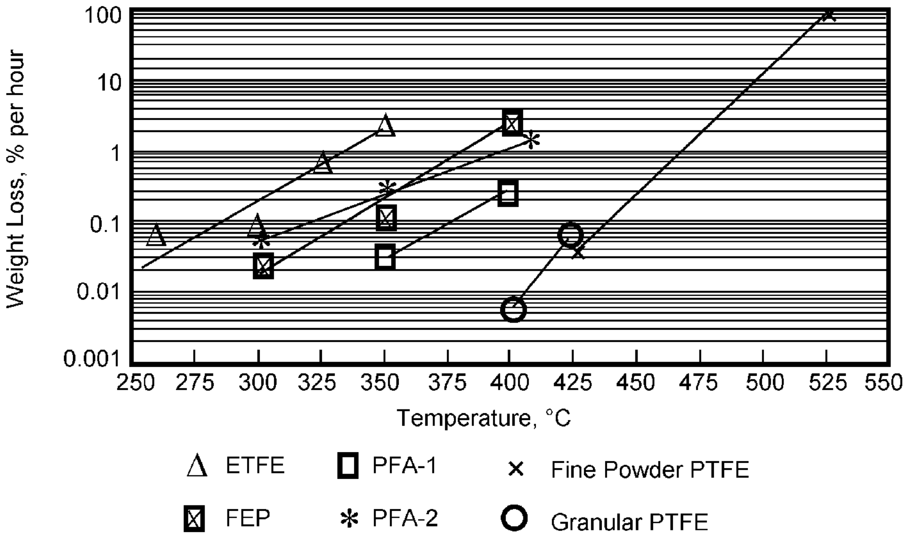

Figure 3.92 Degradation rate of fluoroplastics in air.[46] Note: This figure (see Fig. 3.31) is intentionally reproduced here for the reader's convenience.)

Table 3.58. Degradation (TGA) Rates of Fluoroplastics in Air as a Function of Time and Temperature[46]

Resins	Temperature, °C	% Weight Loss/hr		
		Thermal equilibrium to 15 min	15 to 65 min	Thermal equilibrium + 60 min
ETFE	150			<0.05
	260	0.31	0.06	0.11
	300	0.42	0.09	0.14
	325			0.67
	350	~2		6.8
FEP	205			<0.05
	300		~0.03	<0.05
	350	0.45	0.13	0.18
	375			0.67
	400			3.2
PFA-1	300	0.18	0.05	0.07
	350			0.22
	400			0.58
PFA-2	300			<0.05
	350	0.12	~0.03	0.05
	400			0.26
PTFE Fine Powder	400			~0.06
	425			0.15
	425			0.04[b]
	525	255[a]		95.0
PTFE Granular	350			0.02
	350			0.005[c]
	400			0.03
	400			0.006[c]
	425			0.06
	425			0.06[b]

[a] Gross decomposition in one hour. Initial rate 255% per hour.

[b] Hourly rate from 8 to 11.8 hours after beginning run.

[c] Hourly rate from 3.3 to 6.6 hours after beginning run.

Table 3.59. Degradation (TGA) Products of Fluoroplastics in Air After 1 Hour at Temperature[46]

Weight of Evolved Gases as % of Sample						
Resin	**°C**	**TGA % Loss**	**PFIB**	**TFE**	**HFP**	**HCF_3**
TEFZEL®, 200	350	5.3		0.06		
FEP 100	400	2.5	0.003	~0.06	0.38	0.19
PFA 340	400	0.43				
PFA 440	400	0.26				
Resin	**PFBE(1)**	**COF_2**		**CO**	**SUM**	**% REC**
		Meas.	**Calc.**			
TEFZEL®, 200	0.3	0.11 2.5		0.06	4.7(3)	89
FEP 100		0.64 1.2			2.7(4)	110(2)
PFA 340			0.53		0.53	123(2)
PFA 440		0.01 1.2			1.2	460(2)

(1) Perfluorobutylethylene

(2) Artifact of the analytical technique for values 100%

(3) This sum includes 1.7% CO_2 from oxidation of the ethylene units

(4) Includes 0.19% of CF_3COF

Table 3.60. Thermogravimetric (10°C/min Heating Rate to 1,000°C) Analysis of Polyvinylidene Fluoride[47]

Characteristic	**Kynar® 2750**		**Kynar® 2800**	
Atmosphere	Air	Nitrogen	Air	Nitrogen
5% wt loss temperature, °C	431.6	457.3	427.4	459.4
10% wt loss temperature, °C	440.6	465.6	442	469.7
Derivative Peak Temperature, °C	479.0	491.2	469.7	493.2
Residual mass at 1,000°C, %	—	11.9	—	11.3
1st wt loss region, °C	400–478	399–508	400–478	382–510
1st wt loss, %	58.2	81.9	90.1	82.3
2nd wt loss region, °C	478–625	508–1,000	476–625	510–1,000
2nd wt loss, %	41.8	6.2	9.9	6.4

3.7.2.2 Temperature-related Properties

Fluoropolymers are semicrystalline polymers; most do not exhibit glass transition in the conventional sense during which all crystalline structures are converted to the amorphous. The glass transitions of fluoroplastics have been described as molecular relaxation (conformational disorder) that takes place in the amorphous phase of the polymer. These temperatures are also called second order transitions; their value depends on the technique and the frequency of energy addition to the polymer sample. Table 3.61 presents these temperatures and melting points of perfluorinated and partially fluorinated fluoroplastics.

Some of the thermal properties of perfluoroalkoxy polymers (PFA and MFA) and FEP have been listed in Tables 3.62 and 3.63. Table 3.64 and Fig. 3.93 provide similar data for PVDF and Tables 3.65 and 3.66 for ETFE and ECTFE.

3.7.2.3 Thermal Aging

Fluoroplastics are used in a large number of applications that involve operations at temperature extremes because of the ability of these plastics to withstand very high or low temperatures. A popular method of testing a part is based on monitoring the physical or mechanical properties, such as tensile strength and break elongation, as a result of thermal exposure over time. To check the impact of processing on the polymer, melt flow rate is measured as a function of time and temperature. The effect of thermal aging on the properties of these resins is discussed in this section.

Figures 3.94 and 3.95 illustrate[32] the change in the tensile strength and break elongation (measured at room temperature and at 200°C) of PFA wire coating as a function of exposure time at 285°C. Interestingly, the tensile strength of the wire coating increased about 15% after 20,000 hours at 285°C, at both measurement temperatures. Elongation similarly increased by 25% with thermal aging. The increase in tensile properties has been attributed to an increase in the molecular weight during aging. Figure 3.96 indicates that while aging at 230°C has a gradual effect on reducing MFR (increasing molecular weight), thermal exposure at 285°C drastically reduces the MFR of PFA.

Effect of thermal aging, in air, on tensile strength and break elongation of MFA and PVDF can be seen in Figs. 3.97–3.99. Figures 3.100 and 3.101 present the change in tensile strength and break elongation after thermal exposure of ETFE for extended periods of time; Figure 3.102 shows the same for ETFE compounded with 25% glass fiber. Elongation values were in the 5%–10% range in Fig. 3.102 regardless of test temperature. ETFE has good hydrolytic stability as demonstrated by the retention of tensile strength and break elongation after extended exposure to boiling water, as seen in Table 3.67.

Table 3.61. Glass Transition Temperatures and Melting Points of Fluoroplastics[32][34][48]–[50]

Resin	Glass Transition Temperatures, K			Melting Point, K
	Alpha (I)	Beta	Gamma (II)	
PTFE	399	303	193	605
FEP	343–399	203–263	268–302	530–536
PFA	363	271	193	599
MFA	-	258	-	583
PVDF	323, 373	235	203	483
ECTFE	413	363	208	536
ETFE	403	273	233	599
PCTFE	325	406	-	493

Table 3.62. Thermal Properties of PFA and MFA[32][33]

Property	**Temperature, °C**	**MFR, g/10 min**	
		13	**2**
Thermal Conductivity of PFA, W/(m·K)	23	0.19	0.19
Coefficient of Linear Thermal Expansion of PFA (10^{-5}mm/mm/°C)	23–100	14	14
	100–150	17	18
	150–210	21	22
Heat Capacity PFA, J/(kg·K)	-	1,172	1,172
Coefficient of Linear Thermal Expansion of MFA (10^{-5}mm/mm/°C)	23–150	12–20	12–20

Table 3.63. Thermal Properties of FEP[34]

Property	**Temperature, °C**	**MFR, g/10 min**		
		7	**3**	**1.5**
Thermal Conductivity, W/(m·K)	23	0.2	-	-
Heat Capacity, J/kg	23	5.1	-	-
Specific Heat, kJ/(kg·K)	25	0.240	0.242	0.268
	100	0.266	0.267	0.294
	150	0.288	0.290	0.315
Heat of Combustion, kJ/kg	-	5,114		
Coefficient of Linear Thermal Expansion, 10^{-5}mm/mm/°C	0–100	13.5	13.9	13.5
	100–150	20.8	21.2	23.4
	150–200	26.6	27.0	27.8
Deflection Temperature, °C	-			
0.455 Mpa		77	77	74
1.820 MPa		48	48	48

Table 3.64. Thermal Properties of PVDF[36]

Property	**Temperature,°C**	**Value**
Thermal Conductivity, W/(m·K)	23	0.101–0.125
Homopolymer		0.19
Copolymer		0.17
Specific Heat, kJ/(kg·K)	23	0.96–1.42
Homopolymer		0.96
Copolymer		1.30
Coefficient of Linear Thermal Expansion, 10^{-5}mm/mm/°C	23	7.2–14.4
Homopolymer		13
Copolymer		14–16
Heat Deflection Temperature, °C @ 1.820 MPa	—	84–118
Homopolymer		104–108
Copolymer		50–72

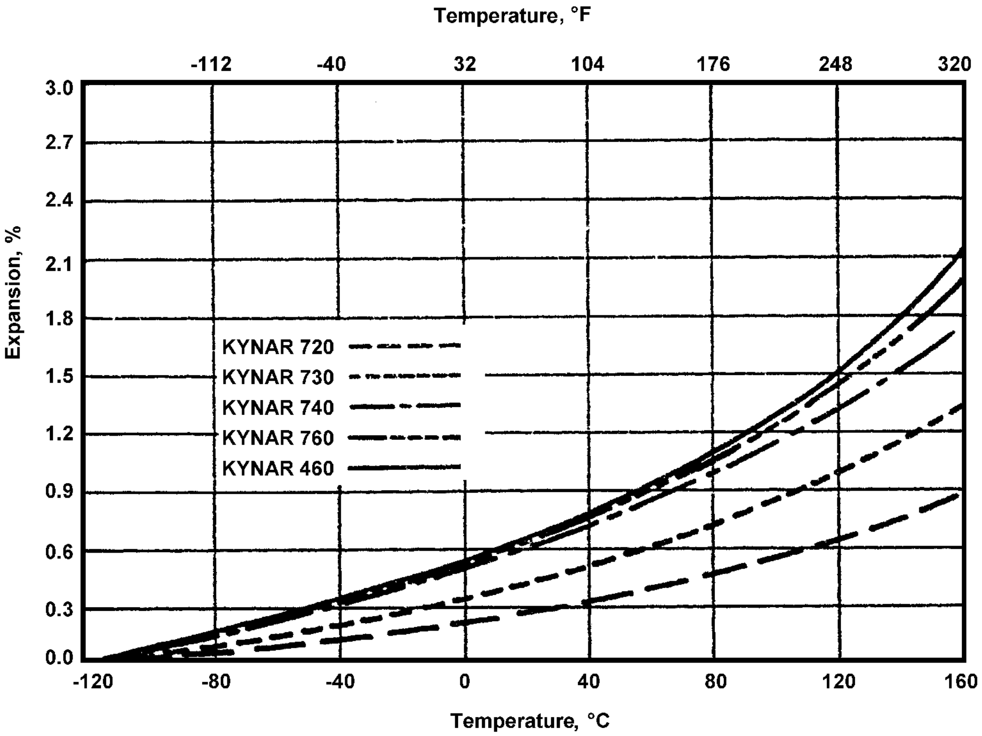

Figure 3.93 Expansion of polyvinylidene fluoride vs temperature.[36]

Table 3.65. Thermal Properties of ETFE[37]

Property	Temperature, °C	MFR, g/10 min		
		23	7	4
Thermal Conductivity, W/(m·K)	23	—	0.24	—
Specific Heat, kJ/(kg·K)	25 100 150 300	—	0.25 0.30 0.34 0.38	—
Heat of Combustion, kJ/kg	—	—	13,700	—
Coefficient of Linear Thermal Expansion, 10^{-5}mm/mm/°C	0–100 100–150 150–200	12.6 17.6 22.3	13.1 18.5 25.2	13.3 20.9 25.7
Deflection Temperature,°C 0.455 Mpa 1.820 MPa	—	81 51	81 51	81 51

Table 3.66. Thermal Properties of ECTFE[38]

Property	Temperature, °C	MFR, g/10 min
		2
Thermal Conductivity, W/(m·K)	40	0.151
	95	0.153
	150	0.157
Specific Heat, cal/(g·°C)	25	0.226
	100	0.300
	200	0.370
	300	0.390
Coefficient of Linear Thermal Expansion, 10^{-5} mm/mm/°C	-30–50	8
	50–85	10
	85–125	13.5
	125–180	16.5
Deflection Temperature,°C		
0.455 Mpa	-	90
1.820 MPa		63

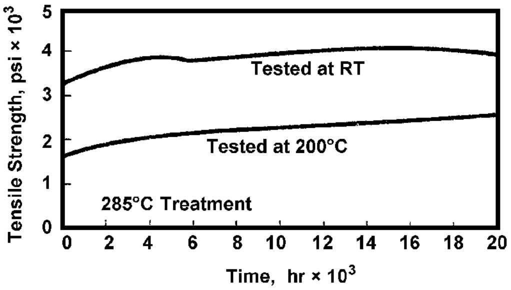

Figure 3.94 Change in tensile strength of PFA wire coating due to thermal exposure in air.[32]

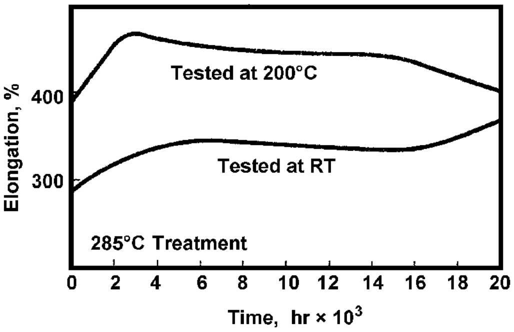

Figure 3.95 Change in break elongation of PFA wire coating due to thermal exposure in air.[32]

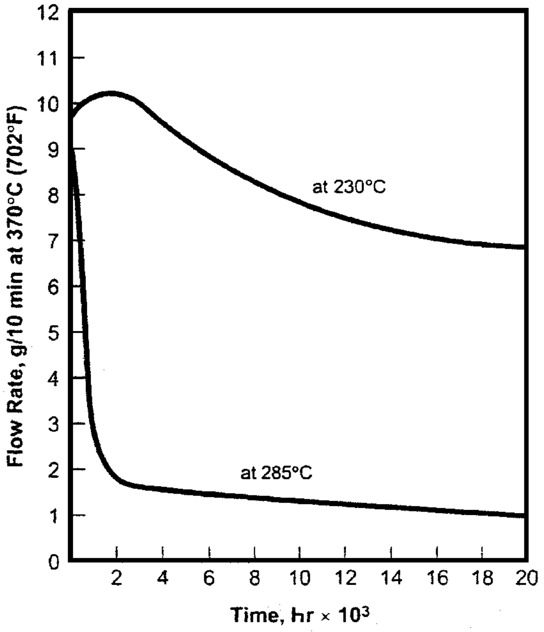

Figure 3.96 Change in MFR of PFA wire coating due to thermal exposure in air.[32]

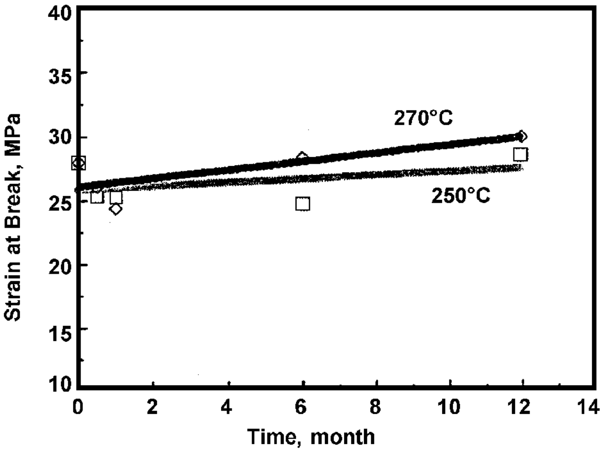

Figure 3.97 Change in tensile strength of MFA due to thermal exposure in air.[33]

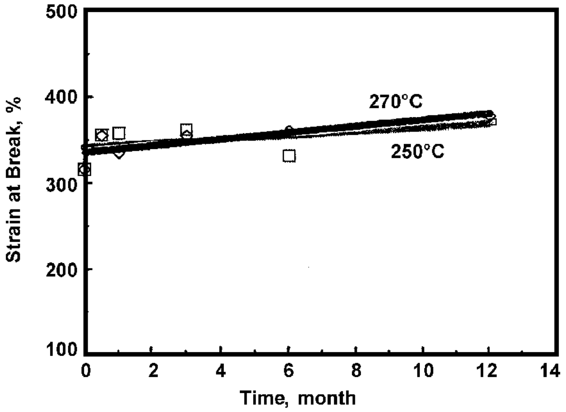

Figure 3.98 Change in break elongation of MFA due to thermal exposure in air.[33]

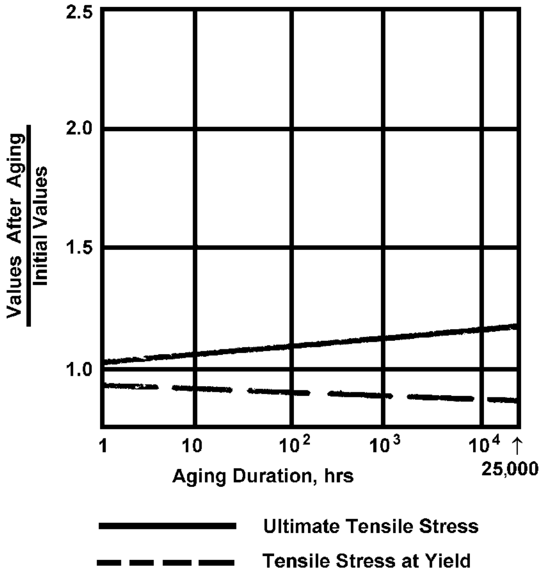

Figure 3.99 Change in tensile strength and break elongation of PVDF due to thermal exposure in air at 165°C.[35]

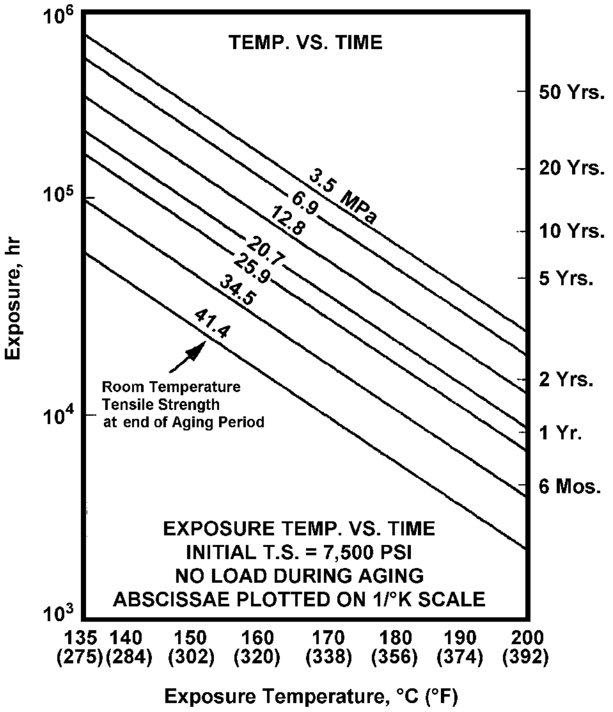

Figure 3.100 Change in tensile strength of ETFE (MFR = 7) due to thermal exposure in air.[37]

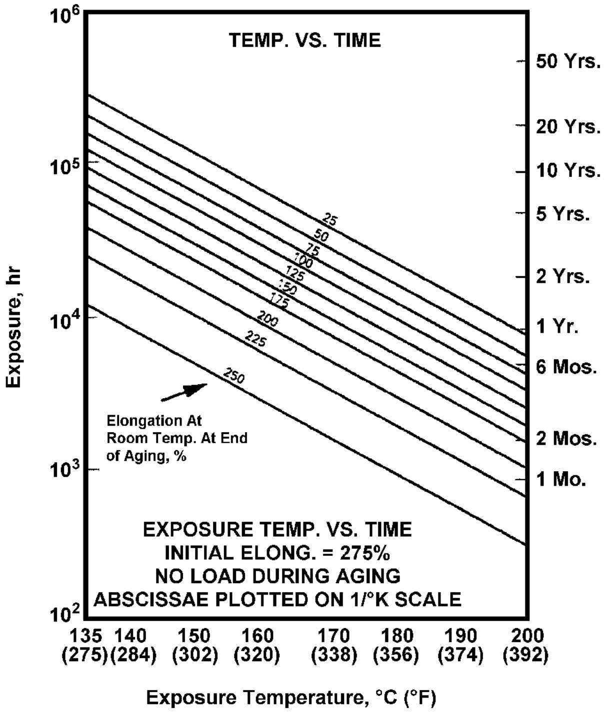

Figure 3.101 Change in break elongation of ETFE (MFR = 7) due to thermal exposure in air.[37]

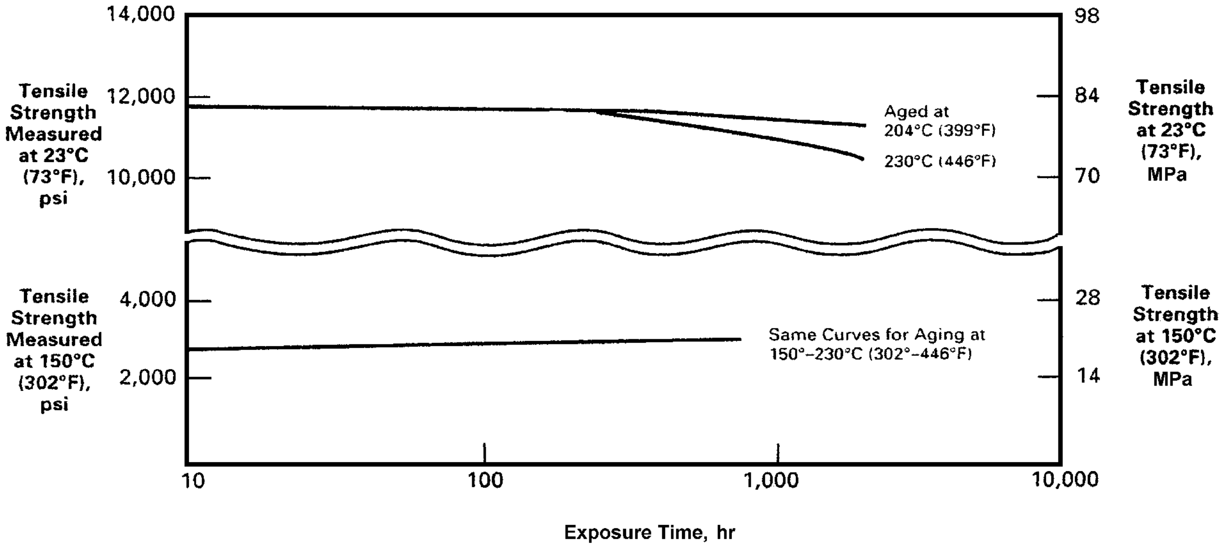

Figure 3.102 Change in tensile strength and break elongation of 25% glass compound of ETFE due to thermal exposure in air.[37]

Table 3.67. Hydrolytic Stability of ETFE by Exposure to Boiling Water[37]

Exposure Length	Tensile Strength, MPa	Break Elongation, %
ETFE (MFR = 7)		
0	40	145
3,000	40	135
25% Glass Compound		
0	82	7
1,000	60	5
2,000	57.6	5
3,000	55.8	5

3.7.3 Weatherability of Melt-processible Fluoroplastics

Weatherability is defined as the retention of the general mechanical, chemical, electrical, and other physical properties when exposed outdoors for extended time periods. Good weatherability is important to the selection of materials for outdoor use. Sunlight, oxygen, moisture, and pollutants like acid gases can be destructive to plastic materials. The nature of attacks is by photodegradation, oxidative, and chemical mechanisms because of the presence of light, strong oxidizers, and reactive chemicals such as acids and moisture. In addition to field testing outdoors, weatherability of different materials can be assessed by accelerated exposure in special machines called *weather-o-meters*. Machine conditions can be adjusted to allow “dry,” or “humid” exposure to closely simulate the environmental elements.

Fluoropolymers, in general, have the ability to withstand continuous outdoor exposure. This resistance is due to the unique nature of carbon fluorine bonds that withstand oxidative, chemical, and photodegradation attack. Examples of the properties of fluoropolymers after outdoor or accelerated exposure are discussed in this section.

Figure 3.103 illustrates that weathering PTFE films in outdoor South Florida has virtually no effect on the dielectric constant or the dissipation factor. Both properties remained constant throughout the exposure period. Table 3.68 presents the tensile strength, break elongation, and modulus of FEP over a period of twenty years of exposure in South Florida. Thickness seems to have a small effect on the retention of film properties, according to the data in Table 3.69. The films have retained more than 62% of the initial elongation and 84% of the initial tensile strength. In the case of 500 µm thick film, tensile strength increased slightly.

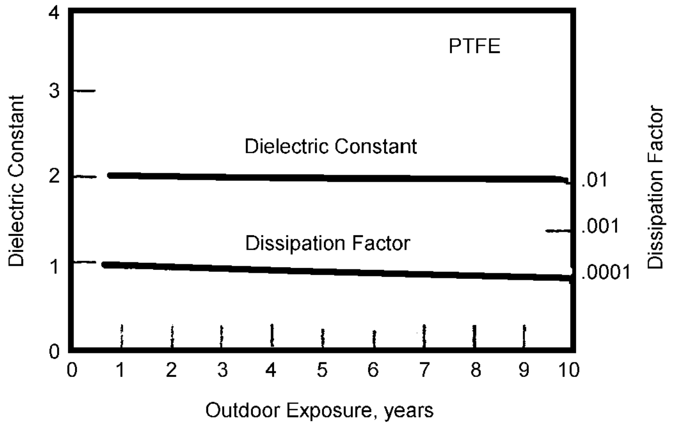

Figure 3.103 Dielectric constant and dissipation factor vs outdoor exposure time.[51]

Table 3.68. Tensile Properties of FEP Film after Exposure in South Florida *(Courtesy DuPont Fluoroproducts)*

Film Thickness, µm	Years of Exposure	Tensile Strength, MPa		Break Elongation, %		Tensile Modulus, MPa	
		MD	TD	MD	TD	MD	TD
50	0	21.4	18.6	270	290	462	407
50	5	20	13.8	365	310	462	407
50	7	20	16.6	290	300	428	434
50	10	18.6	16.6	145	221	428	476
50	15	19.4	15.4	200	190	-	-
500	0	21.4	20	470	435	496	538
500	6	20	20	580	575	476	469
500	10	20.7	17.2	515	415	455	503
500	15	25.3	25.7	330	334	-	-
500	20	21.1	22.0	292	294	-	-

Table 3.69. Retention of Tensile Properties of FEP Film after Exposure in South Florida *(Courtesy DuPont Fluoroproducts)*

Film Thickness, µm	Years of Exposure	Tensile Strength, % of initial retained		Break Elongation, % of initial retained	
		MD	TD	MD	TD
50	20	91	84	74	65
500	20	100	110	62	68

Tables 3.70 through 3.72 summarize the effect of one-year South Florida outdoor exposure on the electrical and mechanical properties of FEP. Little change has occurred in the dielectric breakdown strength, dielectric constant, and dissipation factor of FEP due to exposure. Tensile strength and break elongation measurements are essentially unchanged. The only decline is in the MIT flex life (ASTM D2176) of the one-year sample, which could be due to measurement error. The reason for a decrease in flex life could be the MIT method that has a high degree of uncertainty. Certainly, the other mechanical properties do not support the measured decline in the flex life.

Table 3.73 shows the impact on a PTFE film's tensile properties of weathering it in South Florida for ten years.

ETFE weathering data has been summarized in Table 3.74; 94% of tensile strength and more than 84% of elongation has been retained after fifteen years of exposure in South Florida. The unexposed ETFE film transmitted 95.5% of visible light while the exposed film had a transmission of 93.7%. In other words, exposed film retained 98% of its original transmission.

In a study of weathering resistance,[53] three partially fluorinated polymers (ETFE, PVDF, and PVF) were exposed to ultraviolet light in a QUV Weather-o-meter, Q-Panel Co., at 50°C. The machine was equipped with ultraviolet (UV) lamps producing rays in the wavelength range of 313–550 nm. The difference among the resistance of these three fluoroplastics was characterized (Fig. 3.104) by the change in their tensile properties as a result of exposure time. ETFE had the most resistance in that break elongation, tensile strength, and modulus did not change after exposure of up to 2,400 hours. Tensile strength and tensile modulus of PVDF remained constant while its break elongation decreased due to exposure. All three properties of PVF declined because of UV light exposure. Fluorine content, in addition to the molecular structure, influences the UV light resistance of the fluoropolymer. Deficiencies have been overcome by incorporating organic UV light absorbers and inorganic absorbing pigments such as titanium dioxide in a commercial film called Tedlar® produced by DuPont.

3.7.4 Electrical Properties of Melt-processible Fluoroplastics

Fluoropolymers are widely used in electrical and electronic applications including wire coating from small sizes (high gauge) to heavy wall cables, coaxial cables, and jacketing. Other applications include insulation for electrical components. A number of electrical properties such as dielectric strength, dielectric constant, dissipation factor, electrical resistivity, and arc tracking are significant to these applications. Electrical property data for various fluoroplastics are presented in this section.

3.7.4.1 Perfluoroalkoxy Polymers

The dielectric constant of PFA is about 2.1 over a broad range of frequencies, temperatures, and densities. The variation of PFA density is slight (2.13–2.17) and the dielectric constant only varies 0.03 units over this density range.[32] Humidity has almost no effect on the dielectric constant of PFA.

The short-term dielectric strength of PFA is 80 kV/mm at a thickness of 0.25 mm, measured by ASTM D149. FEP films give similar results while PTFE has a typical dielectric strength of 47 kV/mm. The dielectric strength of PFA decreases in the presence of corona discharge, a behavior similar to other fluoropolymers.

The volume resistivity of fluoropolymers is about 10^{18} $\Omega\cdot$cm and the surface resistivity is about 10^{18} $\Omega\cdot$per square (measured by ASTM D257). These extremely high values make them good electrical insulation materials. These properties are not affected by time and temperature.

PFA does track arc as many other polymers do. *Arc tracking* refers to the formation of a carbonized track on a wire insulation that forms a path for conducting electricity. PFA has been tested by ASTM D495 and exhibited no arc tracking over the 180 second duration of the test.

Electrical properties of MFA have been listed in Table 3.75.

Table 3.70. Test Results for Exposure of FEP Film (75 µm, 0.003 inch) in South Florida *(Courtesy DuPont Fluoroproducts)*

Length of Exposure, months	Dielectric Strength, kV/mm	Machine Direction		Transverse Direction		MIT Flex Life, cycles
		Tensile Strength, MPa	Elongation at Break, %	Tensile Strength, MPa	Elongation at Break, %	
0	124	18.0	295	15.9	300	24,000
3	112	18.8	305	16.8	265	16,300
6	132	19.0	310	16.9	300	24,400
12	132	15.9	280	15.0	305	17,400

Table 3.71. Physical Property Results for Exposure of FEP Film (250 µm, 0.010 inch) in South Florida *(Courtesy DuPont Fluoroproducts)*

Length of Exposure, months	Machine Direction		Transverse Direction	
	Tensile Strength, MPa	Elongation at Break, %	Tensile Strength, MPa	Elongation at Break, %
0	19.9	306	23.9	294
6	21.1	276	18.5	279
12	19.9	285	23.2	305

Table 3.72. Electrical Property Results for Exposure of FEP Film (250 µm, 0.010 inch) in South Florida *(Courtesy DuPont Fluoroproducts)*

Length of Exposure, months	Dielectric Strength, kV/mm	Dielectric Constant, 1 kHz	Dissipation Factor, 1 kHz
0	60	2.3	0.00015
6	82	2.4	0.00035
12	79	2.2	0.0002

Table 3.73. Tensile Properties of PTFE Film after Ten Years Exposure in South Florida[52]

Years of Exposure	Tensile Strength, MPa		Break Elongation, %	
	MD	TD	MD	TD
0	45.5	8.5	320	400
10	31.5	14.9	190	390
Property Retention, %	69	175	59	98

Table 3.74. Tensile Properties of ETFE Film after Fifteen Years Exposure in South Florida *(Courtesy DuPont Fluoroproducts)*

Years of Exposure	Tensile Strength, MPa		Break Elongation, %	
	MD	TD	MD	TD
0	61	63.5	418	440
15	57.6	59.5	364	370
Property Retention, %	94	94	87	84

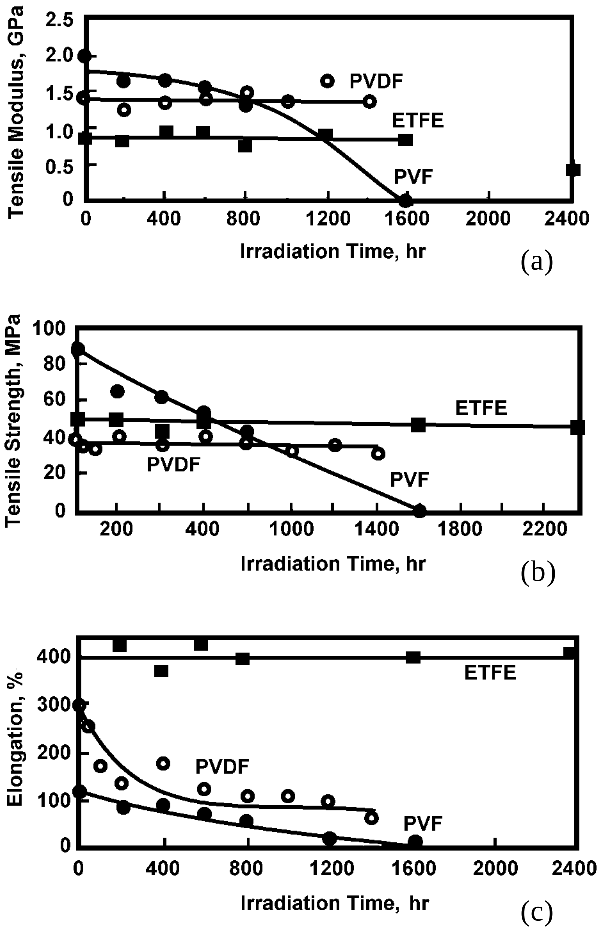

Figure 3.104 Effect of UV irradiation in a QUV Weather-o-meter on the tensile properties of PVF, PVDF and ETFE: (*a*) tensile modulus; (*b*) tensile strength; (*c*) break elongation.[53]

Table 3.75. Typical Electrical Properties of MFA Film at 23°C[33]

Property	Value
Volume Resistivity, Ω·cm	> 10^{17}
Surface Resistivity, Ω per square	> 10^{17}
Arc Resistance, sec	210
Dielectric Strength, kV/mm	34–38
Dielectric Constant	
50 Hz	2.0
10^5 Hz	1.95
Dissipation Factor	
50 Hz	< 5×10^{-4}
10^5 Hz	< 5×10^{-4}

3.7.4.2 FEP

Electrical properties of FEP have been listed in Table 3.76. FEP has a dielectric constant of 2.04[34] over a range of frequencies from 1 kHz to 13 GHz. Dissipation factor increases slowly from 0.00006 at 1 kHz to 0.0006 at 30 MHz, approaching a maximum of 0.001 at 1 GHz.

3.7.4.3 PVDF

Table 3.77 gives a number of electrical properties of PVDF measured at room temperature.

Certain polymers, such as polyvinylidene fluoride (PVDF) and polyvinyl fluoride (PVF), possess special properties in the film form, called *piezoelectricity* and *pyroelectricity*. Piezoelectricity is electric polarization of a film, produced by mechanical strain in some crystals.[54] The polarization is proportional to the amount of strain and changes sign with it. The reverse is true and an electrical polarization induces a mechanical strain in piezoelectric sensors. Pyroelectricity is electric polarization of a film induced by thermal absorption in some polymer crystals. The induced polarization is proportional to the level of thermal change. These properties can be used in the manufacture of transducers, microphones, loudspeakers, pressure gauges, pickup heads, hydrophones, motion sensors, and other devices from biaxially oriented PVDF films. Table 3.78 gives the properties of a piezoelectric film of polyvinylidene fluoride.

The "*d*" coefficients in Table 3.78 are obtained by measuring the charge density (coulombs/m^2) which appears on the surface of the film ("3" stands for the thickness direction) when a stress of 1 newton/m^2 is applied:

d_{33} is perpendicular to the plane of the film

d_{31} is in the plane of the film in the machine direction

d_{32} is in the plane of the film in the transverse direction

If the film cannot be freely deformed in its plane, the piezoelectric current is called $d_{33}{}^{*}$ or d_T. If the variation in the electric field is measured per unit of stress, "*g*" coefficients are obtained that are connected by the correlation of $g = d/e$ where e is the dielectric constant depending on the film thickness. Constants "*g*" and "*d*" are most widely used in the design of electromechanical transducers. The yield from the conversion of mechanical energy into electrical energy is represented by the electromechanical coupling coefficient K_T by Eq. (3.3).

Eq. (3.3) $$K_T = 100d\sqrt{\frac{\text{Modulus of Elasticity}}{\text{Dielectric Constant}}}$$

where $d \cong d_T + \frac{2}{3}(d_{31} + d_{32})$

Excess heating can destroy the piezoelectric effect in PVDF films.

Table 3.76. Typical Electrical Properties of FEP Film at 23°C[34]

Property	Value
Volume Resistivity, Ω·cm	10^{17}
Surface Resistivity, Ω per square	10^{15}
Arc Resistance, sec	165
Dielectric Strength, kV/mm	
0.254 mm	71–79
3.18 mm	20–21
Dielectric Constant	
1 kHz-500 MHz	2.01–2.05
13 GHz	2.02–2.04
Dissipation Factor	
1 kHz	6×10^{-5}
1 MHz	6×10^{-4}
1 GHz	11×10^{-4}
13 GHz	7×10^{-4}

Table 3.77. Typical Electrical Properties of PVDF Film at 23°C[36]

Property	Value
Volume Resistivity, Ω·cm	1.5×10^{14} - 2.3×10^{14}
Surface Resistivity, Ω per square	$>10^{13}$
Arc Resistance, sec	50–60
Dielectric Strength, kV/mm	
0.1 mm thick	63
1.0 mm thick	23–27
Dielectric Constant	
1 kHz	8.2–10.5
10 kHz	8.0–9.9
100 kHz	7.8–9.6
Dissipation Factor	
1 kHz	0.005–0.026
10 kHz	0.015–0.021
100 kHz	0.039–0.058

Table 3.78. Characteristics of Piezoelectric Polyvinylidene Fluoride Film[4]

Characteristic	Value
Thickness, μm	9–50
Thickness Uniformity	±10
Piezoelectric Properties (non-metalized), 10^{-12} C/N	
$d_T = d_{33}{}^{*}$	13–22
d_{31}	6–10
d_{32}	6–10
Piezoelectric Property Uniformity	±10
Relative Dielectric Constant ($\varepsilon/\varepsilon_0$) T = 25 to 90°C Frequency = 50 Hz to 100 kHz $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m	10–12
g_{33}, V·m/N	0.14–0.22
Pyroelectric Coefficient, p 10^{-6} C/m^2·K	24–26
Volume Resistivity, Ω·cm	5×10^{14}
Electromechanical Coupling Factor, K_T, %	10–15

3.7.4.4 ETFE

Some of the electrical properties of ETFE are given in Table 3.79. ETFE has a dielectric constant of 2.5–2.6 at frequencies below 10 MHz; it decreases to 2.3 at 10 GHz. The dissipation factor of ETFE is less than 0.001 at low frequencies, increasing to 0.023 at 100 MHz, and finally decreasing to less than 0.01 at 10 GHz.

3.7.4.5 ECTFE

Some electrical properties of ECTFE are given in Table 3.80. The dielectric strength (ASTM D149) is higher than the breakdown strength of PVDF.

3.7.5 Optical and Spectral Properties of Melt-processible Fluoroplastics

Films of PFA have excellent optical properties with low haze. Table 3.81 gives the value of refractive index, transmission, and haze for a PFA film. An infrared absorption spectrum of PFA is shown in Fig. 3.105. A comparison of light transmission of FEP, PFA, and MFA is given in Fig. 3.106. FEP transmits a high percentage of ultraviolet and visible light. The solar transmission of FEP in thin film form is about 96%. FEP is much more transparent in the infrared region of the light spectrum than glass. The infrared absorption spectrum of FEP is given in Fig. 3.107.

Figures 3.108 and 3.109 show two measurements of visible light transmission (ASTM D542) of FEP as a function of film thickness. In Fig. 3.108, the light measured is restricted to a narrow beam of roughly 2° and thus excludes most of the scattered light transmitted through the film. Figure 3.109 includes scattered transmitted light up to 180°. This yields a higher value for total light transmitted compared to Fig. 3.108. In applications where it is important to consider resolution, the data in Fig. 3.108 is more appropriate. Transmission of visible light through PFA film is similar to FEP.[55]

PVDF films up to 100–125 μm are transparent to translucent when the molten polymer is quenched in water to minimize crystallization. The transmittance spectra of PVDF in the ultraviolet, visible, and near-infrared light regions are shown in Fig. 3.110. Infrared absorbance of PVDF is given in Fig. 3.111. Optical properties of homopolymer PVDF films and sheets produced by different fabrication techniques are summarized in Table 3.82.

Figure 3.112 shows the extinction coefficient in relation to the wavelength calculated according to Beer-Lambert's Law ($I = I_0 e^{-kx}$). Figure 3.113 depicts an infrared scan of an ETFE at a thickness of 0.025 mm. Table 3.83 provides a select list of ETFE transmittance at different wavelengths in the ultraviolet and visible light regions.

ECTFE has good transmission over a wide range of light frequencies. Its index of refraction is 1.4476 at a wavelength of 589 nm. Figures 3.114 and 3.115 show the transmittance of an ECTFE film in the ultraviolet range and ultraviolet plus visible range, respectively.

The refractive index of polymers provides fundamental information that can be used in the analysis of parts, processing, and characterization. It has been demonstrated that the square of refractive index is related to the dielectric constant of a polymer, both in direction and magnitude.[56][57] Table 3.84 shows the values of the refractive index of fluoroplastics, measured at a light wavelength of 589.3 nm and referred to as n_D in literature.

3.7.6 Radiation Effect on Melt-processible Fluoroplastics

High-energy radiation (x-ray, γ-ray, and electron beams) has two effects on fluoroplastics, molecular weight reduction and degradation, and crosslinking by forming intermediate free radicals. The degradation effect is more severe in the presence of oxygen (in air) than in vacuum, and is further intensified at elevated temperatures. Oxygen allows the formation of unstable peroxide bonds in the polymer backbone. Each peroxide bond breaks and generates two shorter chains from the original polymer chain. In a vacuum, crosslinking and recombination of free radicals offset some of the chain scission effect of radiation. A number of studies have been made on the effect of radiation on fluoroplastics in different atmospheres; they can be consulted for a more in-depth study of the subject.[61]–[71]

Perfluorinated fluoropolymers, such as polytetrafluoroethylene, are more susceptible to degradation by radiation than partially fluorinated fluoropolymers, especially in air. Exposure to high-energy (ionizing) radiation, regardless of the source, degrades PTFE by breaking down the molecules and reducing its molecular weight, resulting in a marked decrease in melt viscosity. As in thermal degradation, radiation stability of PTFE is much better under vacuum compared to air. For example, exposure of PTFE film to a dose of one megarad of γ-rays from a Co^{60} in air resulted in 87% loss of initial elongation and 54% loss of tensile strength (Table 3.85). A significantly less loss of tensile properties occurs when PTFE is exposed to the same radiation dose in a vacuum.

PFA and FEP are somewhat more resistant to high-energy radiation than PTFE. Tables 3.86 and 3.87 show the effect of radiation on PFA and FEP in air. After exposure to one megarad of radiation, PFA loses 8% of its elongation and 15% of its tensile strength in contrast to 87% elongation and 54% tensile strength loss for PTFE after the same exposure. Tensile strength of FEP drops 10% after one megarad (Mrad) radiation and remains virtually unchanged up to 5 megarads.

Partially fluorinated fluoropolymers (PVDF, ETFE, ECTFE) are much more resistant to electron beam and γ-radiation than perfluorinated fluoroplastics. Table 3.88 provides mechanical property data for ECTFE as a function of Co^{60} radiation (γ-rays). Figure 3.116 shows the effect of γ-rays on the break elongation and yield strength of PVDF. Exposure of PVDF to 20 megarads of radiation has a modest effect on these two properties. After 40 megarads of exposure, elongation approaches a level of 40% while yield strength gradually increases. Hardness of the polymer grows up to 40 megarads.[73] Two competitive phenomena of degradation and crosslinking occur in competition up to 100 megarads, which bring about a relative stability in the mechanical properties (Fig. 3.116) and, at the same time, browning. Discoloration becomes considerable above 100 megarads; after which degradation becomes progressive and rapid. Evidence of crosslinking is the insoluble fraction of the PVDF that increases with the amount of radiation exposure (Fig. 3.117).

Figure 3.118 shows the effect of γ radiation on the break elongation of PVF, PVDF, ETFE, FEP, and PFA. It can be seen that the impact on PVF, PVDF, and ETFE is smaller than the radiation impact on FEP and PFA; FEP fares better than PFA. Figure 3.119 provides a comparison of the radiation resistance of several fluoroplastics as a function of radiation dose, as expressed by the retained elongation as percent of initial break elongation of the polymer. FEP is the most radiation resistant of the perfluoropolymers while PTFE is the most susceptible. ETFE has far superior radiation resistance to all the perfluoroplastics shown in Fig. 3.119.

Table 3.79. Typical Electrical Properties of ETFE Film at 23°C[37]

Property	Value
Volume Resistivity, Ω·cm	10^{15}–10^{16}
Surface Resistivity, Ω per square	>10^{17}
Dielectric Strength, kV/mm	
0.25 mm	64
3.20	15

Table 3.80. Typical Electrical Properties of ECTFE Film at 23°C[38]

Property	Value
Volume Resistivity, Ω·cm	5.5×10^{15}
Dielectric Strength, kV/mm	
0.025 mm	80
3.20	14
Dielectric Constant	
1 kHz	2.47–2.50
1 MHz	2.57–2.59
Dissipation Factor	
1 kHz	0.0014–0.0017
1 MHz	0.0013–0.0017

Table 3.81. Optical Properties of PFA[32]

Property	Test Method	Value
Refractive Index	ASTM D542-50 (at 0.546 μm)	1.35
Haze, %	ASTM D1003-52	4
Light Transmission, %	Spectrophotometry 0.025 mm film thickness	
UV (0.25-0.40 μm)		77-91%
Visible (0.40-0.70 μm)		91-96%
Infrared (0.70-2.40 μm)		96-98%

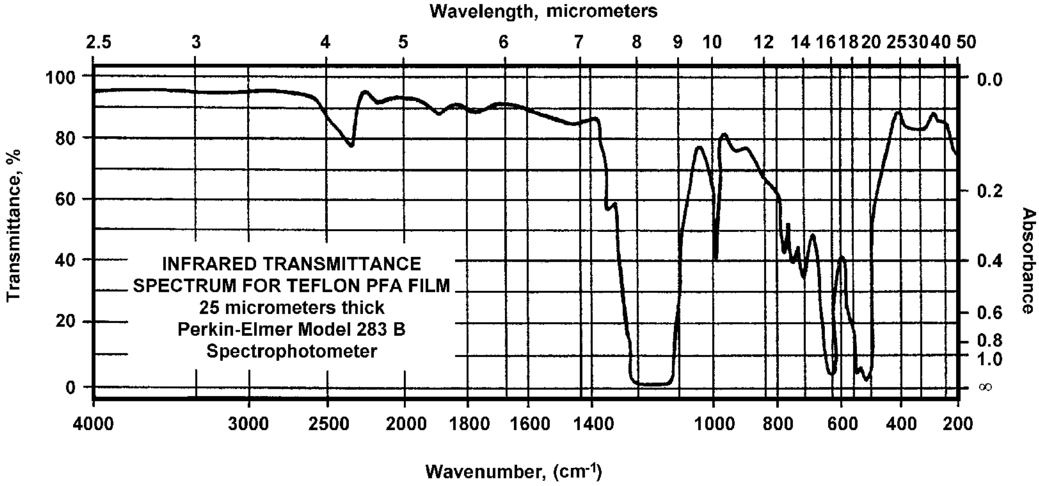

Figure 3.105 Infrared transmittance spectrum of PFA film (1.350 mm thickness).[55]

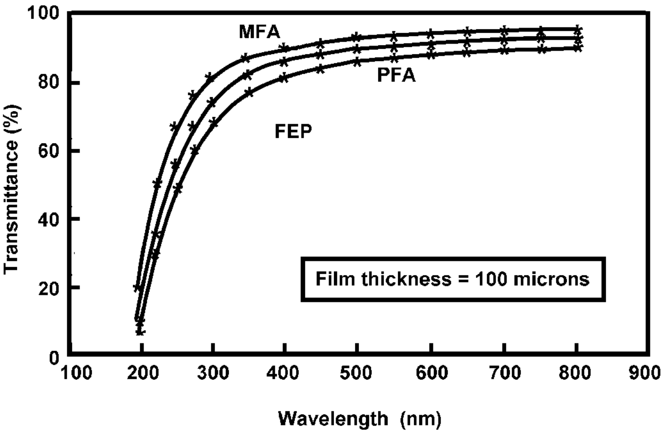

Figure 3.106 A comparison of transmittance of FEP, PFA, and MFA in the UV and visible light regions.[33]

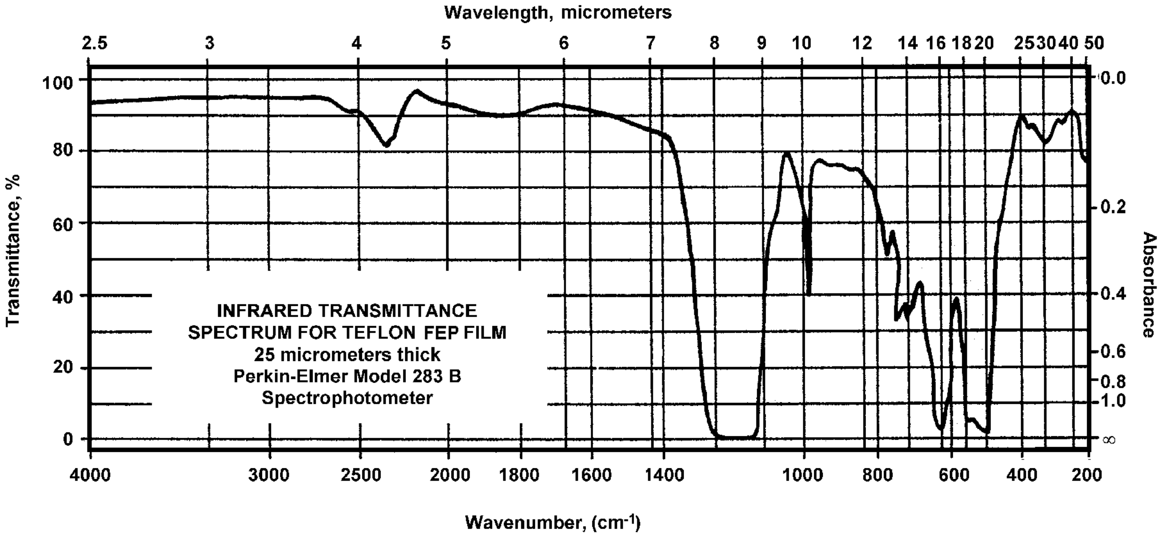

Figure 3.107 Infrared transmittance spectrum of FEP film (1.344 mm thickness).[55]

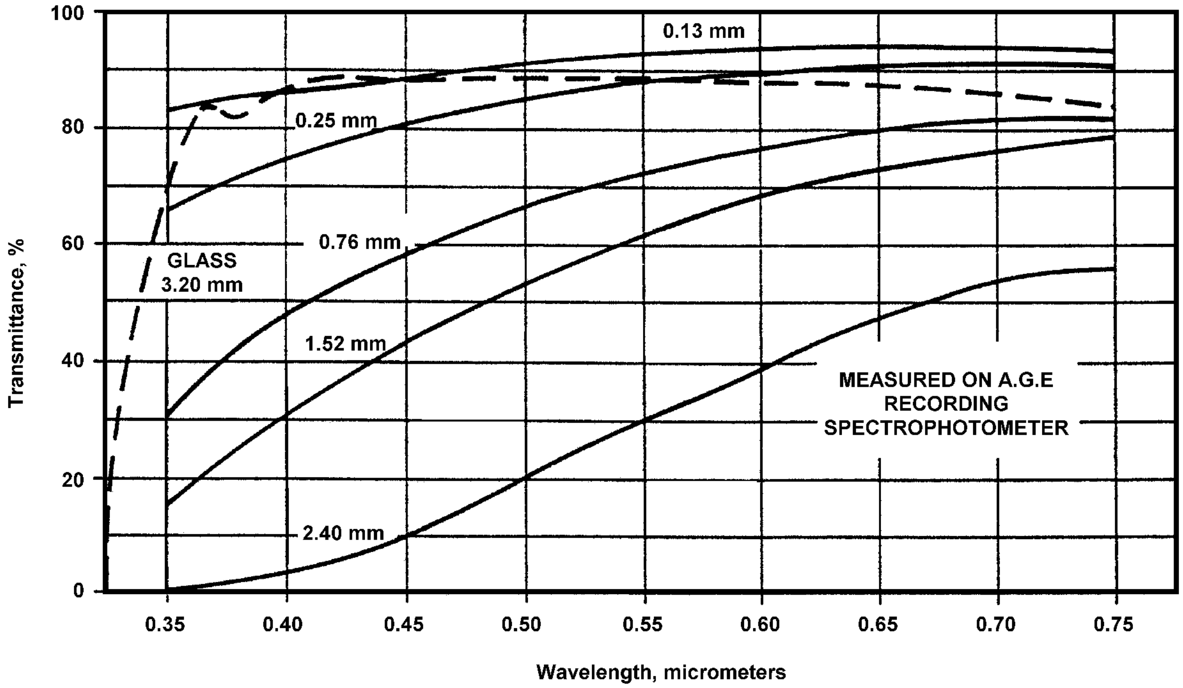

Figure 3.108 Transmission (narrow beam) of visible light through FEP vs film thickness.[55]

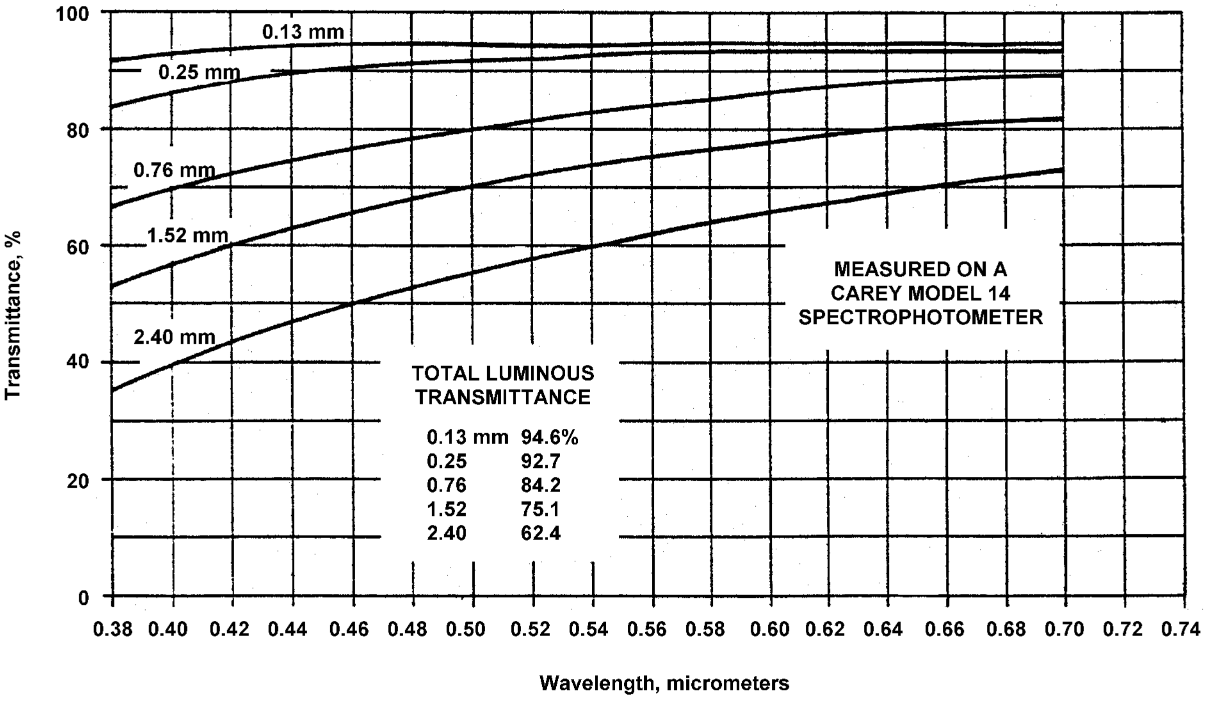

Figure 3.109 Transmission (wide beam) of visible light through FEP vs film thickness.[55]

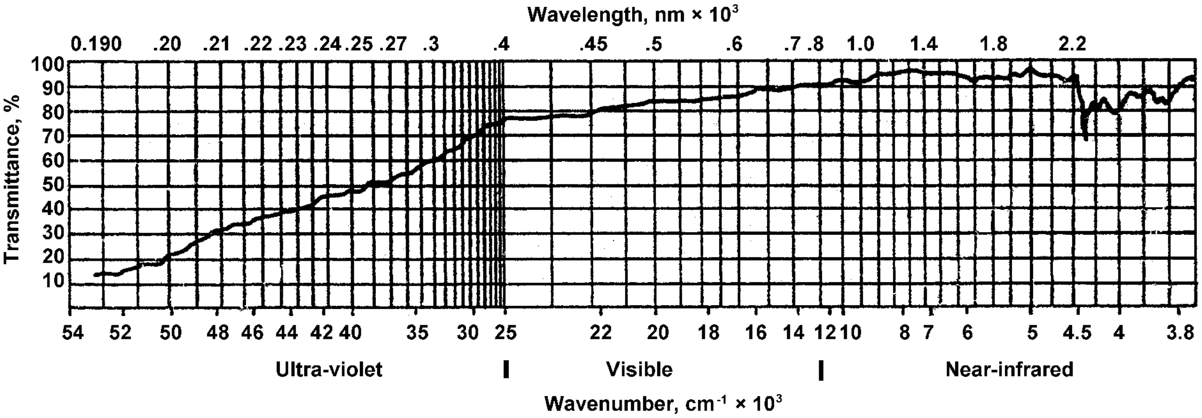

Figure 3.110 Ultraviolet, visible, and near-infrared light transmittance spectra of PVDF film (96.5 μm thickness).[36]

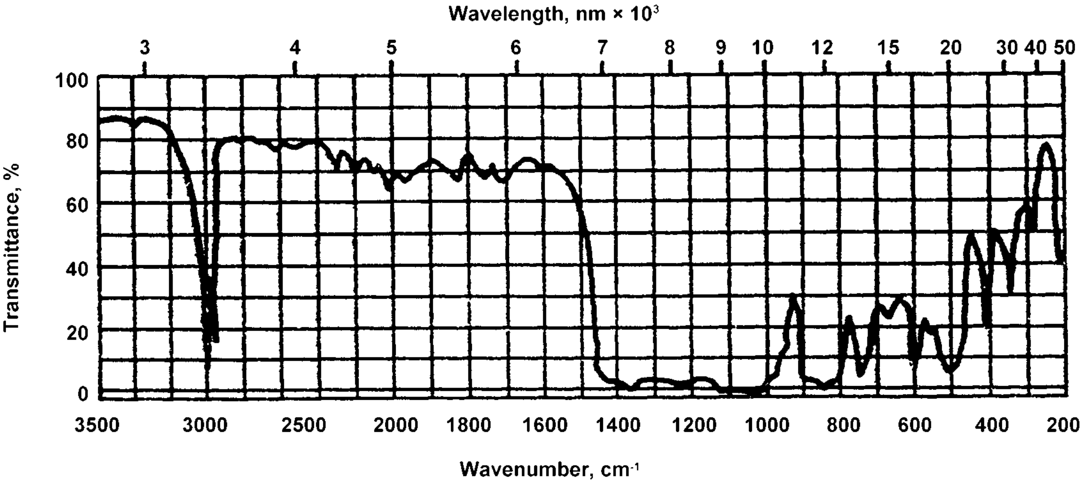

Figure 3.111 Infrared absorption spectrum of PVDF film.[36]

Table 3.82. Optical Properties of PVDF[35]

Film/Sheet –Wavelength	Average Refractive Index	Haze, %	Transmission, %	Absorption, %	Reflection, %
Blow-extruded Film (25 μm thickness)	1.42	10	91	-	-
Flat die-extruded Film (25 μm thickness)	1.42	3	94	-	-
Flat die-extruded Film (100 μm thickness)	1.42	13	93	-	-
Calendared-sheet (200 μm thickness) - 400 nm	1.42	-	85	3	12
Calendared-sheet (200 μm thickness) - 700 nm	1.42	-	88	4	8

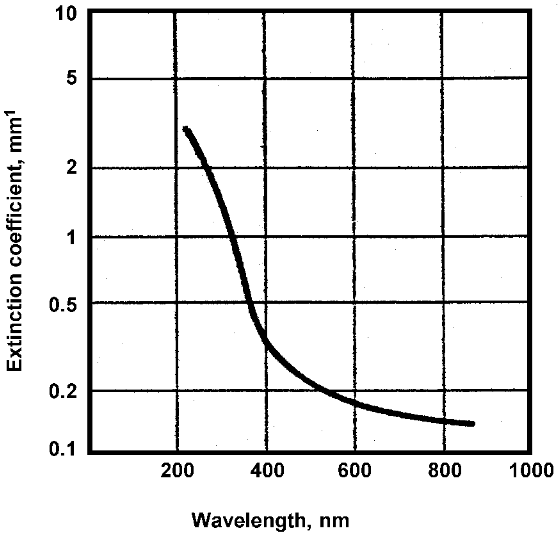

Figure 3.112 Development of extinction coefficient of PVDF in relation to the wavelength.[35]

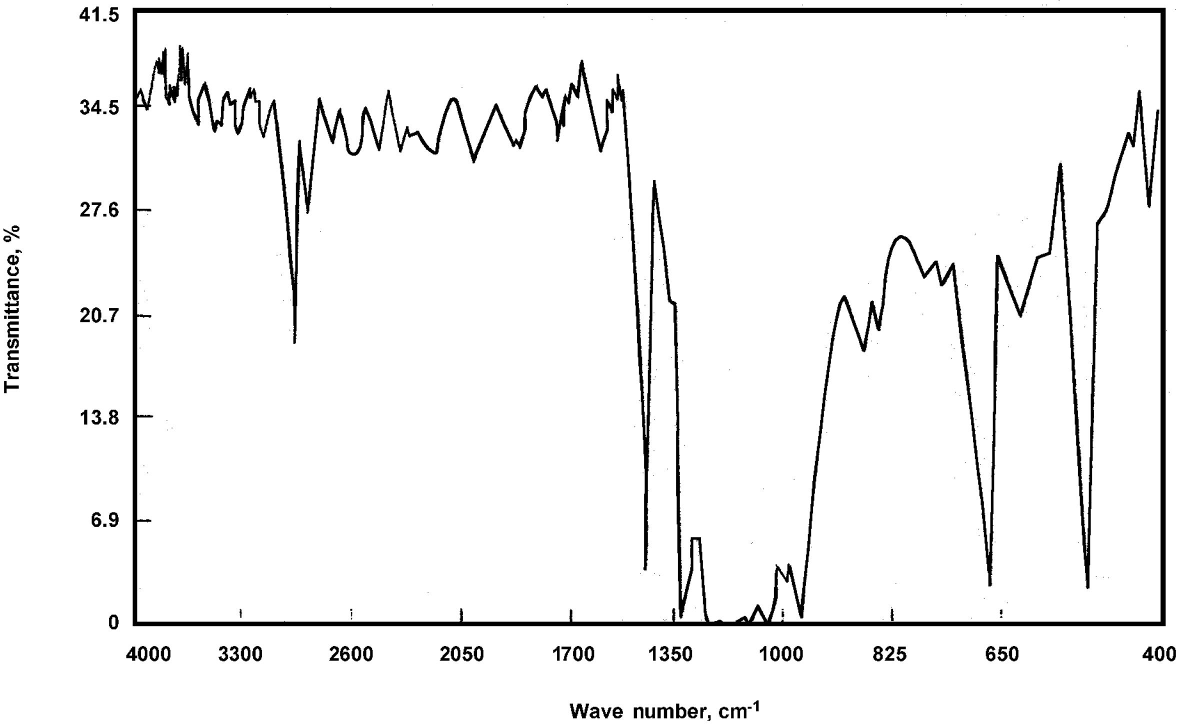

Figure 3.113 Infrared scan of ETFE film at 0.025 mm thickness.[37]

Table 3.83. Transmittance vs Wavelength of ETFE in Ultraviolet and Visible Regions (0.025 mm thickness)

Wavelength, nm	Light Region	Transmittance, %
200	Ultraviolet	91.5
250	Ultraviolet	92
300	Ultraviolet	92
350	Ultraviolet	93
400	Ultraviolet	94
500	Visible	94
600	Visible	94
700	Visible	95
800	Visible	95

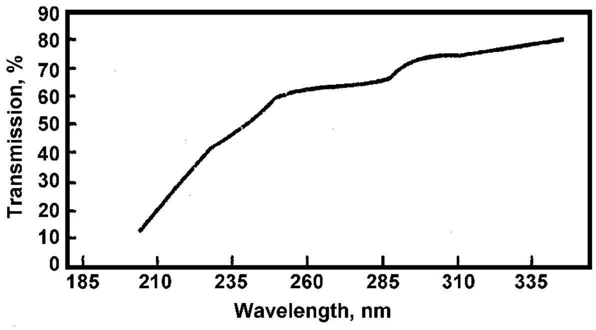

Figure 3.114 Transmittance of a 25 µm thick ECTFE film vs wavelength in the ultraviolet region.[38]

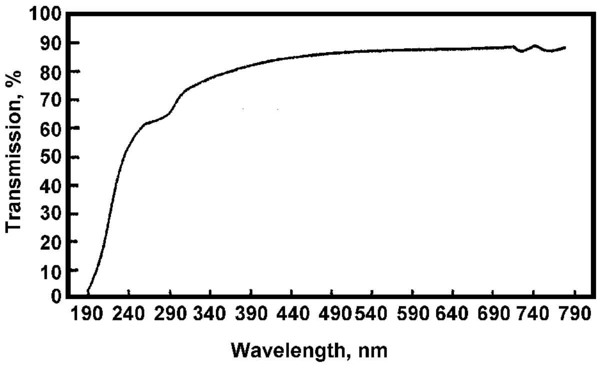

Figure 3.115 Transmittance of a 25 µm thick ECTFE film vs wavelength in the ultraviolet and visible regions.[38]

Table 3.84. Refractive Index of Fluoroplastics (ASTM D542)[58]–[60]

Fluoroplastic	Temperature, °C	Refractive Index (n_D)
PTFE	25	1.376
PFA	25	1.350
FEP	25	1.344
PVDF	25	1.42
ETFE	25	1.403
ECTFE	-	1.45
PVF	30	1.46
PCTFE	25	1.435

Table 3.85. Effect of Radiation (1 Mrad) on PTFE[72]

Environment	Elongation Loss, %	Tensile Strength Loss, %
Air	87	54
Vacuum	44	17

Table 3.86. Effect of Radiation on PFA[32]

Exposure, Mrad	Break Elongation, %	Tensile Strength, %
0	358	30
0.5	366	28
1.0	333	25
2.0	302	21
5.0	35	15
20	<5	-
50	<5	-

Table 3.87. Effect of Radiation on FEP (*Courtesy DuPont Fluoroproducts*)

Exposure, Mrad	Break Elongation, %	Tensile Strength, %
0	113	33.1
1.0	88	27.3
2.5	71	24.3
3.5	66	24.1
5	53	23.3

Table 3.88. Effect of γ-Radiation on ECTFE[38]

Exposure, Mrad	Break Elongation, %	Tensile Strength, %
0	210	48
50	105	32
100	65	30
500	20	28
1000	10	19

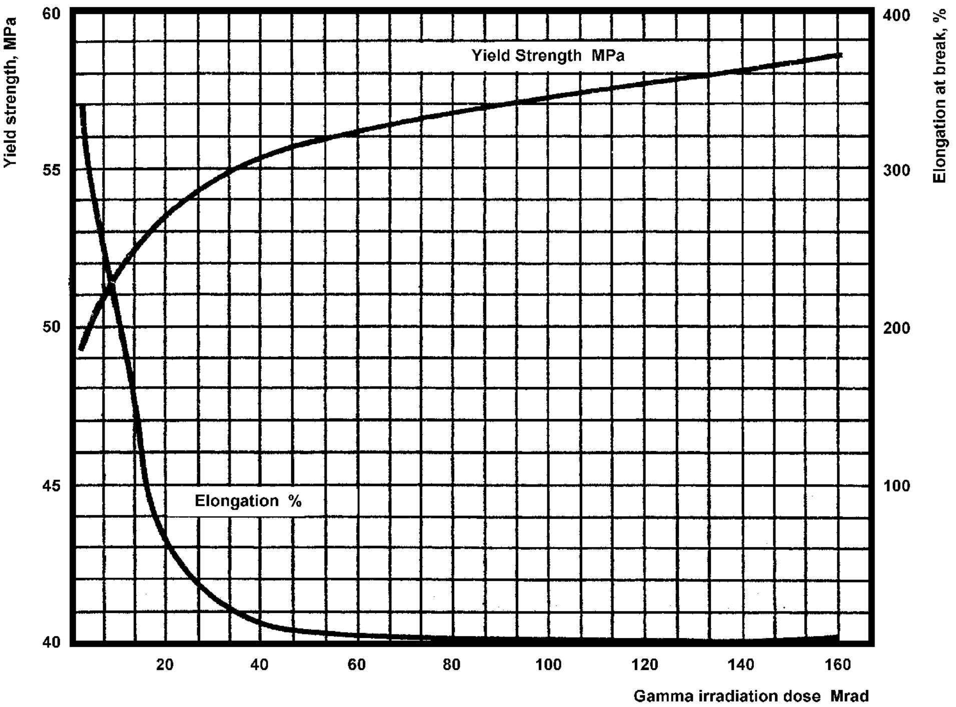

Figure 3.116 Effect of γ-rays on the mechanical properties of PVDF.[73]

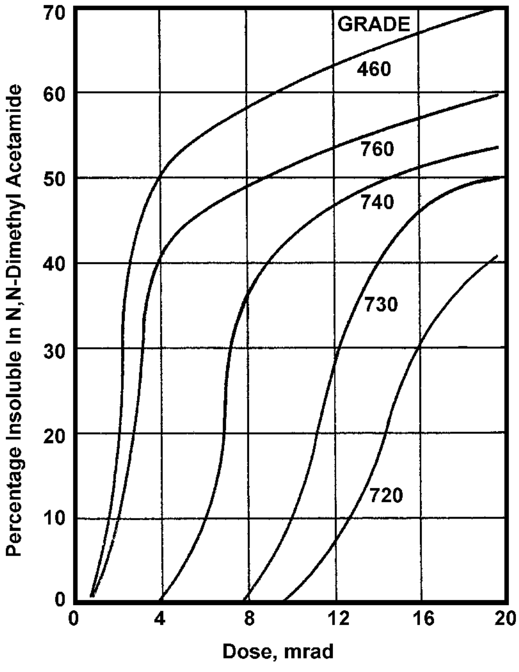

Figure 3.117 Insoluble fraction of PVDF (Kynar®) homopolymer after electron beam irradiation.[36]

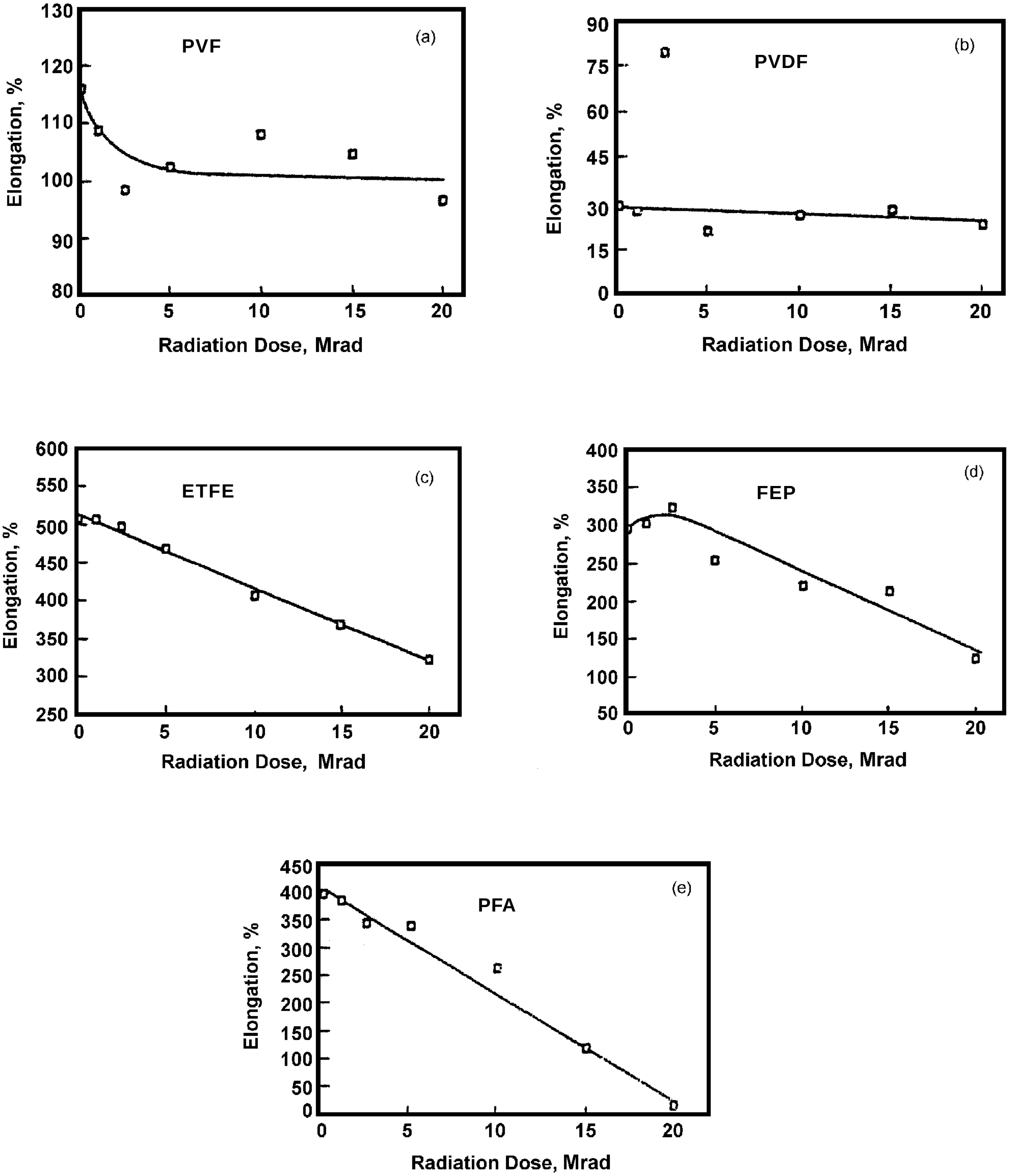

Figure 3.118 Effect of γ-radiation on the break elongation of fluoroplastics; (*a*) PVF, (*b*) PVDF,(*c*) ETFE, (*d*) FEP, and (*e*) PFA.[74]

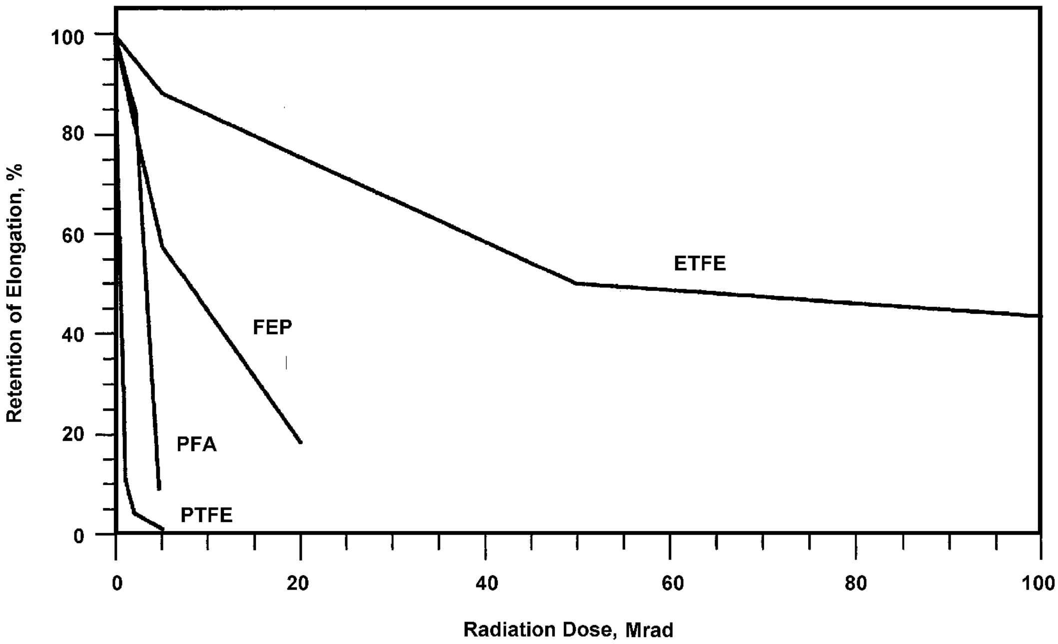

Figure 3.119 Radiation resistance of fluoroplastics. (*Courtesy DuPont Fluoroproducts.*)

3.7.7 Flammability of Melt-processible Fluoroplastics

Perfluoropolymers burn, but do not continue to burn when the flame is removed. All perfluorinated fluoropolymers pass a UL 83 vertical flame test and are classified 94 V-0 according to Underwriters Laboratory (UL) in their burning test classification for polymeric materials. Limiting oxygen index (LOI) by ASTM D2863 is 95% or higher for PTFE, PFA, FEP, and PCTFE. Partially fluorinated fluoropolymers are more flame resistant than other thermoplastics but not quite as resistant as the perfluorinated fluoropolymers, as evidenced by their lower LOI values. PVDF, ETFE, and ECTFE meet UL 94 V-0. Table 3.89 lists the LOI of various fluoropolymers.

3.7.8 Biofilm Formation of Melt-processible Fluoroplastics

There has been a great deal of interest in the buildup of microorganism films on substrate surfaces. Biofilm formation is a longstanding problem in ultrapure water and bioprocessing fluid transfer lines. A frequent cause of infection in conjunction with the use of biomedical devices is the buildup of *Staphylococcus epidermis* film on the surfaces. In addition to the surface roughness and topography, the nature of material affects biofilm formation. Fluoroplastics are among the materials that allow the smallest amount of biofilm formation on surfaces. PTFE, FEP, and PFA have been preferred materials of construction for medical devices and vascular grafts. A significant body of research has been devoted to the adhesions of biofilms to various substrates.[75]–[85]

An early study utilizing *Limulus amoebocyte lysate* indicated a PTFE surface containing the least number of bacteria per unit area followed by the increasing bacterial adhesion order of FEP, PVDF, PVF, polyethylene, and glass. Another study[76] focused on the adhesion of *Staphylococcus epidermidis*, *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella aerogenes*, and *Pseudomonas aeruginosa* adhesion to intravascular material. Overall, PTFE and FEP showed less affinity for bacteria than PVC, polypropylene, or silicon rubber. All organisms exhibited significant preference for silicone rubber. In a more recent study, using a dynamic system, increase in fluid flow past the PTFE surface was found to reduce bacterial adhesion in contrast to stainless steel.[85]

No commercial substrate is completely resistant to surface bacterial growth and biofilm formation. In a study at the University of Minnesota,[86] PFA with a smooth surface was found to be least hospitable to bacterial growth. Biofilm removal from PFA was easily and completely accomplished (Table 3.90). PFA was cleaned more completely than glass, stainless steel, and PVDF. Figure 3.120 shows the results of bacterial count in a dynamic ultrapure water system in which fouling of the surfaces of stainless steel, PVDF, and ECTFE were studied.[87] ECTFE and PVDF were orders of magnitude less susceptible to biofouling than stainless steel.

Table 3.89. Limiting Oxygen Index (LOI) according to ASTM D2863[36][38][58][60]

Fluoropolymer	LOI, %
PTFE	>95
PFA	>95
FEP	95
PCTFE	100
PVDF	
Homopolymer	40-75
Copolymer	>40
ETFE	30
ECTFE	52
PVF	22.6

Table 3.90. Biofilm Removal (%) in Virtually Quiescent Dilute Sodium Hypochlorite Reported by the BioProcess Technical Institute, University of Minnesota[86]

Commercial Substrate	Bacteria Type		
	Klebsiella pneumonia	*Staphylococcus choleraisuis*	*Escherichia coli*
Polished Stainless Steel	67	25	56
Polypropylene	67	75	75
Borosilicate Glass	89	0	0
Silicone-coated Glass	89	89	78
PVDF	89	89	89
PFA	99	99	98

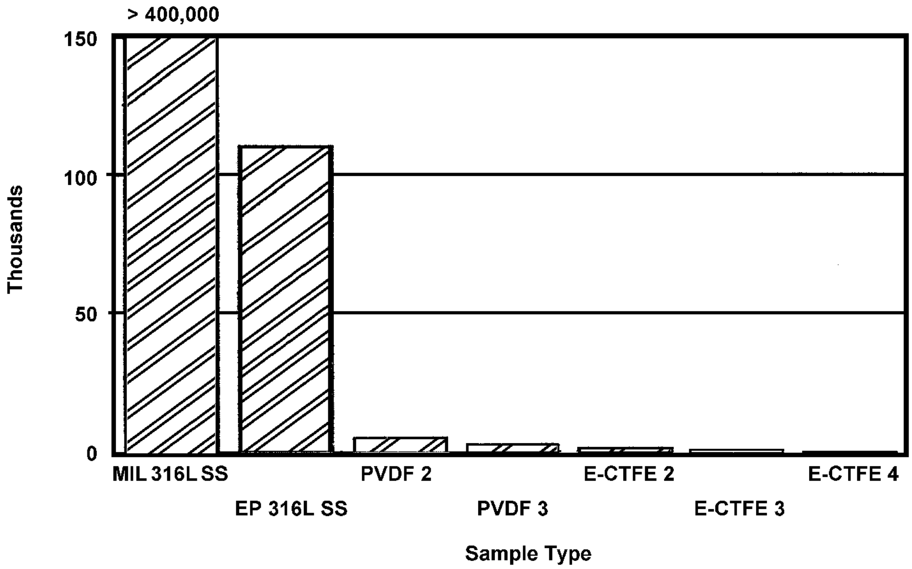

Figure 3.120 Microbial fouling of materials in ultrapure water—average cell count/cm^2 at a fluid velocity of 91 cm/sec.[87]

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4 Selecting Fluoropolymers for Corrosion Control

4.1 Introduction

This chapter deals with the two distinct aspects of materials selection:

1. Selection of fluoropolymers from the entire spectrum of materials such as metals, ceramics, and polymers.
2. Selection of a specific fluoropolymer.

Fluoropolymers are used in the chemical processing industry, principally for their outstanding resistance to almost all chemicals. Their ability to withstand high temperatures also plays an important part in their functional role. The low mechanical properties and high permeation rates of fluoropolymers at higher temperatures limit their use for linings to about 175°C, although they remain chemically inert up to 260°C.

Selection of fluoropolymers is an integral part of the overall material selection process. This implies that all the available materials such metals, ceramics, and plastics are considered candidates for an application. The end user then considers these materials against established criteria such as required life, mean time between inspection (MTBI), ease of fabrication, frequency of inspection, extent of maintenance and, of course, capital cost. More often than not it is the initial capital cost, rather than the life cycle cost of equipment, that affects the decision made during the material selection step. However, the most important piece of data is the corrosion resistance of a material in the medium under consideration over the life of the equipment. This information is available in a different format for plastics than for metals. A comparison is appropriate.

4.1.1 Corrosion of Metals

Metals corrode by an electrochemical reaction where metal loss occurs as oxidation at the anode sites and plating out occurs at the cathode. This phenomenon manifests in two distinct ways: general corrosion or localized corrosion. General corrosion refers to a uniform loss of the metal thickness due to the interaction of the metal and the chemical to which it is exposed. This degradation can be measured as corrosion rate in thickness per year. Localized corrosion can be of various types: typical are *pitting, intergranular corrosion, crevice corrosion,* and *stress corrosion cracking*. Pitting corrosion can be measured as pitting velocity in thickness per year. Intergranular, crevice, and stress corrosion cracking are not measurable in a linear direction. However, these are well-established phenomena where a great deal of information is available.[1]–[3] Additionally, the methodology for detecting and analyzing is carried out at a very sophisticated level using microscopic techniques. Laboratory techniques of measuring corrosion rates or tendencies are also well developed where instantaneous corrosion rates can be measured and reasonably accurate data can be generated in a very short time.

4.1.2 Corrosion of Polymer Materials

Polymeric materials do not corrode by an electrochemical process, so all the electrochemical rate measuring techniques available to a metallurgist are of little use here. Conventionally, the terms “chemical degradation” and “chemical attack” are used to describe the polymer/chemical interaction. Phenomenology of polymers is complex and currently is based on visual observations. The following descriptions are often used: cracking, blistering, chalking, swelling, discoloration, and delamination. These descriptions do not lend themselves to quantitative measurements. Sometimes the visual observations are further analyzed for the underlying phenomena such as oxidative attack, chain scission, permeation, etc.

4.1.3 Approaches to Selection

Selection of any material will depend on identifying the degradation mechanism, its rate, and criteria based on the expected life of the unit. Such information can be generated by experience, literature data, or testing. Testing is done either in the field under real life operating conditions or in the lab simulating real conditions. Testing can be used for screening or to make a final decision.

The ability to fabricate the fluoropolymers in the required shape is also a consideration in its selection. As discussed in Ch. 2, “Materials of Construction,” fluoropolymers are principally used in barrier applications. Selection and related testing discussed in this chapter concentrates heavily on that aspect.

The ability to inspect and maintain the equipment or piping is also an important consideration in the selection process. Many operations are reluctant to shutdown equipment for reasons of downtime, safety, and costs associated with the cleanup. Metals have a clear advantage over polymer materials.

Lastly, selection methodology of fluoropolymers depends on the nature of the application. Fluoropolymers are principally used for chemical resistance, nonstick, and product purity applications. Data search and testing will depend on the application under consideration. Except for screening methods, testing is very application specific.

4.2 Economics of Selecting Fluoropolymers

Carbon steels, stainless steels, high nickel alloys, and exotic metals (Ti and Ta) represent an upward progression in terms of corrosion resistance and cost. Things are simpler for polymeric materials. Polyolefins, vinyls, and some types of fiberglass represent the low end of the spectrum. Some other forms of fiberglass and thermoplastics such as polypropylene are in the middle. Fluoropolymers are at the high end of the spectrum; they compete with the high-nickel alloys and exotic metals. Evaluation of fluoropolymers is done on the basis of installed cost, for example, a solid high-nickel alloy vessel versus a fluoropolymer-lined carbon steel vessel. The thickness of the fluoropolymer can be varied so evaluation becomes more complicated since various thicknesses have their own fabrication issues.

4.3 Preparing to Determine Compatibility

When it is decided that fluoropolymers are candidates for a given application, the next step is to note all the relevant information about them. This makes it easier to define a test program or search for similar experience in the field. A list of the pertinent information includes:

- Type of application (vessel lining, hose, column internal, etc.)
- Description of the unit (vessel dimensions, geometry, other details such as nozzles, internals, etc.)
- Operating and design conditions (chemicals—normal and upset, temperature and pressure—normal and upset)
- Startup and shutdown details
- Other requirements such as agitation, abrasion, nonstick, allowable meantime between inspections, or expected life
- Heat transfer: jacketed vessels with internal linings
- Maintenance and repair requirements or restrictions
- Connecting piping and equipment information and related sealing requirements

4.4 Current Technology for Determining Compatibility

4.4.1 Experience

Nothing works like success. When the decision is made to look at non-metallic candidates, it is often on the basis of anecdotal evidence of a success story. Rarely does the experience in the field match the operating conditions of the application under consideration; however, experience does provide information about the possibility of using the material in the entire context of chemical resistance, fabrication, etc., and acts as a starting point. Experience comes in the form of written case histories, information provided by materials suppliers, or other information in the public or private domain.

4.4.2 Manufacturers' Literature

There is an abundance of compatibility information provided by resin manufacturers. The information can be of two kinds. One is actual coupon exposure data with no judgement as to the suitability, and other is a list of chemicals against which a rating system (A, B, C, etc.) is given. Often the maximum operating temperature is also given as additional useful information.

Tables 4.1 through 4.16 contain the typical rating data supplied by resin manufacturers. Tables 4.1–4.5 show the chemical resistance of PTFE to solvents, acids and bases, halogenated chemicals, and various other chemicals. Tables 4.6 and 4.7 show the effects on PFA of immersion in various inorganic and organic chemicals. Tables 4.8–4.11 show the chemical resistance of FEP to solvents, acids and bases, halogenated chemicals, and various other chemicals. Tables 4.12, 4.13, and 4.14 show the maximum usable temperature of ETFE with various chemicals, the effects its immersion in various chemicals, and its hydrolytic stability in boiling water. PVDF's maximum use-temperatures with numerous chemicals are given in Table 4.15. Table 4.16 shows the chemical compatibility of ECTFE, and Table 4.17 shows the room-temperature swelling of PVF in organic solvents.

In addition to manufacturer-supplied data, information is provided by a number of independent sources. Appendix V contains comprehensive data showing the chemical resistance of various fluoropolymers to numerous reagents under different conditions. These data have been compiled by the Plastics Design Library (PDL) from manufacturers' literature. A rating system used by the PDL is applied to the data for efficiently determining potential compatibility.

Table 4.1. Chemical Resistance of PTFE to Common Solvents[4]

Solvent	Exposure Temp., °C	Exposure Time	Weight Gain, %
Acetone	20	12 mo	0.3
	50	12 mo	0.4
	70	2 wk.	0
Benzene	78	96 hr	0.5
	100	8 hr	0.6
	200	8 hr	1.0
Carbon Tetrachloride	25	12 mo	0.6
	50	12 mo	1.6
	70	2 wk	1.9
	100	8 hr	2.5
	200	8 hr	3.7
Ethanol (95%)	25	12 mo	0
	50	12 mo	0
	70	2 wk	0
	100	8 hr	0.1
	200	8 hr	0.3
Ethyl Acetate	25	12 mo	0.5
	50	12 mo	0.7
	70	2 wk	0.7
Toluene	25	12 mo	0.3
	50	12 mo	0.6
	70	2 wk	0.6

Table 4.2. Chemical Resistance of PTFE to Common Acids and Bases[4]

Reagent	Exposure Temp., °C	Exposure Time	Weight Gain, %
Hydrochloric Acid			
10%	25	12 mo.	0
10%	50	12 mo.	0
10%	70	12 mo.	0
20%	100	8 hr	0
20%	200	8 hr	0
Nitric Acid			
10%	25	12 mo.	0
10%	70	12 mo.	0.1
Sulfuric Acid			
30%	25	12 mo.	0
30%	70	12 mo.	0
30%	100	8 hr	0
30%	200	8 hr	0.1
Sodium Hydroxide			
10%	25	12 mo.	0
10%	70	12 mo.	0.1
50%	100	8 hr	0
50%	200	8 hr	0
Ammonium Hydroxide			
10%	25	12 mo.	0
10%	70	12 mo.	0.1

Table 4.3. Chemical Compatibility of PTFE with Halogenated Chemicals[3]

Chemical	Effect on PTFE Sample
Chloroform	Wets, insoluble at boiling point
Ethylene Bromide	0.3% weight gain after 24 hr at 100ºC
Fluorinated Hydrocarbons	Wets, swelling occurs in boiling solvent
Fluoro-naphthalene	Insoluble at boiling point, some swelling
Fluoronitrobenzene	Insoluble at boiling point, some swelling
Pentachlorobenzamide	Insoluble
Perfluoroxylene	Insoluble at boiling point, slight swelling
Tetrabromoethane	Insoluble at boiling point
Tetrachloroethylene	Wets, some swelling after 2 hr at 120ºC
Trichloroacetic Acid	Insoluble at boiling point
Trichloroethylene	Insoluble at boiling point after 1 hr

Table 4.4. Chemical Compatibility of PTFE with Various Chemicals[3]

Chemical	Effect on PTFE Sample
Abietic Acid	Insoluble at boiling point
Acetic Acid	Wets
Acetophenone	Insoluble – 0.2% weight gain after 24 hr. at 150ºC
Acrylic Anhydride	No effect at room temperature
Allyl Acetate	No effect at room temperature
Allyl Methacrylate	No effect at room temperature
Aluminum Chloride	Insoluble in solution with NaCl; 1%–5% anhydrous AlCl$_3$ affects mechanical properties
Ammonium Chloride	Insoluble at boiling point
Aniline	Insoluble – 0.3% weight gain after 24 hr. at 150ºC
Borax	No wetting or effect by 5% solution
Boric Acid	Insoluble at boiling point
Butyl Acetate	Insoluble at boiling point
Butyl Methacrylate	No effect at room temperature
Calcium Chloride	No effect by saturated solution in methanol
Carbon Disulfide	Insoluble at boiling point
Cetane	Wets, insoluble at boiling point
Chromic Acid	Insoluble at boiling point
Cyclohexanone	No effect observed
Dibutyl Phthalate	Wets, no effect at 250ºC
Diethyl Carbonate	No effect at room temperature
Dimethyl Ether	No effect observed
Dimethyl Formamide	No effect observed
Ethyl Ether	Wets
Ethylene Glycol	Insoluble at boiling point
Ferric Chloride	1%–5% FeCl$_3$.6H$_2$O reduces mechanical properties
Ferric Phosphate	No effect by 5% solution
Formaldehyde	Insoluble at boiling point after 2 hr
Formic Acid	Insoluble at boiling point
Hexane	Wets
Hydrogen Fluoride	Wets, no effect by 100% HF at room temperature
Lead	No effect
Magnesium Chloride	Insoluble at boiling point
Mercury	Insoluble at boiling point
Methacrylic Acid	No effect at room temperature
Methanol	Wets
Methyl Methacrylate	Wets above melting point
Naphthalene	No effect
Nitrobenzene	No effect
2-Nitro-Butanol	No effect
Nitromethane	No effect
2-Nitro-2-Methyl Propanol	No effect
n-Octadecyl Alcohol	Wets
Phenol	Insoluble at boiling point
Phthalic Acid	Wets
Pinene	Wets, insoluble at boiling point
Piperidene	No effect, 0.3%–0.5% weight gain after 24 hr at 106ºC
Polyacrylonitrile	No effect
Potassium Acetate	Insoluble at boiling point
Pyridine	No effect
Stannous Chhloride	No effect at melting point (246ºC)
Sulfur	No effect at 445ºC
Triethanolamine	Wets, no effect
Vinyl Methacrylate	No effect at room temperature
Water	Insoluble at boiling point
Xylene	0.4% weight gain after 48 hr at 137ºC
Zinc Chloride	No effect at melting point (260ºC)

Table 4.5. Chemical Resistance of Filled PTFE Compounds[5]

Chemical	Filler		
	Carbon/ Graphite	Glass	Bronze
Acetaldehyde	A	A	A
Acetone	A	A	A
Aluminum sulphate	A	A	B
Ammonium chloride	A	A	C
Ammonium hydroxide	A	B	C
Aniline	A	A	C
Benzene	A	A	A
Boric acid	A	A	A
Brine	A	A	A
Bromine (anhydrous)	C	B	C
Carbon disulphide	A	A	A
Chloroacetic acid	A	A	B
Chlorobenzene	A	A	A
Chloroform	A	A	A
Chromic acid	B	B	C
Citric acid	A	A	A
Diethyl ether	A	A	A
Ethylene glycol	A	A	A
Fatty acids	A	A	A
Ferric chloride	A	A	C
Ferric sulphate	A	A	C
Fluorosilicic acid	B	C	C
Formic acid	A	A	A
Freon* (liquid)	A	A	A
Hydroboric acid	A	B	C
Hydrochloric acid	A	B	C
Hydrocyanic acid	A	B	C
Hydrofluoric acid	A	C	C
Hydrogen sulphide (solution)	A	C	C

Chemical	Filler		
	Carbon/ Graphite	Glass	Bronze
Lead acetate	A	A	C
Maleic acid	A	A	B
Mercury salts	A	A	C
Molasses	A	A	B
Naphtha	A	A	B
Naphthalene	A	A	B
Nickel salts	A	A	A
Nitric acid (0%–50%)	C	B	C
Nitrobenzene	A	A	A
Phenol	A	B	A
Phosphoric acid	A	A	C
Phthalic acid	A	A	A
Picric acid	A	A	A
Pyridine	A	A	C
Salicyclic acid	A	A	B
Silver nitrate	A	A	C
Sodium carbonate	A	A	A
Sodium hydroxide	A	B	A
Sodium nitrite	A	A	A
Sodium peroxide	B	A	C
Sodium silicate	A	C	A
Sodium sulphide	A	A	C
Starch	A	A	A
Sulphuric acid	B	A	C
Tallow	A	A	A
Tannic acid	A	A	A
Tartaric acid	A	A	A
Trichloroethylene	A	A	B
Zinc chloride	A	A	C

* Freon is DuPont’s registered trademark for its fluorocarbon solvents.
A = Excellent. B = Fair. C = Unsatisfactory.

Table 4.6. Effect on PFA of Immersion in Inorganic Chemicals for 168 Hours[6]

Reagent	Exposure Temperature, ºC	Tensile Strength Retained, %	Elongation Retained, %	Weight Gain, %
Acids:				
Hydrochloric (conc.)	120	98	100	0
Sulfuric (conc.)	120	95	98	0
Hydrofluoric (60%)	23	99	99	0
Fuming Sulfuric	23	95	96	0
Oxidizing Acids:				
Aqua Regia	120	99	100	0
Chromic (50%)	120	93	97	0
Nitric (conc.)	120	95	98	0
Fuming Nitric	23	99	99	0
Bases:				
Ammonium Hydroxide (conc.)	66	98	100	0
Sodium Hydroxide (conc.)	120	93	99	0.4
Peroxide:				
Hydrogen Peroxide (30%)	23	93	95	0
Halogens:				
Bromine	23	99	100	0.5
Bromine	59	95	95	—
Chlorine	120	92	100	0.5
Metal Salt Solutions:				
Ferric Chloride	100	93	98	0
Zinc Chloride (25%)	100	96	100	0
Miscellaneous:				
Sulfuryl Chloride	69	83	100	2.7
Chlorosulfonic Acid	151	91	100	0.7
Phosphoric Acid (conc.)	100	93	100	0

Table 4.7. Effect on PFA of Immersion in Organic Chemicals for 168 Hours[6]

Reagent	Exposure Temperature, ºC	Tensile Strength Retained, %	Elongation Retained, %	Weight Gain, %
Acids/Anhydrides:				
Glacial Acetic Acid	118	95	100	0.4
Acetic Anhydride	139	91	99	0.3
Trichloroacetic Acid	196	90	100	2.2
Hydrocarbons:				
Isooctane	99	94	100	0.7
Naphtha	100	91	100	0.5
Mineral Oil	180	87	95	0
Toluene	110	88	100	0.7
Aromatic:				
O-Cresol	191	92	96	0.2
Nitrobenzene	210	90	100	0.7
Alcohol:				
Benzyl Alcohol	205	93	99	0.3
Ether:				
Tetrahydrofuran	66	88	100	0.7
Amine:				
Aniline	185	94	100	0.3
n-Butylamine	78	86	97	0.4
Ethylenediamine	117	96	100	0.1
Aldehyde:				
Benzaldehyde	179	90	99	0.5
Ketone:				
Cyclohexanone	156	92	100	0.4
Methyl Ethyl Ketone	80	90	100	0.4
Acetophenone	202	90	100	0.6
Esters:				
Dimethylphthalate	220	98	100	0.3
n-Butylacetate	125	93	100	0.5
Tri-n-ButylPhosphate	200	91	100	2.0
Chlorinated Solvents:				
Methylene Chloride	40	94	100	0.8
Perchloroethylene	121	86	100	2.0
Carbon Tetrachloride	77	87	100	2.3
Polar Solvents:				
Dimethylformamide	154	96	100	0.2
Dimethylsulfoxide	189	95	100	0.1
Dioxane	101	92	100	0.6

Table 4.8. Chemical Resistance of FEP to Common Solvents[6]

Solvent	Exposure Temperature, ºC	Exposure Time	Weight Gain, %
Acetone	20 50 70	12 mo 12 mo 2 wk	0.3 0.4 0
Benzene	78 100 200	96 hr 8 hr 8 hr	0.5 0.6 1.0
Carbon Terachloride	25 50 70 100 200	12 mo 12 mo 2 wk 8 hr 8 hr	0.6 1.6 1.9 2.5 3.7
Ethanol (95%)	25 50 70 100 200	12 mo 12 mo 2 wk 8 hr 8 hr	0 0 0 0.1 0.3
Ethyl Acetate	25 50 70	12 mo 12 mo 2 wk	0.5 0.7 0.7
Toluene	25 50 70	12 mo 12 mo 2 wk	0.3 0.6 0.6

Table 4.9. Chemical Resistance of FEP to Common Acids and Bases[6]

Reagent	Concentration	Exposure Temperature, ºC	Exposure Time	Weight Gain, %
Hydrochloric Acid	10% 10% 10% 20% 20%	25 50 70 100 200	12 mo 12 mo 12 mo 8 hr 8 hr	0 0 0 0 0
Nitric Acid	10% 10%	25 70	12 mo 12 mo	0 0.1
Sulfuric Acid	30% 30% 30% 30%	25 70 100 200	12 mo 12 mo 8 hr 8 hr	0 0 0 0.1
Sodium Hydroxide	10% 10% 50% 50%	25 70 100 200	12 mo 12 mo 8 hr 8 hr	0 0.1 0 0
Ammonium Hydroxide	10% 10%	25 70	12 mo 12 mo	0 0.1

Table 4.10. Chemical Compatibility of FEP to Halogenated Solvents[6]

Chemical	Effect on Polymer Sample
Chloroform	Wets, insoluble at boiling point
Ethylene Bromide	0.3% weight gain after 24 hr at 100°C
Fluorinated Hydrocarbons	Wets, swelling occurs in boiling solvent
Fluoro-naphthalene	Insoluble at boiling point, some swelling
Fluoronitrobenzene	Insoluble at boiling point, some swelling
Pentachlorobenzamide	Insoluble
Perfluoroxylene	Insoluble at boiling point, slight swelling
Tetrabromoethane	Insoluble at boiling point
Tetrachloroethylene	Wets, some swelling after 2 hr at 120°C
Trichloroacetic Acid	Insoluble at boiling point
Trichloroethylene	Insoluble at boiling point after 1 hr

Table 4.11. Chemical Compatibility of FEP with Various Chemicals[6]

Chemical	Effect on Polymer Sample
Abietic Acid	Insoluble at boiling point
Acetic Acid	Wets
Acetophenone	Insoluble – 0.2% weight gain after 24 hr at 150°C
Acrylic Anhydride	No effect at room temperature
Allyl Acetate	No effect at room temperature
Allyl Methacrylate	No effect at room temperature
Aluminum Chloride	Insoluble in solution with NaCl; 1%–5% anhydrous $AlCl_3$ affects mechanical properties
Ammonium Chloride	Insoluble at boiling point
Aniline	Insoluble – 0.3% weight gain after 24 hr at 150°C
Borax	No wetting or effect by 5% solution
Boric Acid	Insoluble at boiling point
Butyl Acetate	Insoluble at boiling point
Butyl Methacrylate	No effect at room temperature
Calcium Chloride	No effect by saturated solution in methanol
Carbon Disulfide	Insoluble at boiling point
Cetane	Wets, insoluble at boiling point
Chromic Acid	Insoluble at boiling point
Cyclohexanone	No effect observed

(Cont'd.)

Table 4.11. ***(Cont'd.)*** **Chemical Compatibility of FEP with Various Chemicals[6]**

Chemical	Effect on Polymer Sample
Dibutyl Phthalate	Wets, no effect at 250°C
Diethyl Carbonate	No effect at the room temperature
Dimethyl Ether	No effect observed
Dimethyl Formamide	No effect observed
Ethyl Ether	Wets
Ethylene Glycol	Insoluble at boiling point
Ferric Chloride	1%–5% $FeCl_3 \cdot 6H_2O$ reduces mechanical properties
Ferric Phosphate	No effect by 5% solution
Formaldehyde	Insoluble at boiling point after 2 hr
Formic Acid	Insoluble at boiling point
Hexane	Wets
Hydrogen Fluoride	Wets, no effect by 100% HF at the room temperature
Lead	No effect
Magnesium Chloride	Insoluble at boiling point
Mercury	Insoluble at boiling point
Methacrylic Acid	No effect at the room temperature
Methanol	Wets
Methyl Methacrylate	Wets above melting point
Naphthalene	No effect
Nitrobenzene	No effect
2-Nitro-Butanol	No effect
Nitromethane	No effect
2-Nitro-2-Methyl Propanol	No effect
n-Octadecyl Alcohol	Wets
Phenol	Insoluble at boiling point
Phthalic Acid	Wets
Pinene	Wets, insoluble at boiling point
Piperidene	No effect, 0.3%–0.5% weight gain after 24 hr at 106°C
Polyacrylonitrile	No effect
Potassium Acetate	Insoluble at boiling point
Pyridine	No effect
Stannous Chloride	No effect at melting point (246°C)
Sulfur	No effect at 445°C
Triethanolamine	Wets, no effect
Vinyl Methacrylate	No effect at the room temperature
Water	Insoluble at boiling point
Xylene	0.4% weight gain after 48 hr at 137°C
Zinc Chloride	No effect at melting point (260°C)

Table 4.12. Maximum Use Temperatures of ETFE with Various Chemicals[7]

Chemical	Maximum Use Temperature, °C
A	
Acetaldehyde	95
Acetamide	120
Acetic Acid (50%)	110
Acetic Acid (Glacial)	120
Acetic Anhydride	150
Acetone	65
Acetone(50% H_2O)	65
Acetonitrile	65
Acetophenone	150
Acetylchloride	65
Acetylene	120
Acetylene Tetrabromide	150
Acetylene Tetrachloride	150
Acrylonitrile	65
Adipic Acid	135
Air	150
Allyl Alcohol	100
Allyl Chloride	100
Aluminum Ammonium Sulfate	150
Aluminum Chloride	150
Aluminum Fluoride	150
Aluminum Hydroxide	150
Aluminum Nitrate	150
Aluminum Oxychloride	150
Aluminum Potassium Sulfate	150
Amino Acids (H_2O)	100
Ammonia (Anhydrous)	150
Ammonia (Aqueous 30%)	110
Ammonium Bifluoride	150
Ammonium Bromide (50%)	135
Ammonium Carbonate	150
Ammonium Chloride	150
Ammonium Dichromate	135
Ammonium Fluoride	150
Ammonium Hydroxide	150
Ammonium Nitrate (Conc.)	110
Ammonium Perchlorate	135
Ammonium Persulfate	150
Ammonium Phosphate	150
Ammonium Sulfate	150
Ammonium Sulfide	150
Ammonium Thiocyanate	150
Amyl Acetate	120
Amyl Alcohol	150
Amyl Chloride	150
Aniline	110
Aniline Hydrochloride (10%)	65
Anthraquinone	135
Anthraquinone-Sulfonic Acid	135
Antimony Trichloride	100
Aqua Regia	100
Arsenic Acid	150
B	
Barium Carbonate	150
Barium Chloride	150
Barium Hydroxide	150
Barium Sulfate	150
Barium Sulfide	150
Battery Acid	120
Benzaldehyde	100
Benzene	100
Benzene Sulfonic Acid	100
Benzoic Acid	135
Benzoyl Chloride	65
Benzyl Alcohol	150
Benzyl Chloride	150
Bismuth Carbonate	150
Black Liquor	150
Bleach (12.5% Cl_2)	100
Borax	150
Boric Acid	150
Brine	150
Bromic Acid	120
Bromine (Dry)	65
Bromine Water (10%)	110
mono-Bromobenzene	100
Bromoform	100
m-Bromotoluene	100
Butadiene	120
Butane	150
Butanediol	135

(Cont'd.)

Table 4.12. *(Cont'd.)* Maximum Use Temperatures of ETFE with Various Chemicals[7]

Chemical	Maximum Use Temperature, °C
Butyl Acetate	110
Butyl Acrylate	110
n-Butyl Alcohol	150
sec-Butyl Alcohol	150
tert-Butyl Alcohol	150
n-Butylamine	50
sec-Butylamine	50
tert-Butylamine	50
di-n-Butyl Amine	110
tri-n-Butyl Amine	110
Butylene	150
Butyl Bromide	150
Butyl Chloride	150
n-Butyl Mercaptan	150
Butyl Phenol	110
Butyl Phthalate	65
Butyraldehyde	100
Butyric Acid	120
C	
Calcium Bisulfate	150
Calcium Bisulfide	150
Calcium Carbonate	150
Calcium Chlorate	150
Calcium Chloride	150
Calcium Hydroxide	150
Calcium Hypochlorite	150
Calcium Nitrate	150
Calcium Oxide	135
Calcium Sulfate	150
Calcium Sulfide	120
Caprylic Acid	100
Carbon Dioxide (Dry)	150
Carbon Dioxide (Wet)	150
Carbon Disulfide	65
Carbon Monoxide	150
Carbon Tetrachloride	65
Carbonic Acid	150
Castor Oil	150
Caustic Potash (10 and 50%)	100
Caustic Soda (10 and 50%)	100
Cellosolve®	150
Chloral Hydrate	100
Chlorinated Brine	120
Chlorinated Phenol	100
Chlorine (Dry)	100
Chlorine (Wet)	120
Chlorine Dioxide	120
Chloroacetic Acid (50% H_2O)	110
Chlorobenzene	100
Chlorobenzyl Chloride	65
Chloroform	100
Chlorohydrin (Liquid)	65
Chlorosulphonic Acid	25
Chromic Acid (50%)	65
Chromic Chloride	100
Chromyl Chloride	100
Clorox Bleach Solution (5-1/2% Cl_2)	100
Coal Gas	100
Copper Chloride	150
Copper Cyanide	150
Copper Fluoride	150
Copper Nitrate	150
Copper Sulfate	150
Cresol	135
Cresylic Acid	135
Crotonaldehyde	100
Crude Oil	150
Cyclohexane	150
Cyclohexanol	120
Cyclohexanone	150
D	
DDT	100
Decalin	120
Decane	150
Dextrin	150
Diacetone Alcohol	100
1,2-Dibromopropane	95
Dibutyl Phthalate	65
Dichloroacetic Acid	65
o-Dichlorobenzene	65
Dichloroethylene	65

(Cont'd.)

Table 4.12. ***(Cont'd.)*** **Maximum Use Temperatures of ETFE with Various Chemicals[7]**

Chemical	Maximum Use Temperature, °C
Dichloropropionic Acid	65
Diesel Fuels	150
Diethyl Benzene	135
Diethyl Cellosolve	150
Diethyl Ether	100
Diethylamine	110
Diethylene Triamine	100
Diglycolic Acid	100
Diisobutyl Ketone	110
Diisobutylene	135
Dimethyl Formamide	120
Dimethyl Phthalate	100
Dimethyl Sulfate	65
Dimethyl Sulfoxide	100
Dimethylamine	50
Dimethylaniline	135
Dioctyl Phthalate	65
p-Dioxane	65
Diphenyl Ether	80
Divinyl Benzene	80
E	
Epichlorhydrin	65
Ether	100
Ethyl Acetate	65
Ethyl Alcohol	150
Ethylamine	40
Esters	65
Ethylacetoacetate	65
Ethyl Acrylate	100
Ethyl Chloride	150
Ethyl Chloroacetate	100
Ethyl Cyanoacetate	100
Ethylene Bromide	150
Ethylene Chloride	150
Ethylene Chlorohydrin	65
Ethylene Diamine	50
Ethylene Glycol	150
Ethylene Oxide	110
F	
Fatty Acids	150
Ferric Chloride (50% in H_2O)	150
Ferric Hydroxide	150
Ferric Nitrate	150
Ferric Sulfate	150
Ferrous Chloride	150
Ferrous Hydroxide	150
Ferrous Nitrate	150
Ferrous Sulfate	150
Fluorine (Gaseous)	40
Fluoroboric Acid	135
Fluosilicic Acid	135
Formaldehyde (37% in H_2O)	110
Formic Acid	135
FREON® 11	110
FREON® 12	110
FREON® 22	110
Fuel Oil	150
Fumaric Acid	95
Furane	65
Furfural	100
G	
Gallic Acid	100
Gas—Manufactured	150
Gas—Natural	150
Gasoline—Leaded	150
Gasoline—Sour	150
Gasoline—Unleaded	150
Glycerol	150
Glycol	135
Glycolic Acid	120
H	
Heptane	150
Hexane	150
Hydrazine	40
Hydrazine Dihydrochloride	50
Hydriodic Acid	150
Hydrobromic Acid (50%)	150
Hydrochloric Acid (20%)	150
Hydrochloric Acid (Conc.)	150
Hydrochloric Acid (Gas)	150
Hydrocyanic Acid	150
Hydrofluoric Acid (35%)	135

(Cont'd.)

Table 4.12. ***(Cont'd.)*** **Maximum Use Temperatures of ETFE with Various Chemicals**[7]

Chemical	Maximum Use Temperature, °C
Hydrofluoric Acid (70%)	120
Hydrofluoric Acid (100%)	110
Hydrofluorosilicic Acid	150
Hydrogen	150
Hydrogen Cyanide	150
Hydrogen Peroxide (30%)	120
Hydrogen Peroxide (90%)	65
Hydrogen Phosphide	65
Hydrogen Sulfide (Dry)	150
Hydrogen Sulfide (Wet)	150
Hydroquinone	120
Hypochlorous Acid	150
I	
Inert Gases	150
Iodine (Dry)	110
Iodine (Wet)	110
Iodoform	110
Isobutyl Alcohol	135
Isopropylamine	50
J	
Jet Fuel—JP4	110
Jet Fuel—JP5	110
L	
Lactic Acid	120
Lard Oil	150
Lauric Acid	120
Lauryl Chloride	135
Lauryl Sulfate	120
Lead Acetate	150
Linoleic Acid	135
Linseed Oil	150
Lithium Bromide (Saturated)	120
Lithium Hydroxide	150
Lubricating Oil	150
M	
Magnesium Carbonate	150
Magnesium Chloride	150
Magnesium Hydroxide	150
Magnesium Nitrate	150
Magnesium Sulfate	150
Maleic Acid	135
Maleic Anhydride	95
Malic Acid	135
Mercuric Chloride	135
Mercuric Cyanide	135
Mercuric Nitrate	135
Mercury	135
Methacrylic Acid	95
Methane	120
Methane Sulfonic Acid (50%)	110
Methyl Alcohol	150
n-Methylaniline	120
Methyl Benzoate	120
Methyl Bromide	150
Methyl Cellosolve®	150
Methyl Chloride	95
Methyl Chloroform	65
Methyl Chloromethyl Ether	80
Methyl Cyanoacetate	80
Methyl Ethyl Ketone	110
Methyl Isobutyl Ketone	110
Methyl Methacrylate	80
Methyl Salicylate	95
Methyl Sulfuric Acid	100
Methyl Trichlorosilane	95
Methylene Bromide	100
Methylene Chloride	100
Methylene Iodide	100
Mineral Oil	150
Monochlorobenzene	110
Monoethanolamine	65
Morpholine	65
N	
Naphtha	150
Naphthalene	150
Nickel Chloride	150
Nickel Nitrate	150
Nickel Sulfate	150
Nicotine	100
Nicotinic Acid	120
Nitric Acid (50%)	105
Nitric Acid (Conc. 70%)	120

(Cont'd.)

Table 4.12. ***(Cont'd.)*** **Maximum Use Temperatures of ETFE with Various Chemicals[7]**

Chemical	Maximum Use Temperature, °C
Nitric Acid—Sulfuric Acid (50/50)	100
Nitrobenzene	150
Nitrogen Dioxide	100
Nitrogen Gas	150
Nitromethane	100
Nitrous Acid	100
O	
Octane	150
Octene	150
Oleic Acid	135
Oleum	50
Oxalic Acid	110
Oxygen	150
Ozone (<1% in Air)	100
P	
Palmitic Acid	135
Perchlorethylene	135
Perchloric Acid (10%)	110
Perchloric Acid (72%)	65
Petrolatum	150
Petroleum	150
Petroleum Ether	100
Phenol (10%)	110
Phenol (100%)	100
Phenolsulfonic Acid	100
Phenylhydrazine	100
Phenylhydrazine Hydrochloride	100
o-Phenylphenol	100
Phosgene	100
Phosphoric Acid (30%)	150
Phosphoric Acid (85%)	135
Phosphorus Pentoxide	110
Phosphorus Oxychloride	100
Phosphorus Pentachloride	100
Phosphorus Trichloride	120
Phthalic Acid	100
Phthalic Anhydride	100
Picric Acid	50
Polyvinyl Acetate	150
Polyvinyl Alcohol	150

Chemical	Maximum Use Temperature, °C
Potassium Aluminum Chloride	150
Potassium Aluminum Sulfate (50%)	150
Potassium Bicarbonate	150
Potassium Borate	150
Potassium Bromate	150
Potassium Bromide	150
Potassium Carbonate	150
Potassium Chlorate	150
Potassium Chloride	150
Potassium Chromate	150
Potassium Cyanide	150
Potassium Dichromate	150
Potassium Ferrocyanide	150
Potassium Fluoride	150
Potassium Hydroxide (50%)	100
Potassium Hypochlorite	135
Potassium Nitrate	150
Potassium Perborate	135
Potassium Perchlorate	100
Potassium Permanganate	150
Potassium Persulfate	65
Potassium Sulfate	150
Potassium Sulfide	150
Propane	135
Propionic Acid	100
Propyl Alcohol	150
Propylene Dibromide	100
Propylene Dichloride	100
Propylene Glycol Methyl Ether	100
Propylene Oxide	65
Pyridine	65
Pyrogallol	65
S	
Salicylaldehyde	100
Salicylic Acid	120
Salt Brine	150
Sea Water	150
Silicon Tetrachloride	120
Silver Chloride	150
Silver Cyanide	150

(Cont'd.)

Table 4.12. ***(Cont'd.)*** **Maximum Use Temperatures of ETFE with Various Chemicals[7]**

Chemical	Maximum Use Temperature, °C
Silver Nitrate	150
Sodium Acetate	150
Sodium Benzene-Sulfonate	150
Sodium Benzoate	150
Sodium Bicarbonate	150
Sodium Bisulfate	150
Sodium Bisulfite	150
Sodium Borate	100
Sodium Bromide	150
Sodium Carbonate	150
Sodium Chlorate	150
Sodium Chloride	150
Sodium Chromate	150
Sodium Cyanide	150
Sodium Dichromate (Alkaline)	100
Sodium Ferricyanide	150
Sodium Ferrocyanide	150
Sodium Fluoride	150
Sodium Glutamate	135
Sodium Hydroxide (10%)	110
Sodium Hydroxide (50%)	110
Sodium Hypochlorite	150
Sodium Hyposulfite	150
Sodium Iodide	150
Sodium Lignosulfonate	150
Sodium Metasilicate	150
Sodium Nitrate	150
Sodium Nitrite	150
Sodium Perborate	100
Sodium Perchlorate	65
Sodium Peroxide	150
Sodium Persulfate	80
Sodium Phosphate	150
Sodium Silicate	150
Sodium Silicofluoride	150
Sodium Sulfate	150
Sodium Sulfide	150
Sodium Sulfite	150
Sodium Thiosulfate	150
Sorbic Acid	135
Sour Crude Oil	150

Chemical	Maximum Use Temperature, °C
Stannic Chloride	150
Stannous Chloride	150
Stannous Fluoride	120
Stearic Acid	150
Stoddard's Solvent	135
Styrene Monomer	100
Succinic Acid	135
Sulfamic Acid	100
Sulfur (Molten)	120
Sulfur Dioxide	110
Sulfur Trioxide (Liquid)	25
Sulfuric Acid (60%)	150
Sulfuric Acid (Conc.)	150
Sulfuric Acid (Fuming—Oleum)	50
Sulfurous Acid	110
T	
Tall Oil	150
Tannic Acid	135
Tartaric Acid	135
2,3,4,6-Tetrachlorophenol	100
Tetraethyl Lead	150
Tetrahydrofuran	100
Tetramethyl Ammonium Hydroxide (50%)	100
Tin Tetrachloride	110
Toluene	120
Tributyl Phosphate	65
Trichloracetic Acid	100
Trichloroethylene	135
Trichloromethane	100
2,4,5-Trichlorophenol	100
Triethylamine	110
Triethylamine	110
Trisodium Phosphate	135
Thionyl Chloride	100
Titanium Dioxide	150
Titanium Tetrachloride	100
Turpentine	135
U	
UDMH-Hydrazine (50/50)	50
Urea (50% H_2O)	135

(Cont'd.)

Table 4.12. ***(Cont'd.)*** **Maximum Use Temperatures of ETFE with Various Chemicals[7]**

Chemical	Maximum Use Temperature, °C
V	
Varsol	135
Vinyl Acetate	135
Vinyl Chloride (Monomer)	65
W	
Water	150
Water Sewage	135
Wax	150
X	
Xylene	120
Z	
Zinc Acetate	120
Zinc Chloride	150
Zinc Hydrosulfite (10%)	120
Zinc Nitrate	150
Zinc Sulfate	150
Zinc Sulfide	150
PLATING SOLUTIONS	
Brass	135
Cadmium	135
Chrome	135
Copper	135
Gold	135

Table 4.13. Effect of Immersion in Various Chemicals on ETFE[7]

Chemical	Boiling Point, °C	Test Temp., °C	Days	Retained Properties—%		
				Tensile Strength	Elong.	Weight Gain
Acid/Anhydrides						
Acetic Acid (Glacial)	118	118	7	82	80	3.4
Acetic Anhydride	139	139	7	100	100	0
Trichloroacetic Acid	196	100	7	90	70	0
Trichloroacetic Acid	196	120	30	100	100	—
Aliphatic Hydrocarbons						
Mineral Oil	—	180	7	90	60	0
Naphtha	—	100	7	100	100	0.5
Aromatic Hydrocarbons						
Benzene	80	80	7	100	100	0
Toluene	110	110	7	—	—	—
Functional Aromatics						
O-Cresol	191	180	7	100	100	0
Amines						
Aniline	185	120	7	81	99	2.7
Aniline	185	120	30	93	82	—
Aniline	185	180	7	95	90	—
N,N-Dimethylaniline	190	120	7	82	97	—
N-Methylaniline	195	120	7	85	95	—
N-Methylaniline	195	120	30	100	100	—

NOTES: Change in properties of 15% is considered insignificant. Samples were 10–15 mil microtensile bars. TS/E and wt. gain determined within 24 hours after removal from exposure media.

(Cont'd.)

Table 4.13. ***(Cont'd.)*** **Effect of Immersion in Various Chemicals on ETFE[7]**

Chemical	Boiling Point, °C	Test Temp., °C	Days	Retained Properties—%		
				Tensile Strength	Elong.	Weight Gain
n-Butylamine	78	78	7	71	73	4.4
Di-n-Butylamine	159	120	7	81	96	—
Di-n-Butylamine	159	120	30	100	100	—
Di-n-Butylamine	159	160	7	55	75	—
Tri-n-Butylamine	216	120	7	81	80	—
Tri-n-Butylamine	216	120	30	100	100	—
Pyridine	116	116	7	100	100	1.5
Chlorinated Solvents						
Carbon Tetrachloride	78	78	7	90	80	4.5
Chloroform	62	61	7	85	100	4.0
Dichloroethylene	77	32	7	95	100	2.8
FREON® 113	46	46	7	100	100	0.8
Methylene Chloride	40	40	7	85	85	0
Ethers						
Tetrahydrofuran	66	66	7	86	93	3.5
Aldehyde/Ketones						
Acetone	56	56	7	80	83	4.1
Acetophenone	201	180	7	80	80	1.5
Cyclohexanone	156	156	7	90	85	0
Methyl Ethyl Ketone	80	80	7	100	100	0
Esters						
n-Butyl Acetate	127	127	7	80	60	0
Ethyl Acetate	77	77	7	85	60	0
Polymer						
Dimethylformamide	154	90	7	100	100	1.5
Dimethylformamide	154	120	7	76	92	5.5
Dimethylsulfoxide	189	90	7	95	90	1.5
Other Organics						
Benzoyl Chloride	197	120	7	94	95	—
Benzoyl Chloride	197	120	30	100	100	—
Benzyl Alcohol	205	120	7	97	90	—
Decalin	190	120	7	89	95	—
Phthaloyl	276	120	30	100	100	0
Acids						
Aqua Regia	—	90	6 hrs	93	89	0.2
Chromic	125	125	7	66	25	—
Hydrobromic (Conc)	125	125	7	100	100	—
Hydrochloric (Conc)	106	23	7	100	90	0

NOTES: Change in properties of 15% is considered insignificant. Samples were 10–15 mil microtensile bars. TS/E and wt. gain determined within 24 hours after removal from exposure media.

(Cont'd.)

Table 4.13. ***(Cont'd.)*** **Effect of Immersion in Various Chemicals on ETFE[7]**

Chemical	Boiling Point, °C	Test Temp., °C	Days	Retained Properties—%		
				Tensile Strength	Elong.	Weight Gain
Hydrochloric (Conc)	106	106	7	96	100	0.1
Hydrofluoric (Conc)	—	23	7	97	95	0.1
Nitric—25%	100	100	14	100	100	—
Nitric—50%	105	105	14	87	81	—
Nitric—70% (Conc)	120	23	105	100	100	0.5
Nitric—70% (Conc)	120	60	53	100	100	—
Nitric—70% (Conc)	120	120	2	72	91	—
Nitric—70% (Conc)	120	120	3	58	5	—
Nitric—70% (Conc)	120	120	7	0	0	—
Phosphoric (Conc)	—	100	7	—	—	—
Phosphoric (Conc)	—	120	7	94	93	0
Sulfuric (Conc)	—	100	7	100	100	0
Sulfuric (Conc)	—	120	7	98	95	0
Sulfuric (Conc)	—	150	6 hrs	98	90	0
Halogens						
Bromine (Anhy)	59	23	7	90	90	1.2
Bromine (Anhy)	59	57	7	99	100	—
Bromine (Anhy)	59	57	30	94	93	3.4
Chlorine (Anhy)	—	120	7	85	84	7
Bases						
Ammonium Hydroxide	—	66	7	97	97	0
Potassium Hydroxide (20%)	—	100	7	100	100	0
Sodium Hydroxide (50%)	—	120	7	94	80	0.2
Peroxides						
Hydrogen Peroxide (30%)	—	23	7	99	98	0
Salt-Metal Etchants						
Ferric Chloride (25%)	104	100	7	95	95	0
Zinc Chloride (25%)	104	100	7	100	100	0
Other Inorganics						
Sulfuryl Chloride	68	68	7	86	100	8
Phosphoric Trichloride	75	75	7	100	98	—
Phosphoric Oxychloride	104	104	7	100	100	—
Silicon Tetrachloride	60	60	7	100	100	—
Water	100	100	7	100	100	0
Miscellaneous						
Skydrol	—	149	7	100	95	3.0
Aerosafe	—	149	7	92	93	3.9
A-20 Stripper Solution	—	140	7	90	90	—

NOTES: Change in properties of 15% is considered insignificant. Samples were 10–15 mil microtensile bars. TS/E and wt. gain determined within 24 hours after removal from exposure media.

Table 4.14. Hydrolytic Stability of ETFE to Boiling Water[8]

Resin	Length of Exposure, Hours	Tensile Strength, MPa	Elongation, %
Unfilled ETFE	0 3,000	40 40	145 135
Filled ETFE (containing 25% weight glass fiber)	0 1,000 2,000 3,000	82 60 57.6 55.8	7 5 5 5

Table 4.15. Maximum Use Temperature of Polyvinylidene Fluoride (PVDF) with Various Chemicals[9]

Chemical Substance	Concentration	Maximum Temp., °C
A		
Acetaldehyde		NR
Acetamide		25
Acetic Acid		50
Acetic Acid	10% in water	110
Acetic Acid	50% in water	95
Acetic Acid	80% in water	80
Acetic Anhydride		NR
Acetone		NR
Acetone	10% in water	50
Acetonitrile		50
Acetophenone		NR
Acetyl Bromide		50
Acetyl Chloride		50
Acetylacetone		NR
Acetylene		120
Acrylonitrile		25
Adipic Acid		65
Air		140
Alcoholic Spirits	40% Ethyl Alcohol	95
Allyl Alcohol		50
Allyl Chloride		100
Aluminum Acetate	Aqueous solution or solid	135
Aluminum Bromide		135
Aluminum Chloride	Up to 40% in water	135
Aluminum Fluoride	Aqueous solution or solid	135
Aluminum Hydroxide		135
Aluminum Nitrate	Aqueous solution or solid	135
Aluminum Oxychloride		135
Aluminum Sulfate	Aqueous solution or solid	135
Ammonia, Gas		NR
Ammonia, Liquid		NR
Ammonium Acetate	Aqueous solution or solid	80
Ammonium Alum	Aqueous solution or solid	135
Ammonium Bifluoride	Aqueous solution or solid	65
Ammonium Bromide	Aqueous solution or solid	120
Ammonium Carbonate	Aqueous solution or solid	135

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals**[9]

Chemical Substance	Concentration	Maximum Temp., °C
Ammonium Chloride	Aqueous solution or solid	135
Ammonium Dichromate	Aqueous solution or solid	120
Ammonium Fluoride	Aqueous solution or solid	135
Ammonium Hydroxide	Up to "concentrated"	110
Ammonium Metaphosphate	Aqueous solution or solid	135
Ammonium Nitrate	Aqueous solution or solid	135
Ammonium Persulfate	Aqueous solution or solid	25
Ammonium Phosphate	Aqueous solution or solid	135
Ammonium Sulfate	Aqueous solution or solid	135
Ammonium Sulfide	Aqueous solution or solid	50
Ammonium Thiocyanate	Aqueous solution or solid	135
Amyl Acetate		50
Amyl Alcohol		135
Sec-Amyl Alcohol		50
Amyl Chloride		135
Aniline		50
Aniline Hydrochloride	Aqueous solution or solid	25
Aqua Regia		25
Arsenic Acid	Aqueous solution	135
Asphalt		120
B		
Barium Carbonate		135
Barium Chloride	Aqueous solution or solid	135
Barium Hydroxide		135
Barium Nitrate	Aqueous solution or solid	135
Barium Sulfate		135
Barium Sulfide		135
Beer		95
Beet Sugar Liquors		110
Benzaldehyde		20
Benzene		75
Benzenesulfonic Acid	Aqueous solution or solid	50
Benzoic Acid		110
Benzoyl Chloride		75
Benzoyl Peroxide		75
Benzyl Alcohol		120
Benzyl Chloride		135
Benzyl Ether		40
Benzylamine	Aqueous solution or liquid	25
Black Liquor		80
Bleaching Agents		135
Borax		135
Boric Acid		135
Boron Trifluoride		25
Brine		135
Brine, acid		135
Brine, basic		135
Brine, chlorinated acid		95
Bromic Acid	Aqueous solution	95
Bromine dry gas		65
Bromine, liquid		65
Bromine, Water		100
Bromobenzene		65
Bromoform		65
m-Bromotoluene		80
Butadiene		120
Butane		120
Butanediol	Aqueous solution or liquid	135

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals**[9]

Chemical Substance	Concentration	Maximum Temp., °C
Butyl Acetate		25
Butyl Alcohol	Aqueous solution or liquid	110
sec-Butyl Alcohol	Aqueous solution or liquid	95
t-Butyl Alcohol	Aqueous solution or liquid	95
Butyl Acrylate		50
Butyl Bromide		135
Butyl Chloride		135
Butyl Ether		40
Butyl Mercaptan		135
Butyl Stearate		40
Butylamine	Aqueous solution or liquid	NR
sec-Butylamine	Aqueous solution or liquid	20
t-Butylamine	Aqueous solution or solid	20
1-Butylene		135
Butylphenol		110
Butyraldehyde		65
Butyric Acid		110
C		
Calcium Acetate	Aqueous solution or solid	135
Calcium Bisulfate	Aqueous solution or solid	135
Calcium Bisulfite	Aqueous solution or solid	135
Calcium Bromide	Aqueous solution or solid	135
Calcium Carbonate		135
Calcium Chlorate	Aqueous solution or solid	135
Calcium Chloride	Aqueous solution or solid	135
Calcium Hydroxide		135
Calcium Hypochlorite	Aqueous solution or solid	95
Calcium Nitrate	Aqueous solution or solid	135
Calcium Oxide		120
Calcium Phosphate		135
Calcium Sulfate		135
Cane Sugar Liquors		135
Caprylic Acid		80
Carbon Dioxide		135
Carbon Disulfide		25
Carbon Monoxide		135
Carbon Tetrachloride		135
Carbonic Acid		135
Casein		135
Castor Oil		135
Chloral Hydrate		25
Chlorinated Phenol		65
Chlorine	5% in CCl_4	95
Chlorine, gas		95
Chlorine, liquid		95
Chlorine Dioxide		65
Chlorine Water		110
Chloroacetic Acid	Aqueous solution or pure	NR
Chloroacetyl Chloride		50
Chlorobenzene		75
Chlorobenzene-sulfonic Acid	Aqueous solution or pure	95
Chlorobenzyl Chloride		50
Chlorofluorocarbon 11		95
Chlorofluorocarbon 12		95
Chlorofluorocarbon 13		95

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
Chlorofluorocarbon 14		95
Chlorofluorocarbon 21		95
Chlorofluorocarbon 22		95
Chlorofluorocarbon 113		95
Chlorofluorocarbon 114		95
Chloroform		50
6-Chlorohexanol		75
Chlorohydrin		50
Chloropicrin		65
Chlorosulfonic Acid		NR
Chlorotrimethylsilane		50
Chrome Alum	Aqueous solution or solid	95
Chromic Acid	Up to 40% in water	80
Chromic Acid	50% in water	50
Chromyl Chloride		50
Cider		60
Citric Acid	Aqueous solution or solid	135
Coal Gas		110
Coconut Oil		135
Copper Acetate	Aqueous solution or solid	120
Copper Carbonate, basic		135
Copper Chloride	Aqueous solution or solid	135
Copper Cyanide		135
Copper Fluoride		135
Copper Nitrate	Aqueous solution or solid	135
Copper Sulfate	Aqueous solution or solid	135
Corn Oil		135
Corn Syrup		120
Cottonseed Oil		135
Cresol		65
Cresylic Acid		65
Crotonaldehyde		50
Crude Oil		135
Cryolite		120
Cuprous Chloride		120
Cyclohexane		135
Cyclohexanol		65
Cyclohexanone		25
Cyclohexyl Acetate		95
D		
Decane		120
Dextrin	Aqueous solution or solid	120
Diacetone Alcohol		25
p-Dibromobenzene		95
1,2-Dibromopropane		95
Dibutyl Phthalate		NR
Dibutyl Sebacate		NR
Dibutylamine	Aqueous solution or liquid	20
Dichloroacetic Acid	Aqueous solution or liquid	50
o-Dichlorobenzene		65
Dichlorodimethylsilane		50
Dichloroethylene		110
2,2-Dichloropropionic Acid		50
αα-Dichlorotoluene		65
Diesel Fuels		135
Diethanolamine	Aqueous solution or liquid	NR

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
Diethylamine	Aqueous solution or liquid	25
Diethyl Malonate		NR
Diethylenetriamine	Aqueous solution or liquid	50
Diglycolic Acid		25
Diisobutyl Ketone		95
Diisobutylene		135
Diisopropyl Ketone		20
Dimethyl Acetamide		NR
Dimethyl Formamide		NR
Dimethyl Phthalate		25
Dimethyl Sulfate		25
Dimethyl Sulfoxide		
Dimethylamine	Aqueous soluton or gas	25
Dimethylaniline		25
2,6—Dimehyl-4-heptanol		95
2,5-Dimethyl-1,5-hexadiene		120
Dioctyl Phthalate		25
1,4,1,4-Dioxane		NR
Dioxolane		NR
Dipropylene Glycol Methyl Ether		25
Disodium Phosphate	Aqueous solution or solid	95
Divinyl Benzene		50
E		
Epichlorohydrin		NR
Epsom Salts	Aqueous solution or solid	80
Ethanethiol		25
Ethanolamine	Aqueous solution or liquid	NR
2-Ethoxyethyl Acetate	Aqueous solution or liquid	95
Ethyl Acetate		NR
Ethyl Acetoacetate		25
Ethyl Acrylate		25
Ethyl Alcohol	Aqueous solution or liquid	135
Ethyl Chloride		135
Ethyl Chloroacetate		25
Ethyl Chloroformate		50
Ethyl Cyanoacetate		25
Ethyl Ether		50
Ethyl Formate		25
Ethylbenzene		50
Ethylene Chlorohydrin	Aqueous solution or liquid	25
Ethylene Dichloride		135
Ethylene Glycol	Aqueous solution or liquid	135
Ethylene Oxide		NR
Ethylenediamine	Aqueous solution or liquid	110
2-Ethyl-1-hexanol		120
F		
Fatty Acids		135
Fatty Acids, Sulfonates		80
Ferric Chloride	Aqueous solution or solid	135
Ferric Hydroxide		120
Ferric Nitrate	Aqueous solution or solid	135
Ferric Sulfate		135
Ferric Sulfide		120
Ferrous Chloride	Aqueous solution or solid	135
Ferrous Hydroxide		120
Ferrous Nitrate	Aqueous solution or solid	135

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
Ferrous Sulfate		135
Fluorine		25
Fluoroboric Acid	Aqueous solution	135
Fluorosilic Acid		135
Formaldehyde	37% in water	50
Formic Acid	Aqueous solution or liquid	120
Fructose	Aqueous solution or solid	135
Fruit Juices, pulp		95
Fuel Oil		135
Fumaric Acid		65
Furan		NR
Furfural		25
Furfuryl Alcohol	Aqueous solution or liquid	40
G		
Gallic Acid		25
Gas, manufactured		135
Gas, natural		135
Gasoline, leaded		135
Gasoline, sour		135
Gasoline, unleaded		135
Gelatin		120
Gin		95
Glucose	Aqueous solution or solid	135
Glue		120
Glutamic Acid		95
Glycerin	Aqueous solution or liquid	135
Glycine	Aqueous solution or solid	25
Glycolic Acid		25
H		
Heptane		135
Hexachloro-1,3-butadiene		50
Hexamethylene-diamine		NR/50
Hexamethylphosphotriamide		NR
Hexane		135
Hexyl Alcohol		80
Hydrazine	Aqueous solution or liquid	95
Hydrazine Dihydrochloride	Aqueous solution or solid	25
Hydrazine Hydrate	Aqueous solution or liquid	50
Hydriodic Acid	Aqueous solution	135
Hydrobromic Acid	Up to 50% in water	135
Hydrochloric Acid	Up to "concentrated"	135
Hydrocyanic Acid	Aqueous solution	135
Hydrofluoric Acid	Up to 40% in water	120
Hydrofluoric Acid	41%–100% in water	95
Hydrogen		135
Hydrogen Chloride		135
Hydrogen Cyanide		135
Hydrogen Fluoride		95
Hydrogen Peroxide	Up to 30% in water	95
Hydrogen Peroxide	90% in water	20
Hydrogen Sulfide		135
Hydrogen Sulfide	Aqueous solution	110
Hydroquinone		120
Hypochlorous Acid	Aqueous solution	20

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals**[9]

Chemical Substance	Concentration	Maximum Temp., °C
I		
Iodine	10% in Non-aqueous solvent	65
Iodine, gas		65
Iodoform		95
Isoamyl Ether		120
Isobutyl Alcohol		120
Isooctane		120
Isophorone		80
Isopropyl Alcohol	Aqueous solution or liquid	60
Isopropyl Chloride		40
Isopropyl Ether		50
Isopropylbenzene		40
J		
Jet Fuel (JP4, JP5)		95
K		
Kerosene		135
L		
Lactic Acid	Aqueous solution or pure	50
Lanolin		120
Lard Oil		135
Lauric Acid		110
Lauroyl Chloride		120
Lauryl Mercaptan		95
Lauryl Sulfate		120
Lead Acetate	Aqueous solution or solid	135
Lead Chloride		120
Lead Nitrate	Aqueous solution or solid	120
Lead Sulfate		120
Lemon Oil		120
Linoleic Acid		120
Linseed Oil		135
Lithium Bromide	Aqueous solution or solid	110
Lithium Chloride	Aqueous solution or solid	120
Lubricating Oil		135
M		
Magnesium Carbonate		135
Magnesium Chloride	Aqueous solution or solid	135
Magnesium Citrate		120
Magnesium Hydroxide		135
Magnesium Nitrate	Aqueous solution or solid	135
Magnesium Sulfate	Aqueous solution or solid	135
Maleic Acid	Aqueous solution or solid	120
Maleic Anhydride		25
Malic Acid	Aqueous solution or solid	120
Manganese Sulfate	Aqueous solution or solid	120
Mercuric Chloride		120
Mercuric Cyanide		120
Mercuric Nitrate	Aqueous solution or solid	135
Mercury		135
Methacrylic Acid		50
Methane		135
Methanesulfonic Acid	Aqueous solution or liquid	95
Methyl Acetate		40
Methyl Acrylate		40
Methyl Alcohol	Aqueous solution or liquid	135
Methyl Bromide		135
Methyl Chloride		135
Methyl Chloroacetate		25
Methyl Chloromethyl Ether		25

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals**[9]

Chemical Substance	Concentration	Maximum Temp., °C
Methyl Ethyl Ketone		NR
Methyl Isobutyl Ketone		NR
Methyl Methacrylate		50
Methyl Salicylate		65
Methylamine		NR
Methylchloroform		50
Methylene Bromide		80
Methylene Chloride		NR
Methylene Iodine		95
Methylsufuric Acid	Aqueous solution or liquid	50
Methyltrichlorosilane		65
Milk		110
Mineral Oil		135
Motor Oil		135
Molasses		65
Morpholine	Aqueous solution or liquid	25
N		
Naphtha		135
Naphthalene		95
Nickel Acetate	Aqueous solution or solid	120
Nickel Chloride	Aqueous solution or solid	135
Nickel Nitrate	Aqueous solution or solid	135
Nickel Sulfate	Aqueous solution or solid	135
Nicotine		20
Nicotinic Acid		120
Nitric Acid	Up to 10% in water	50
Nitric Acid	11-50% in water	50
Nitric Acid	"Concentrated"	NR
Nitric Acid, fuming		NR
Nitrobenzene		25
Nitroethane		20
Nitrogen		135
Nitrogen Dioxide		75
Nitroglycerin		50
Nitromethane		50
Nitrotoluene		80
Nitrous Oxide		NR
O		
Octane		135
Octene		135
Oleic Acid		120
Oleum		NR
Olive Oil		120
Oxalic Acid		50
Oxygen		135
Ozone		110
P		
Palm Oil		95
Palmitic Acid		120
Paraffin		120
Paraffin Oil		120
Peanut Oil		120
Perchloric Acid	10% in water	95
Perchloric Acid	70% in water	50
Perchloroethylene		135
Perchloromethyl Mercaptan		50
Petrolatum		135
Petroleum		120
Phenol	5% in water	80
Phenol		50
1-Phenol-2-sulfonic Acid		50
Phenyl Ether		50
Phenylhydrazine		50
Phenylhydrazine Hydrochloride	Aqueous solution or solid	50
o-Phenylphenol		80
Phosgene		80

(Cont'd.)

Table 4.15. *(Cont'd.)* Maximum Use Temperature of PVDF with Various Chemicals[9]

Chemical Substance	Concentration	Maximum Temp., °C
Phosphoric Acid	Less than 85% in water	135
Phosphoric Acid	85% in water	110
Phosphorus, red		25
Phosphorus, Oxychloride		NR
Phosphorus, Pentachloride		95
Phosphorus, Pentoxide		95
Phosphorus, Trichloride		95
Phthalic Acid		95
Picric Acid		25
Plating Solutions: Brass		95
Plating Solutions: Cadmium		95
Plating Solutions: Chrome		95
Plating Solutions: Copper		95
Plating Solutions: Iron		95
Plating Solutions: Lead		95
Plating Solutions: Nickel		95
Plating Solutions: Rodium		95
Plating Solutions: Silver		95
Plating Solutions: Speculum		95
Plating Solutions: Tin		95
Plating Solutions: Zinc		95
Polyethylene Glycol		95
Polyvinyl Acetate		135
Polyvinyl Alcohol		135
Potassium		NR

Chemical Substance	Concentration	Maximum Temp., °C
Potassium Acetate	Aqueous solution or solid	135
Potassium Alum	Aqueous solution or liquid	135
Potassium Aluminum Chloride		135
Potassium Bicarbonate	Aqueous solution or solid	95
Potassium Bisulfate	Aqueous solution or solid	135
Potassium Borate	Aqueous solution or solid	135
Potassium Bromate	Aqueous solution or solid	135
Potassium Bromide	Aqueous solution or solid	135
Potassium Carbonate	Aqueous solution or solid	135
Potassium Chlorate		95
Potassium Chloride	Aqueous solution or solid	135
Potassium Chromate	Aqueous solution or solid	135
Potassium Cyanide	Aqueous solution or solid	135
Potassium Dichromate		135
Potassium Ferricyanide	Aqueous solution or solid	135
Potassium Ferrocyanide	Aqueous solution or solid	135
Potassium Fluoride	Aqueous solution or solid	135
Potassium Hydroxide	Up to 10% in water	85
Potassium Hydroxide	Greater than 50% in water	NR
Potassium Hypochlorite	Aqueous solution	95
Potassium Iodide	Aqueous solution or solid	120
Potassium Nitrate	Aqueous solution or solid	135

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
Potassium Perborate		135
Potassium Perchlorate		95
Potassium Permanganate	Aqueous solution or solid	120
Potassium Persulfate		50
Potassium Sulfate	Aqueous solution or solid	135
Potassium Sulfide		135
Propane		135
Propyl Acetate		40
Propyl Alcohol	Aqueous solution or liquid	65
Propylamine		NR
Propylene Dibromide		95
Propylene Dichloride		95
Propylene Glycol	Aqueous solution or liquid	65
Propylene Oxide		NR
Pyridine		NR
Pyrogallol	Aqueous solution or solid	50
S		
Salicylaldehyde		50
Salicylic Acid		95
Selenic Acid	Aqueous solution or pure	65
Silicon Tetrachloride		50
Silicone Oil		120
Silver Cyanide		135
Silver Nitrate	Aqueous solution or solid	135
Silver Sulfate		120
Sodium		NR
Sodium Acetate	Aqueous solution or solid	135
Sodium Amalgam		NR
Sodium Benzoate	Aqueous solution or solid	135
Sodium Bicarbonate	Aqueous solution or solid	135
Sodium Bisulfate	Aqueous solution or solid	135
Sodium Bisulfite	Aqueous solution or solid	135
Sodium Bromate	Aqueous solution or solid	95
Sodium Bromide	Aqueous solution or solid	135
Sodium Carbonate	Aqueous solution or solid	135
Sodium Chlorate	Aqueous solution or solid	120
Sodium Chlorite	Aqueous solution or solid	120
Sodium Chromate	Aqueous solution or solid	95
Sodium Cyanide	Aqueous solution or solid	135
Sodium Dichromate	Aqueous solution or solid	95
Sodium Dithionite	Aqueous solution or solid	40
Sodium Ferricyanide	Aqueous solution or solid	135
Sodium Ferrocyanide	Aqueous solution or solid	135
Sodium Fluoride	Aqueous solution or solid	135
Sodium Fluosilcate		95
Sodium Hydrogen Phosphate	Aqueous solution or solid	120
Sodium Hydroxide	Up to 10% in water	85
Sodium Hydroxide	Greater than 50% in water	NR
Sodium Hypochlorite	Up to 5% in water	135
Sodium Hypochlorite	6%–15% in water	95

(Cont'd.)

Table 4.15. *(Cont'd.)* **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
Sodium Iodide	Aqueous solution or solid	135
Sodium Nitrate	Aqueous solution or solid	135
Sodium Nitrite	Aqueous solution or solid	135
Sodium Palmitate		120
Sodium Perchlorate	Aqueous solution or solid	120
Sodium Peroxide		95
Sodium Phosphate	Aqueous solution or solid	135
Sodium Thiocyanate	Aqueous solution or solid	120
Sodium Thiosulfate	Aqueous solution or solid	135
Sour Crude Oil		135
Soybean Oil		120
Stannic Chloride	Aqueous solution or liquid	135
Stannous Chloride	Aqueous solution or solid	135
Starch		95
Stearic Acid		135
Stilbene		80
Styrene		85
Succinic Acid		65
Sugar Syrup		135
Sulfur		120
Sulfur Chloride		25
Sulfur Dichloride		25
Sulfur Dioxide		80
Sulfur Trioxide		NR
Sulfuric Acid	Up to 60% in water	120
Sulfuric Acid	80%–93% in water	95
Sulfuric Acid	98% in water	65
Sulfuric Acid, fuming		NR
Sulfuryl Chloride		NR
Sulfuryl Fluoride		25
T		
Tall Oil		135
Tallow		135
Tannic Acid		110
Tar		120
Tartaric Acid	Aqueous solution or solid	120
1,1,2,2-Tetrabromoethane		120
1,1,2,2-Tetrachloroethane		120
2,3,4,6-Tetrachlorophenol		65
Tetraethyllead		135
Tetrahydrofuran	Aqueous solution or liquid	NR
Tetramethylammonium Hydroxide	Up to 10% in water	95
Tetramethylurea		NR
Thioglycol		25
Thioglycolic Acid		80
Thionyl Chloride		NR
Thiophosphoryl Chloride		NR
Thread Cutting Oils		95
Titanium Tetrachloride		65
Toluene		80
Toluenesulfonyl Chloride		50
Tomato Juice		95
Tributyl Phosphate		25
Trichloroacetic Acid	Up to 10% in water	95
Trichloroacetic Acid	50% in water to pure	50
1,2,4-Trichlorobenzene		95
1,1,2-Trichloroethane		65
Trichloroethylene		135

(Cont'd.)

Table 4.15. ***(Cont'd.)*** **Maximum Use Temperature of PVDF with Various Chemicals[9]**

Chemical Substance	Concentration	Maximum Temp., °C
2,4,5-Trichlorophenol		65
Tricresyl Phosphate		NR
Triethanolamine	Aqueous solution or liquid	50
Triethyl Phosphate		NR
Triethylamine		50
Trifluoroacetic Acid	50% in water	95
Trifluoroacetic Acid		50
Trimethylamine	Aqueous solution or gas	65
Turpentine		135
U		
Urea	Aqueous solution or solid	120
V		
Varnish		120
Varsol		120
Vegetable Oil		135
Vinegar		110
Vinyl Acetate		120
Vinyl Chloride		95
Vinylidene Chloride		95
W		
Water		135
Water, salt		135
Water, sewage		120
Whiskey		95
Wine		95
X		
Xylene		95
Z		
Zinc Acetate	Aqueous solution or solid	120
Zinc Bromide	Aqueous solution or solid	120
Zinc Chloride	Aqueous solution or solid	135
Zinc Nitrate	Aqueous solution or solid	135
Zinc Sulfate	Aqueous solution or solid	135

Table 4.16. Chemical Compatibility of Ethylene Chlorotrifluoroethylene (ECTFE) Copolymer[10]

Chemical Name	Retained Properties				
	Test Temp., °C	Tensile Strength	Elongation	Weight Gain, %	Color Change
Acetic Acid	140	I	I	3.4	1
Ammonium Hydroxide, 30%	140	I	I	1.2	2
Butanol n	121	I	I	1.9	1
Chromic Acid, 30%	100	I	I	0.0	2
Hydrochloric Acid, 37%	100	I	I	0.7	3
Hydrofluoric Acid, 49%	100	I	I	0.2	2
Hydrogen Peroxide (60%)	30	I	I	0.3	1
Methanol	50	I	I	0.4	1
n-Methylpyrrolidone	20	I	I	1.5	1
Methylene Chloride	50	I	I	4.1	1
Nitric Acid, 10%	121	I	I	0.4	1
Nitric Acid, 90%	71	I	I	2.3	2
Phosphoric Acid, 85%	140	I	I	-0.1	2
Potassium Hydroxide, 50%	121	I	I	-0.1	2
Propanol *	50	I	I	0.16	1
Sodium Hydroxide, 50%	132	I	I	-0.2	2
Sodium Hypochlorite, 5%	121	I	I	0.1	1
Sulfuric Acid, 98%	121	I	I	0.7	3
Toluene	20	I	I	0.7	1

* tested for 28 days; all others tested at 30 days. Values are comparable.

LEGEND

RETAINED PROPERTIES:	COLOR CHANGE:
I – Insignificant	**1**- no change **2**- any shade of tan **3**- brown or black

Table 4.17. Room Temperature Swelling of PVF in Organic Solvents[11]

Solvent	Swelling, wt%
Ethanol	4.8
Acetone	7.0
Dimethyl Formamide	32.3

4.4.3 Testing

4.4.3.1 Coupon Testing

The simplest form of compatibility test is to immerse standard ASTM coupons in a liquid or vapor in the lab. Coupons can be installed in the field in a stream. However making a coupon assembly for installation in a pipe or a vessel may be difficult and persuading plant operators even more so. Lab testing is easy to carry out but will not replicate real life conditions such as flow, agitation, stress (compression for gaskets) and one-sided exposure. For this reason, lab dunk tests are usually done for screening reasons. Application temperature is easy to achieve by space heaters.

The coupons are weighed and dimensions carefully measured prior to exposure. Usually the solution is changed once a week and the test is carried out for a period of one month to six weeks. Often multiple coupons are used and some coupons removed after one week for physical and mechanical testing. Figures 4.1a, b, c, and d show a typical assemblies of a test setup.

Field testing for one-sided panels are conducted by using lined manway covers or blind flanges as shown in Fig. 4.2. Coupons are observed for any obvious signs of degradation such blistering, cracking, and discoloration. Pictorial records are important. The coupons are then tested for change in weight, dimensions, retained tensile strength, elongation, and hardness although it is not uncommon to monitor only weight and dimension changes. Table 4.18 lists the standard mechanical tests. Changes in the properties are plotted against time to identify trends, particularly to see if the curves flatten. Information obtained by testing is used for comparative evaluation of different candidates only, although excessive change in one or more properties may disqualify the candidate altogether. The PDL criteria (in Appendix V) can be useful. Consulting experts is also recommended.

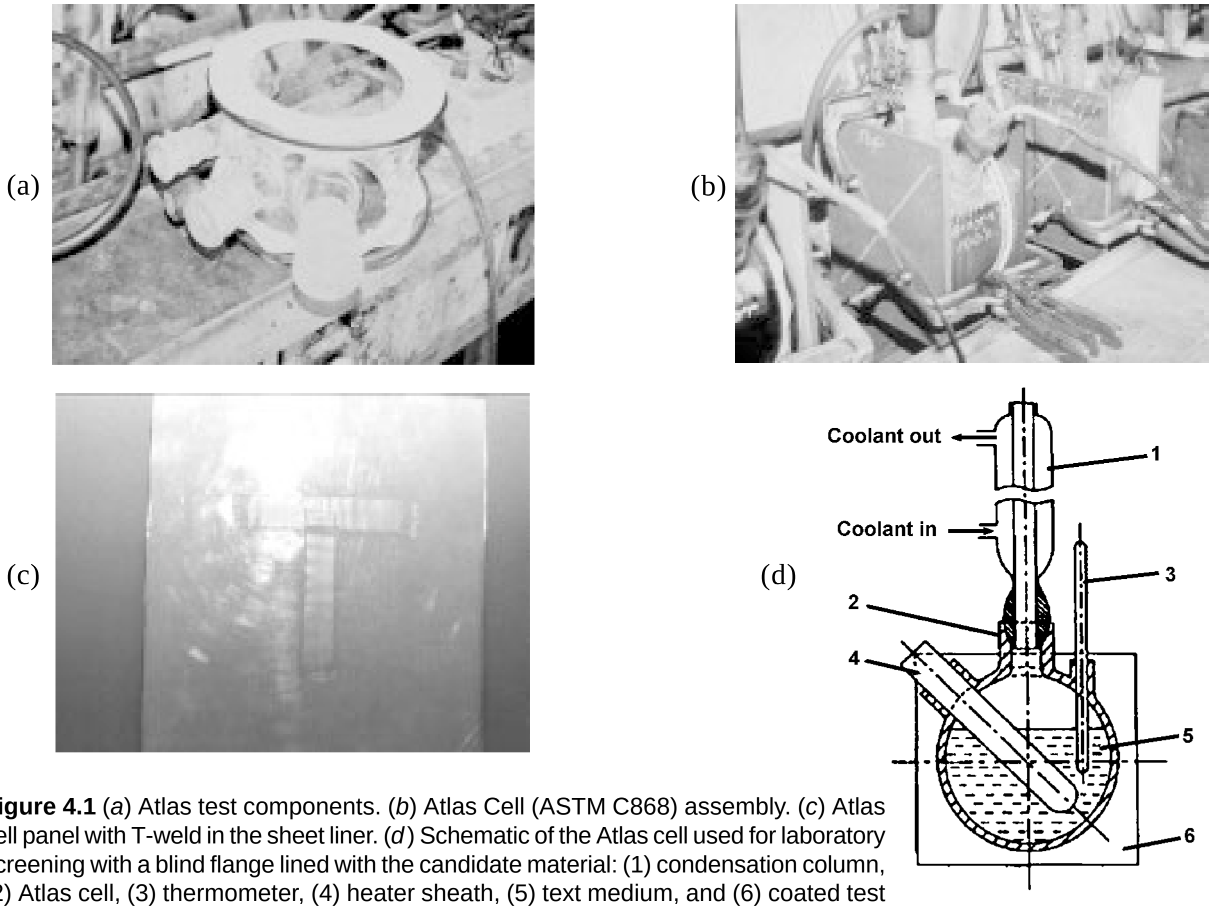

Figure 4.1 (*a*) Atlas test components. (*b*) Atlas Cell (ASTM C868) assembly. (*c*) Atlas cell panel with T-weld in the sheet liner. (*d*) Schematic of the Atlas cell used for laboratory screening with a blind flange lined with the candidate material: (1) condensation column, (2) Atlas cell, (3) thermometer, (4) heater sheath, (5) text medium, and (6) coated test plate. *(Courtesy DuPont Engineering Technology.)*

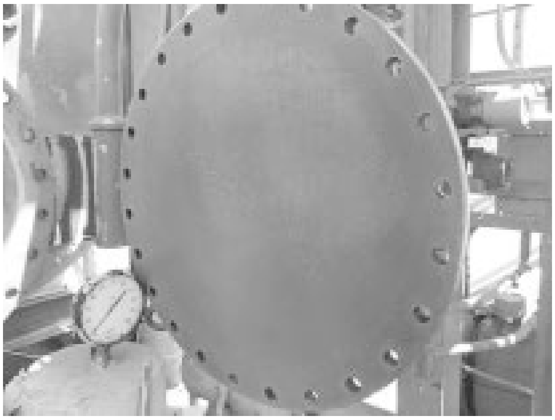

Figure 4.2. Photograph of a typical lined manway. (*Courtesy DuPont Engineering Technology.*)

Table 4.18 Standard Mechanical Tests for Evaluation

	T-Peel (adhesion bond)	Spark	Qualitative scribe	Corrosion of the substrate	Visual, color, cracking, blistering, etc.	Mechanical properties retention
Loose lining		X		X	X	X
Bonded lining	X	X		X	X	
Spray and baked coating		X	X	X	X	
Dual laminate	X				X	
Rotolining	X	X		X	X	

4.4.3.2 Simulated Testing

This approach is used when screening tests are done and candidates are selected for further evaluation. It is important to note that quite often simulated testing is directly carried out. Simulated testing procedures are application specific and are best carried out in the field although lab tests quite often yield useful results. The following classes of testing are usually considered and determined by the application:

- Lining (vessels, piping, valves, pumps, hoses, expansion joints, etc.)
- Seals and gaskets
- Internals (agitators, packing, etc.)

Testing for linings. This is best done in the lab by using the Atlas blind flange test (ASTM C858) or in the field using a blind flange or manway cover on a vessel where possible. (See Ch. 8, "Design and Construction," for details on the type of linings.) A pipe spool of loose lining, rotolining, or dual laminate is also possible. Field testing of any kind depends on a reasonable assurance that the lining will work, as well as the ability to inspect it as often as necessary. The Atlas cell apparatus is shown in Fig. 4.1; it simulates the one-sided exposure which a lining faces. The parameters to be tested are permeation resistance, loss of adhesion to the substrate, absorption, and chemical degradation. The apparatus consists of a container with two removable plates on which the lining is applied. The panels are clamped on both ends and the container is partially filled with the liquid in order to expose the lining to both liquid and vapor. An all-purpose sealing compound is used for the panels. An internal space heater maintains the temperature to the required level and a total reflux condenser is installed. Multiple cells are set up for tracking the performance over a period of time. The solution is typically changed every week and can be analyzed for contamination if the application calls for product purity. The duration is typically six weeks although longer exposures are very desirable. In some cases, test cells have gone on for eighteen months. After the duration, the cell is dismantled and the lining evaluated as described below.

Preparation of the panels needs to be done in accordance with the shop practices that produce the lining or coating. For loose, bonded, and dual laminates, it is important to include a weld in the lining. A T-weld in the panel, as shown in Fig. 4.1c, best achieves this. Once prepared, the panels should be spark tested.

Evaluation of the panels of the Atlas cells. Evaluation of the panels depends on the type of linings used. Table 4.18 lists the post-exposure evaluation tests for the panels.

The peel-pull test is used to determine the level of adhesion retained as a result of permeation and absorption testing (Fig. 4.3). ASTM C865 is typically used to determine the peel strength on a 2.5 cm (1 inch) wide strip. Data are reported in pounds of force per inch of width. A good number is 50 lb_f/in although lower numbers of 10 lb_f/in are acceptable in some cases. The number is also compared to that obtained either on an unexposed panel or on the same panel outside the exposed ring.

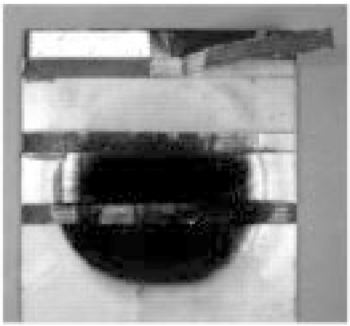

Figure 4.3. Peel pull test on an Atlas cell panel. (*Courtesy DuPont Engineering Technology.*)

The spark test is carried out for pinholes or breaks in the welds as a result of exposure. Depending on the thickness, the voltage used can be anywhere from 5000 to 15,000 V. The scribe test is used for coatings where peel-pull is not possible. It is qualitative and compares the adhesion of the exposed surface to that outside the exposed area. Results are used for comparison only.

Jacketed vessels. Jacketed vessels that require fluoropolymer linings need to go through a heat transfer analysis to make sure that the fluoropolymer barrier is not a hindrance for either cooling or heating. Usually a thin fluoropolymer coating is considered for such application. Figure 4.4 shows the effect of the thickness of the coating on the heat transfer rate.

Testing for seals and gaskets. Unlike lining for vessels, seals and gaskets cannot be tested in full simulation, so the total compatibility is determined piecemeal, i.e., chemical compatibility and evaluation of the material in the gasketed joint. It takes experience to put the information together to make a sound decision.

Chemical compatibility of the material can be determined by a simple dunk test using either the gasket itself or a generically similar material. The exposure conditions should match the actual application condition. Visual observations and retained mechanical properties should yield useful information.

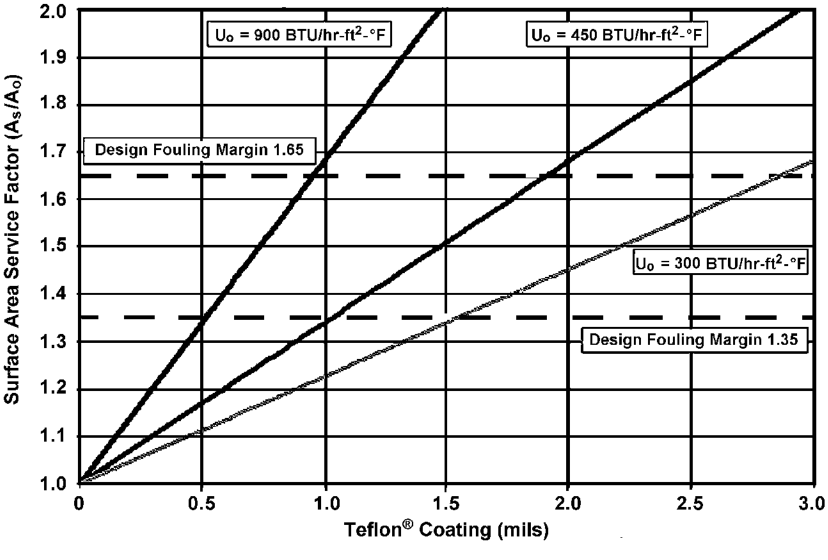

Figure 4.4. Effect on fluoropolymer thickness on heat transfer using Teflon® coated plate heat-exchangers. U_0: clean or unlined heat transfer coefficient; A_0: clean or unlined design area. (*Courtesy DuPont Engineering Technology.*)

If the material is found to be chemically compatible, its performance in a gasketed joint is evaluated. A gasket is under the combined load of bolt compression, hydraulic end forces, and internal pressure at a given temperature. Fluoropolymer gaskets readily creep and cause relaxation of the joint. Gasket manufacturers publish data that can be used to design a gasketed joint for a given application. The traditional, and still used, method is the one required by ASME Boiler and Pressure Vessel code. Using ASTM F586 "m" and "Y", values for a given dimension (ID, OD, and thickness) and a given leak rate are developed, which are used to calculate the bolt loading.

Recent advances have led to the development of the "Room Temperature Tightness Test" known as ROTT.[4] This test closely resembles the actual operating cycle of the gasketed joint (i.e., loading and unloading). It generates parameters that are used to calculate the bolt load for a required maximum allowable leak rate. Gasket manufacturers publish ROTT data.

ROTT is carried out using helium at room temperature. This procedure determines the room temperature gasket constants G_b, G_s, and **a** for seating and operating conditions of gasketing products. The tightness parameter (T_p) is a dimensionless parameter relating leak rate to a standard: T_p equals 1 when 1 lb of helium/sec/(inch diameter) leaks. The tightness parameter, T_p, is proportional to pressure and inversely proportional to the square root of the leak rate. The constant, G_b, is the gasket stress during loading sequence at T_p equal to 1; G_s is the gasket stress during unloading corresponding to T_p equal to 1. Finally, **a** is the slope of the gasket loading line.

Typically the ROTT test includes a seating load sequence, called Part A, which is interrupted at three increasing stress levels in order to run a set of three operating unload-reload sequences, called Part B. Part A represents the initial joint tightening and gasket seating while Part B simulates the load relaxation and retightening of the gasket. Two tests are required for consistency of results.

The end user combines the chemical compatibility information and the ASTM F586 or ROTT data to design a joint. Table 4.19 shows the ROTT data of fluoropolymer gaskets currently used in the industry. For a more complete understanding of ROTT and gaskets in general, see Refs. 12 and 13.

Table 4.19. ROTT (Room Temperature Test) Data for Fluoropolymer Gaskets *(Courtesy Flexitallic, ENPRO Garlock, UCAR, Frenzelit, Clipper, Durabla, W.L. Gore, and Teadit Companies)*

Company	Product	G_b	a	G_s
Flexitallic	CG	3393	0.3	7.1
Flexitallic	CG	2508	0.23	14.9
Garlock	CG	4500	0.14	70
Flexitallic	CG	2300	0.237	13
Flexitallic	CG	2120	0.19	49
Garlock	CG	627	0.35	6.22
Flexitallic	CG	1305	0.3	14.7
Flexitallic	CG	698	0.249	0.0013
Flexitallic	CG	598	0.385	0.03
UCAR	1/16" GHE	450	0.45	0.009
Garlock	1/8" 3125SS	816	0.377	0.066
Frenzelit	1/16" 825F	1180	0.322	0.176
Garlock	1/16" Graphonics	315	0.36	1.856
Clipper	Elastograph	32	0.718	0.001
Garlock	1/8" 8748	1316	0.351	0.7
Garlock	1/16" 8764	26.7	0.514	3.33E-12

(Cont'd.)

Table 4.19. ***(Cont'd.)*** **ROTT Data for Fluoropolymer Gaskets**

Company	Product	G_b	a	G_s
Garlock	1/8" 8764	5.47	0.705	8.33E-02
Durabla	1/16" 9000	550	0.244	0.042
Durabla	1/8" 9000	424	0.242	19
Garlock	1/16" 3504	183	0.357	0.00401
Garlock	1/16" 3510/11	289	0.274	6.61E-11
Garlock	1/8" 3510/11	444	0.332	0.0129
Flexitallic	1/16" 533	115	0.382	6.50E-05
Durabla	1/16" 9400	1701	0.173	99
Durabla	1/8" 9400	1412	0.164	248
Gore	1/16" GR	358	0.334	0.24
Gore	1/8" GR	310	0.352	3.22
Gore	1/4" GR	1160	0.22	8.8
Gore	GR w/metal	238	0.299	6.48E-07
Garlock	1/16" 3540	550	0.304	0.764
Inertex	1/16" SQ/S	1259	0.202	3.58
Inertex	1/8" SQ/S	1416	0.189	0.151
Garlock	1/16" 3545	333	0.38	64
Garlock	1/8" 3545	245	0.43	101
Garlock	3/16" 3545	628	0.249	0.0000793
Inertex	1/8" SQ-SV	969	0.237	0.37
Gore	Gasket Tape	1447	0.205	0.002
Flexitallic	1/16" SF2400	290	0.383	2.288
Garlock	1/8" 3700	1318	0.258	0.6
Durabla	1/16" 9200	5.2	0.873	0.033
Durabla	1/8" 9200	2.3	0.873	25.7
UCAR	1/16" TG323	5	0.921	0.078
	SIR	2.3	0.887	3.83E-06
Garlock	1/16" 3500	949	0.253	2.6
Garlock	1/16" Tephonic	238	0.299	6.46E-07
Gore	1/8" Tex-O-Lon	695	0.189	53.98
Gore	1/8"-1/4" Insertable	738	0.207	0.004
Garlock	3/8" 3535	430	0.286	1.69E-09
Gore	Joint Sealant	382	0.293	16.8
Gore	1/16" TFE Selco-Seal	796	0.208	156
Garlock	1/16" 9405	462	0.251	0.213
Garlock	1/8" 9405	381	0.265	8.38
Garlock	1/8" 3700	1318	0.258	0.6
Garlock	1/16" 5500	1247	0.249	11
Garlock	1/16" 3561	72.3	0.466	0.216
Flexitallic	1/8" Thermiculite 815	1906	0.2	456.12
Flexitallic	1/8" Kammprofile	387	0.334	14
Teadit	1/16" 1080	1071	0.264	2.6

4.4.3.3 Special Testing

Permeation testing. Permeation is a major and constant concern when fluoropolymers are used in chemical handling. Permeation manifests itself in swelling, blistering, and discoloration.

Permeation is the migration of fluids through the thickness of the polymer barrier. It is a three-step process where there is instant liquid take-up on the polymer surface (determined by the solubility parameter), migration of the liquid through the film (determined by the diffusivity), and desorption on the other side. The steady-state permeation rate, breakthrough time, and identity of the permeating species are of paramount interest to engineers concerned with the corrosion of the housing and environmental implications. Both the coupon and Atlas cell tests provide indications of permeation but do not yield quantitative information

Fluoropolymers are more permeable to fluids than other polymeric materials. However, the permeation rates of different grades of fluoropolymers are not that different. Most of the data that are currently available are based on thin films and must be carefully used. Permeation is also not a very clearly understood phenomenon. As a result the end user has to recognize the problem and manage it. Table 4.20 contains very useful rules-of-thumb when it comes to permeation through fluoropolymers

If, however, more accurate and quantitative information is needed, testing is recommended. There are several test methods that various industries use for permeation testing. Table 4.21 lists all of them.

Environmental Stress Cracking. Where this is a concern, testing is done using any one of the following ISO methods: ISO 175, 4600, or 6252.

Abrasion Resistance Testing. In the chemical process industry, fluoropolymers are typically subjected to abrasive slurries. However, there is no standardized test for slurry abrasion. The Tabor abrader test (ASTM D3884), which measures the weight loss for a certain time using a grinding wheel, is done for comparison purpose only.

4.4.4 Fabrication Considerations in Materials Selection

Fabrication can include welding, thermoforming, spraying, and baking. Assuring the quality of these is particularly important in lining applications where the choice of lining material limits the fabrication methods and the choice of fabrication method limits the lining material. Various fluoropolymer materials and their fabrication technologies have been listed in Table 4.22.

Table 4.20. Permeation Rules-of-Thumb

Rule	Change	Permeation
Voids in polymer	⇓	⇓
Polymer crystallinity	⇑	⇓
Polymer chain stiffness	⇑	⇓
Polymer interchain forces	⇑	⇓
Polymer temperature	⇓	⇓
Permeant size/shape	⇑	⇓
Permeant concentration	⇓	⇓
Polymer thickness	⇑	⇓
Permeant temperature	⇓	⇓
Permeant/polymer chemistry and ratio	⇓	⇓

Table 4.21. Standard Test Methods for Measurement of Permeation

ASTM Standards	
C868-85 (1995)	Standard Test Method for Chemical Resistance of Protective Linings (Atlas cell test)
D814-86 (1991)	Rubber Property-Vapor Transmission of Volatile Liquids
D1434-82 (1998)	Determining Gas Permeability Characteristics of Plastic Film and Sheeting
D1653-93 (1999)	Water Vapor Transmission of Organic Coating Films
D2684-95	Permeability of Thermoplastic Containers to Packaged Reagents or Proprietary Products
D3985-95	Oxygen Gas Transmission Rate Through Plastic Film and Sheet using a Coulometric Sensor
D4491-99a	Water Permeability of Geotextiles by Permittivity
D5052-00	Permeability of Leather to Water Vapor
D5795-95	Determination of Liquid Water Absorption of Coated Hardboard and Other Composite Wood Products via "Cobb Ring" Apparatus
D5886-95	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications
E96-00	Water Vapor Transmission of Materials
F372-99	Water Vapor Transmission Rate of Flexible Barrier Materials using an Infrared Detection Technique
F739-99a	Resistance of Protective Clothing Materials to Permeation by Liquids or Gases under Conditions of Continuous Contact
F790	Standard Guide for Testing Materials for Aerospace Plastic Transparent Enclosures
F903-99a	Resistance of Materials Used in Protective Clothing to Penetration by Liquids
F1249-01	Water Vapor Transmission Rate through Plastic Film and Sheeting using a Modulated Infrared Sensor
F1383-99a	Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Intermittent Contact
F1407-99a	Resistance of Chemical Protective Clothing Materials to Liquid Permeation – Permeation Cup Method
F1769-97	Measurement of Diffusivity, Solubility, and Permeability of Organic Vapor Barriers Using a Flame Ionization Detector
F1770-97e1	Measurement of Solubility, Diffusivity, and Permeability of Flexible Barrier Materials to Water Vapor
F1927-98e1	Determination of Oxygen Gas Transmission Rate, Permeability and Permeance at Controlled Relative Humidity Through Barrier Materials Using a Coulometric Detector
International ISO Standards	
ISO 6179	Method for Determination of the Transmission Rate of Volatile Liquids
ISO 2782	Rubber, Vulcanized – Determination of Permeability to Gases – Constant Pressure Method
ISO 6529:2001	Protective clothing – Protection Against Chemicals – Determination of Resistance of Protective Clothing Materials to Permeation by Liquids and Gases
ISO 8308	Rubber and Plastics Hoses and Tubing – Determination of Transmission of Liquids through Hose and Tubing walls
British BS Standard	
EN 374-3	Protective Gloves Against Chemicals and Microorganisms Determination of Resistance to Permeation by Chemicals
SAE Standards	
J30	Fuel and Oil Hoses
J1737 1997-08	Test Procedure to Determine the Hydrocarbon Losses from Fuel Tubes, Hoses, Fittings and Fuel Line Assemblies by Recirculation
J2405	Low Permeation Fuel Fill and Vent Tube
Ford Standards	
FLTM BZ 104-02	Permeation of Rubber-Coated Diaphragm Cloth
FLTM BZ 105-04	Component Permeation Testing

Table 4.22. Comparison of Fluoropolymer Lining Technologies for Vessels and Columns

Technology	Materials*1	Fabrication	Design	Size limit, ft*2	NDT	Repair
Adhesive-bonded	Synthetic and glass backed: PVDF (60, 90, 118 mils) ECTFE (60, 90) Glass backed: ETFE (60, 90 mils) PTFE (80, 120 mils) FEP (60, 90 mils) PFA (90, 110 mils) MFA (60, 90 mils)	Contact or thermosetting adhesive Weld rod and Cap strip welds Shop or field	Pressure OK Full vacuum up to 120°F (49°C) Max Temp 275°F (135°C)	None	Visual Spark	Possible Testing recommended
Rotolining	ETFE PVDF ECTFE All up to 250 mils (normal thickness: 186 mils)	Rotationally molded No seams No primer Shop only	Pressure OK Limited Vacuum ability	Max size 8×22	Visual Spark	By hot patching Testing recommended
Spray and Baked						
• Dispersion	FEP (10 mils), PFA (10–40 mils and up to 80 mils when reinforced or filled) PVDF (20–40 mils and up to 90 mils when reinforced with carbon cloth)	Primer and multicoated conventional spray equip Each coat baked Shop only	Pressure OK Vacuum OK Pressure OK Vacuum OK	12×12× 37 12	Visual Spark Visual Spark	By hot patching Testing recommended
• Electrostatic spray	ETFE (up to 50 mils), FEP (10 mils), PFA (25–40 mils) ECTFE (35–90 mils), PVDF (35–40 mils)	Primer and multicoated Each coat baked Shop only				By hot patching Testing recommended
Loose lining	FEP PFA Modified PTFE All 60, 90, 125, 187 mils	Liner fabricated outside the housing and slipped inside Liner fabricated by hand and machine welding Shop only	No vacuum. Pressure OK	Determined by body flange (12) and section height (12)	Visual Spark	Difficult
Dual Laminate (Fluoropolymer-lined FRP)	Same as Adhesive-bonded	Fabricate liner first on a mandrel (hand and machine welding) and build FRP laminate over the liner. Use carbon cloth for spark testing Shop and Field	Pressure OK (RTP-1 Dual lam) Vacuum OK for FRP/fluoropolymer bond. Design FRP for vacuum	~ 33 dia max	Visual Spark AE CRBBD	Possible Testing recommended

*1 To convert from mils to mm, multiply by 0.0254.
*2 To convert from ft to m, multiply by 0.3048.

Fabrication method limitations and trade-offs. The principal determining factor of a fabrication method is the size of the vessel. Rotolining technology is restricted to sizes smaller than two meters in diameter. Adhesive-bonded linings can be installed in any sizes including the field fabricated ones. Spray and baked linings can only be done in an oven or by heating the interior of a reasonably sized vessel. Spray and baked linings need to have direct access to the sprayed surface. Loose linings cannot be used for vacuum, and adhesive-bonded linings have vacuum limitations. Permeation can become a problem for the adhesive used in such linings. A selection methodology based on a hierarchy of decisions is needed and appears in Fig. 4.5.

4.4.5 Inspection and Maintenance Aspects of Materials Selection

Inspection and future condition assessment requires that provision be made for as many blind flanges as possible. Since destructive testing is the most reliable method, blind flange linings can enable tracking of the performance over time. Maintenance considerations include repairs and repairability.

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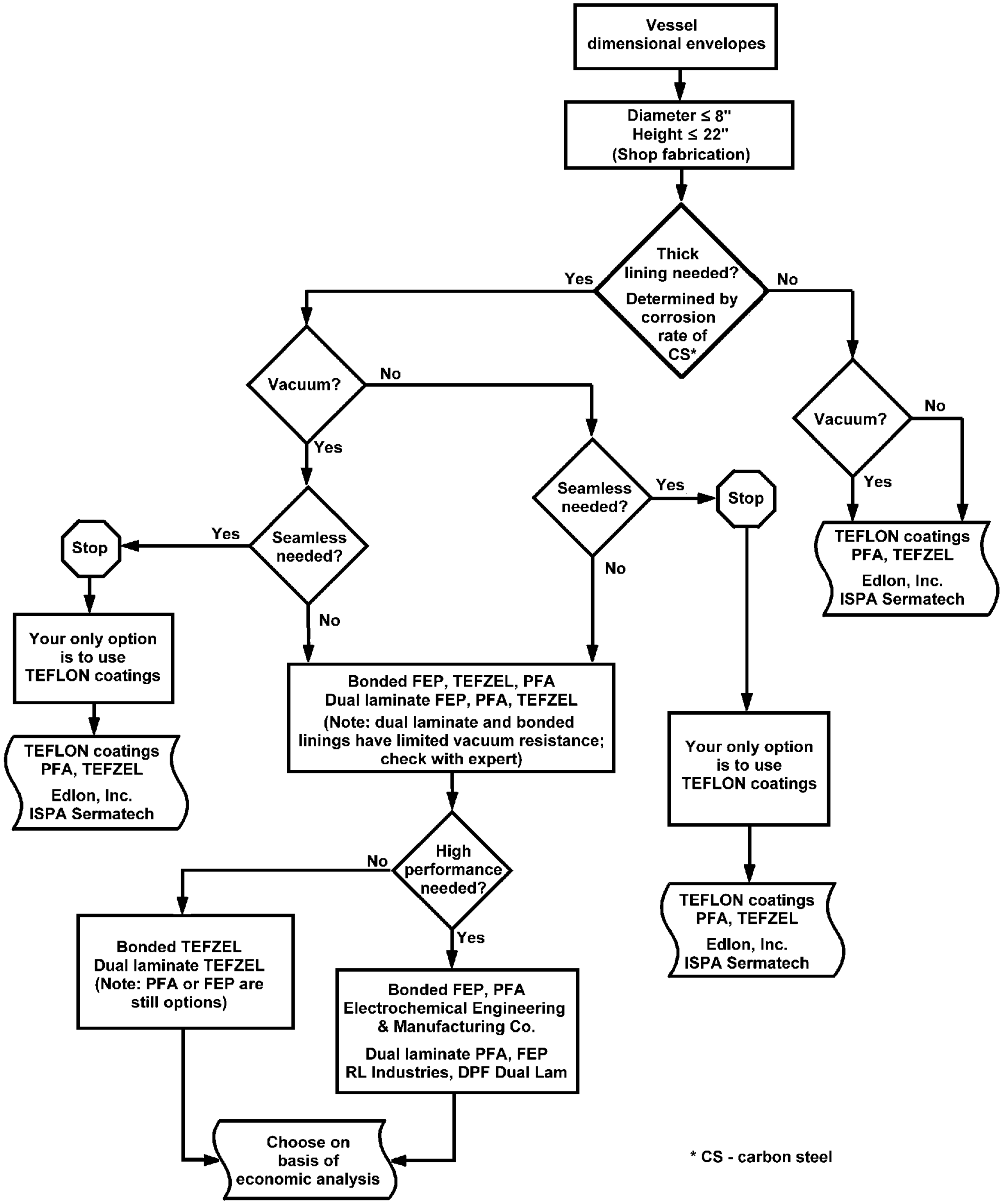
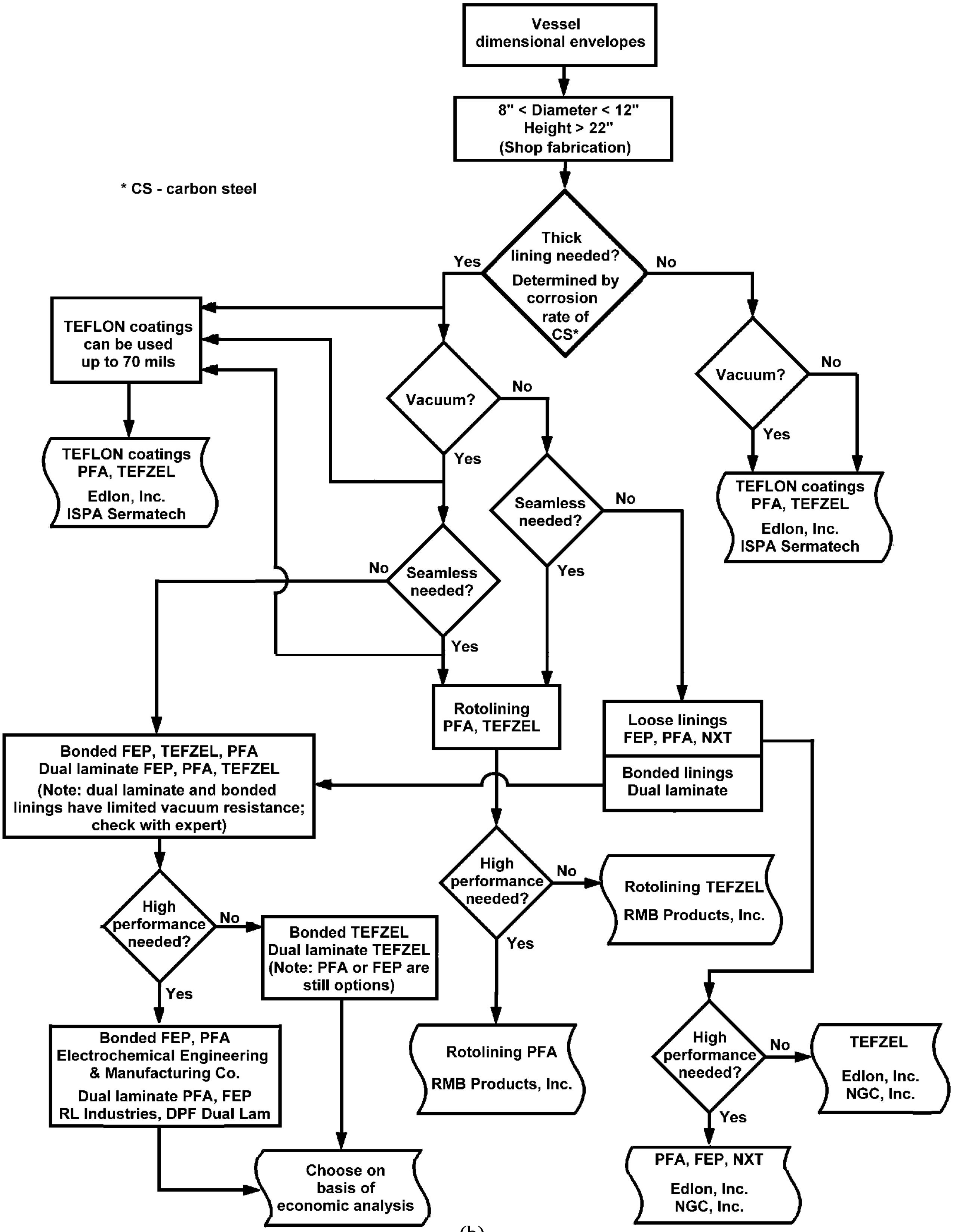


* CS - carbon steel

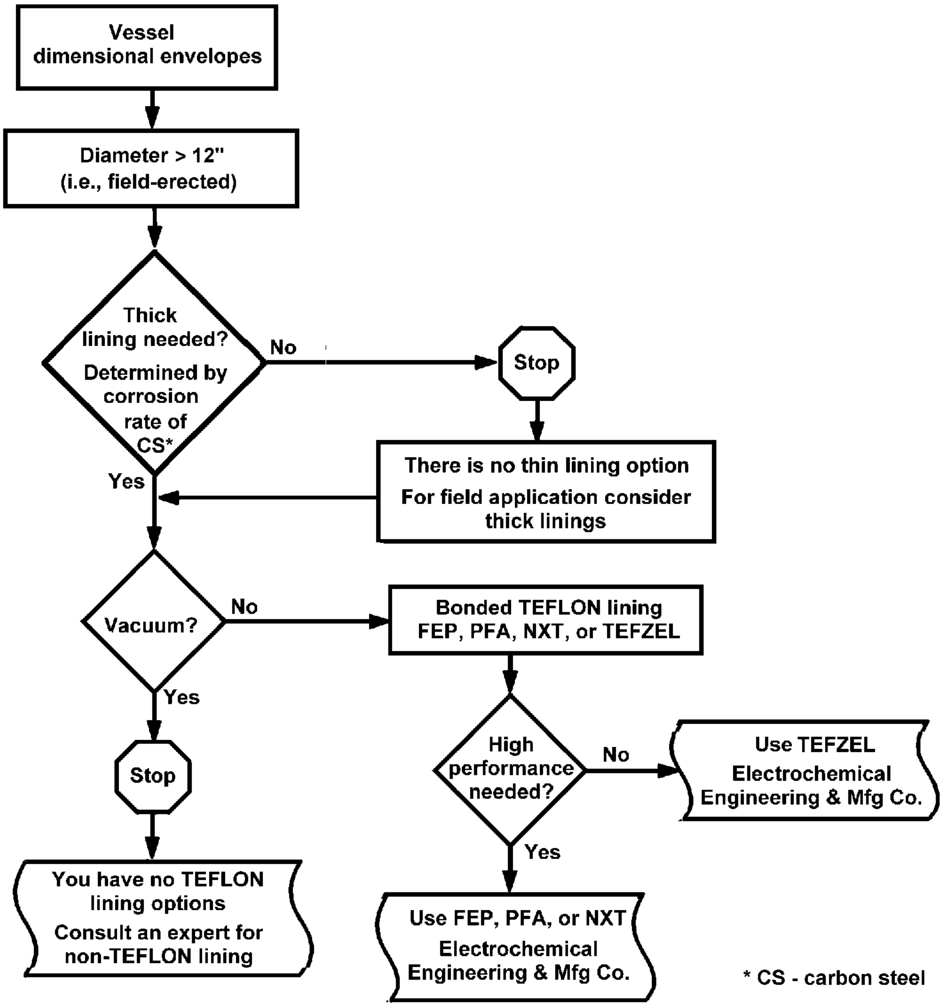
(a)

Figure 4.5. Decision trees for (*a*) vessels under 8” diameter and 22” height; (*b*) vessels between 8” and 12” diameter and greater than 22” height; and (*c*) vessels larger than 12” diameter, field-erected. *(Courtesy DuPont Engineering Technology.)*



(b)

Figure 4.5. *(Cont'd.)*



(c)

Figure 4.5. *(Cont'd.)*

5 Manufacturing of Parts from Polytetrafluoroethylene Polymers

5.1 Granular Resin Processing

Granular PTFE is fabricated by a modified metallurgy technology named *compression molding,* where PTFE powder is compressed into a "preform" at ambient temperature. The preform has sufficient strength to be handled, roughly equivalent to blackboard chalk. After removal from the mold, the preform is heated in an oven above its melting point and is sintered. The consolidation of particles during sintering is referred to as *coalescence*, which produces a homogenous and strong structure. Varying the cooling rate by which the part reaches room temperature controls crystallinity of a part for a given polymer, thus its mechanical properties.

There are four basic molding techniques for processing granular resin; all four rely on the principles of compression molding of PTFE. These procedures are applied to convert granular resins into parts ranging in weight from a few grams to several hundred kilograms (Table 5.1).

The only continuous process for manufacturing parts from granular PTFE is called *ram extrusion*.

5.1.1 Resin Selection

Selection of resin depends on the desired properties of the PTFE part in the application and the manufacturing method used to produce it. Electrical insulation, reactor liners, and most gaskets are typically made using fine cut resins to achieve the best properties. Mechanical parts such as bridge and heavy equipment bearings do not rely on these properties to the same extent, and can therefore be made from free flow (pelletized) resins.

Resin flow is a function of the apparent density of the resin. Resins with an apparent density of >500 g/l are usually obtained by pelletizing fine cut resins and are known as *free flow* (Fig. 5.1a). The consistency of these resins is similar to granulated sugar in contrast to fine cut resins (with apparent density of <500 g/l) which have a consistency close to that of flour.

Resin flow and mechanical properties are inversely related (Fig. 5.1b). A free flow resin produces a part that has lower elongation, tensile strength, specific gravity, and dielectric breakdown strength than the same part produced with a fine cut PTFE powder (Figs. 5.2 and 5.3). Improvement in resin flow raises the efficiency of mold filling. Good resin flow is a requirement for automatic molding, isostatic molding, and ram extrusion processes.

Small particles and bimodal or multimodal particle size distribution of resin powder yield the highest packing density[1] and consequently the lowest void content, leading to improvement in mechanical properties.

Table 5.1. Selection of Granular Fabrication Process Based on Part Geometry

Fabrication Process	Shape	Part Dimension	Part Weight
Billet/Block Molding	Rectangular, cylindrical	One centimeter in diameter or height to 5 meters in diameter or 1.5 meters in height	Ten grams to several hundred kilograms
Sheet Molding	Flat sheet	One centimeter to 1 meter in width and thickness of 3–75 millimeters	A few hundred grams to a few tens of kilograms
Automatic Molding	Small round	A few millimeters to a few centimeters in diameter	A few grams to a few hundred grams
Isostatic Molding	Complex geometry	A few centimeters to 0.5 meters in the major dimension	A few tens of grams to a few tens of kilograms
Ram Extrusion	Rod or tube	2–400 millimeter in diameter	Continuous process

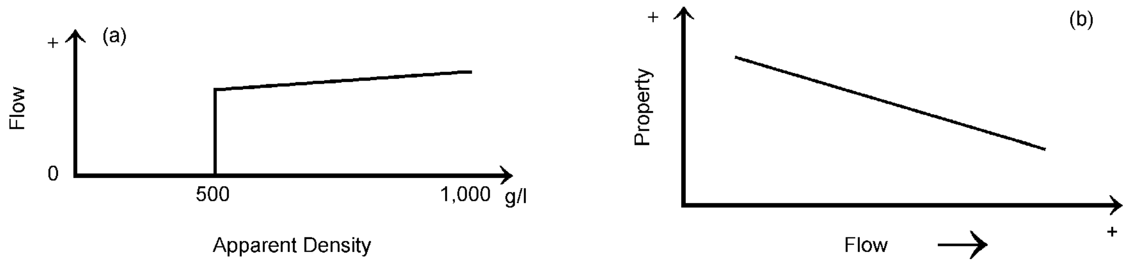


Figure 5.1 The relationships of *(a)* apparent density vs flow and *(b)* property vs flow.

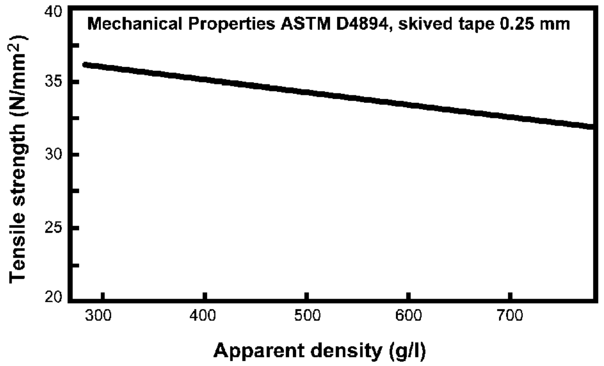


Figure 5.2 Tensile strength vs apparent density. *(Courtesy DuPont.)*

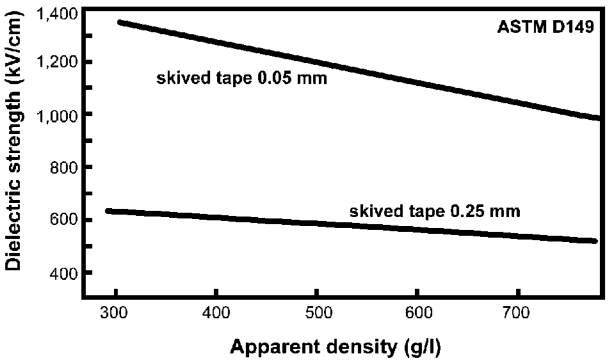


Figure 5.3 Dielectric strength vs apparent density. *(Courtesy DuPont.)*

5.1.2 Compression Molding

Compression molding is the method by which massive (700 kg), cylindrical (billet), rectangular, and sheet shapes of PTFE are produced. The blocks and cylinders can be solid or annular and are by far the heaviest objects produced from any fluoropolymer. The height of a cylinder can exceed 1.5 m. These billets are cut (skived) into wide thin films (<0.5 mm thick) or sheets (7 mm thick). Sheets, blocks, and cylinders are utilized as stock shapes for machining more complex shapes. The same principles are applied to mold any shape.

PTFE's specific gravity is high compared to other plastics. A solid billet 300 mm tall, with a wall thickness of 130 mm, may weigh about 50 kg. The selection of the size of the billet depends on the properties required in the application. Sheets for mechanical applications and for lining chemical processing equipment are sometimes made from 1.5 m tall billets.

The polymer should be conditioned at temperatures of 21°C–25°C before molding to reduce clumping and ease handling. Molding below 20°C should be avoided because PTFE will undergo a 1% volumetric change at a transition temperature of 19°C. Preforms molded below 20°C can crack during sintering.

Molding areas should be equipped with positive pressure to keep out dust and airborne contaminants. Parts intended for the semiconductor industry are preferably molded in cleanrooms. Dust, oil, and particles of an organic nature must be prevented from contaminating the resin because during sintering they will carbonize into dark specks.

5.1.2.1 Equipment

Relatively simple equipment is used for billet molding. It consists of a stainless steel mold and hydraulic press for fabrication of the preform, and an oven for sintering. A lathe and skiving blades are required for preparation of film and sheet.

Mold design. PTFE resins are molded in molds similar to those utilized for thermosetting resins or metal powders. A complete mold consists of a cylindrical or rectangular die and upper and lower end plates and a mandrel for annular parts. These parts are normally made of tool steel to allow machining, and plated with chromium or nickel to protect them from corrosion. Occasionally, the end plates are made of brass or plastics such as nylon. A small diametrical clearance is designed in the end plates to allow easy assembly and air escape.

The mold depth has to be 3.2–4.2 times the height of the tallest billet expected to be made; a 1.5 meter tall billet would require a mold that is 4.8–6.3 meters long. Extensions can be added to the mold to obtain the desired depth. Mold diameter is determined by resin shrinkage, which means that each mold is designed for a specific resin since each has a specific shrinkage value. The word *shrinkage* refers to the shrinkage of the part after sintering has been completed.

Presses. Hydraulic presses are recommended for preform production. Important elements of a press are smooth pressure application, maximum opening ("daylight"), ram stroke, flatness and levelness of the platens, and tonnage. A programmable press allows smooth application and removal of pressure, which is critical to producing a good part. Jerky and uneven motion of the ram will result in nonuniform application of pressure to the resin, resulting in cracking during sintering. The tonnage of the press determines the maximum diameter of the preform. The typical maximum required preform pressure is 60 MPa for unfilled resin and 100 MPa for filled resin.

Ovens. PTFE is an excellent thermal insulator. Its thermal conductivity (0.25 W/m·K), roughly 2,000 times less than copper, impacts the rate of sintering of a preform. The most common way of delivering heat to a preform is by circulation of hot air. Ideally, the sintering oven is electrically heated for use up to 425°C and should be equipped with override controllers to prevent overheating.

Good temperature control is critical to achieving uniform and reproducible part dimensions and properties. The interior of the oven should be designed to maximize air circulation and temperature uniformity, and prevent the formation of "hot spots." A highly rated insulation will minimize heat loss, which is particularly important during the sintering of a full oven load.

Controlled cooling is accomplished by fresh air intake during the cool-down portion of the cycle.

5.1.2.2 Densification and Sintering Mechanism

Resin powder particles are separated by air which is removed during preforming and sintering. Figure 5.4 depicts the changes that PTFE particles undergo from the compression stage to a sintered part. The powder is charged to the mold and compressed and held for a dwell period. After the preform is made, it is removed from the mold and allowed to rest for stress relaxation and degassing.

The preform expands due to relaxation and recovery. The pressure placed on the molded resin exerts three types of changes in the particles of resin. Resin particles undergo plastic deformation and are intermeshed together leading to the development of cohesive or *green* strength. Particles also deform elastically and experience cold flow under pressure. The air trapped in the space between the resin particles is compressed. Removal of pressure allows the recovery of elastic deformation, which creates a quick "snap back" of the preform. Over time, stress relaxation partly reverses the cold flow, and the preform expands.

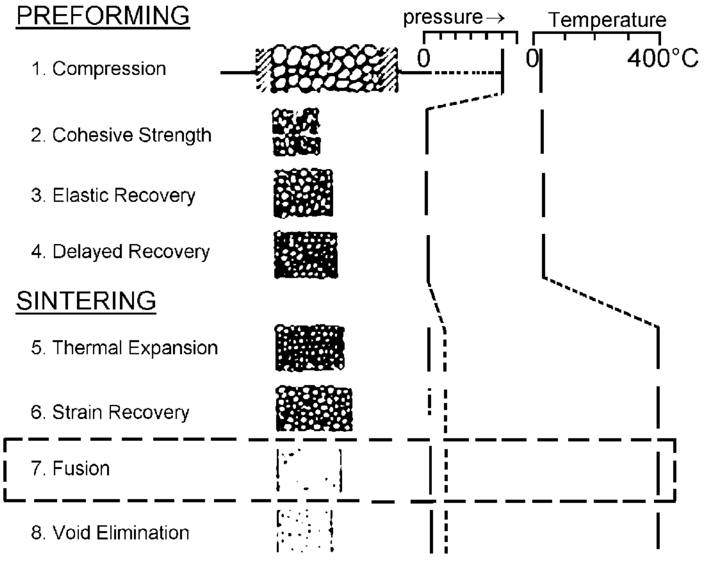


Figure 5.4 Schematic diagram of preforming and sintering sequence with polytetrafluoroethylene.[2]

The trapped air in the preform is under high pressure, theoretically equal to the preforming pressure. The air requires time to leave the preform because it is mostly contained in the void areas surrounded by enmeshed particles. Immediate sintering would lead to a rise in the already high pressure of the air and catastrophic cracking of the part as the PTFE melts and the mechanical strength declines. The preform should be allowed to degas which equalizes the internal air pressure to atmospheric pressure.

Sintering of the preform takes place in an oven where massive volumes of heated air are circulated. Initial heating of the preform leads to thermal expansion (Fig. 5.5) of the part. After PTFE melts, relaxation of the residual stresses occurs (stored because of the application of pressure to the polymer) where additional recovery takes place and the part grows. The remaining air begins to diffuse out of the preform after heating starts. The adjacent molten particles begin to coalesce slowly; usually hours are required because of the massive size of PTFE molecules. Fusion of the particles is followed by elimination of the voids, where almost no air is left. Elimination of all the voids in PTFE is quite difficult because of the limited mobility of the large polymer molecules.

5.1.2.3 Billet Molding

This section describes the three processes for producing a billet from granular PTFE: preforming, sintering, and cooling.

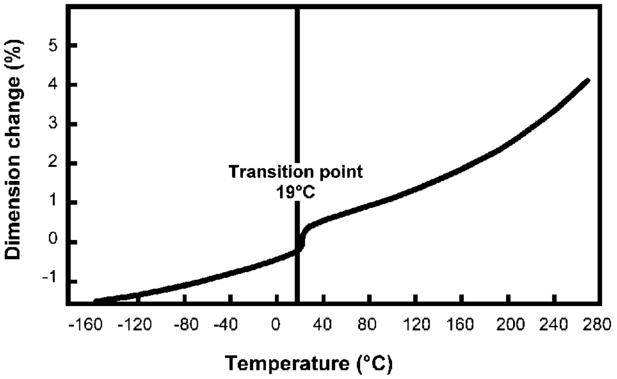


Figure 5.5 Transition point and linear thermal expansion of PTFE. *(Courtesy DuPont.)*

Preforming. Preforming consists of charging the mold with the powder and compacting it by the application of pressure to prepare a green part with sufficient strength to allow handling. Demolding or removal from the mold and placement in the oven are the steps that require green strength. Occasionally, a preform may be machined which increases the importance of green strength.

Adequate and uniform application of pressure is the determining factor of the properties of the final part in the molding step. PTFE becomes softer and exhibits higher plastic flow as the temperature increases and can thus be molded at lower pressures. An increase of temperature from 21°C to >31°C is roughly equivalent to 2 MPa of molding pressure.

Filling the mold must be done uniformly because uneven filling leads to nonuniform density in the preform and cracking. Charging the mold is much simpler with a free flow resin than a fine cut powder. Free flow resins more or less assume the shape of the mold and require little distribution.

Increasingly, processors are molding in cleanrooms (usually portable) to meet the more stringent quality specifications of customers. Wiping and cleaning the exterior of resin drums prior to opening and resealing the unused portion of the powder are among the helpful practices for prevention of contamination.

Pressurization rate or ram closing speed depends on the size and shape of the billet and the type of resin. The slower the ram speed, the more completely the air will leave the preform, but productivity suffers at a low closing rate. Very fast ram speeds lead to entrapment of air, resulting in high porosity and low density areas, even billet cracking. Table 5.2 provides ram speeds that offer compromises between productivity and part quality.

The preform shrinks in the radial (cross direction or CD) during sintering and tends to grow in height or machine direction (MD) as shown in Fig. 5.6. Raising the preform pressure reduces the shrinkage and increases the growth. Typical numerical values for shrinkage and growth of a few commercial resins can be found in Figs. 5.7 and 5.8.

Dwell time is necessary to obtain even compaction of the resin in the preform. Insufficient dwell leads to density gradients in the billet, "hourglassing" which refers to the shape of the billet after sintering, property variation, air entrapment, and microcracks.

Dwell time depends on the type of resin, rate of pressurization, and the size and shape of the preform. The rule of thumb is 2–5 minutes of dwell per 10 mm of final height for billets <100 mm in diameter, and 1–1.5 minutes for 10 mm of height for large billets (>100 mm diameter).

Pressure decay during the molding can be a serious problem in billets that are taller than 100 mm. This can be corrected by pressurizing the resin from both sides if a double action press is available.

Degassing is the last step in preparation of the preform prior to sintering. Air and residual stress remains entrapped in the preform and should be relieved prior to sintering. This air needs time to escape from the preform; otherwise it will increase substantially during the heat-up segment of the sintering cycle and crack the billet. Stresses remaining in the preform can be equally potent and lead to billet cracking during the heat-up period. The higher the heating rate, the more magnified the effect of residual stresses. A time interval is required to relax stresses and allow air to escape. Figure 5.9 presents typical times sufficient to prevent cracking.

Table 5.2. Press Closing Rates (mm/min) ***(Courtesy DuPont)***

Billet size (mm)	% Compaction		
	~60	Next ~20	Last ~20
Small to medium (~100)	500–150	250–25	50–5
Medium to tall (100–500)	150–25	50–5	10–2

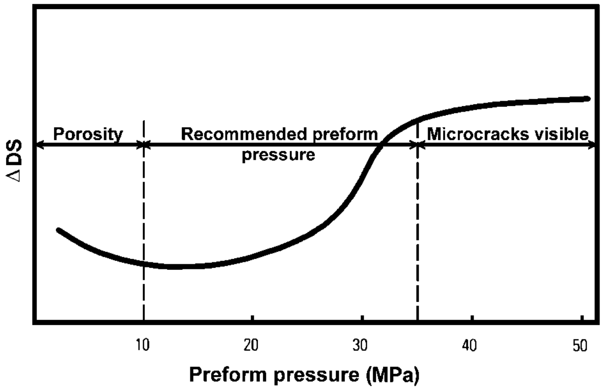


Figure 5.6 Mold shrinkage vs preform pressure. *(Courtesy DuPont.)*

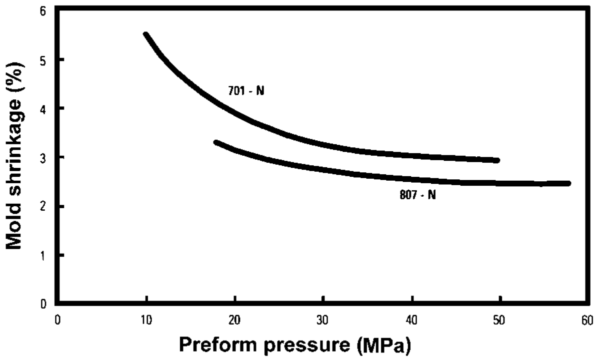
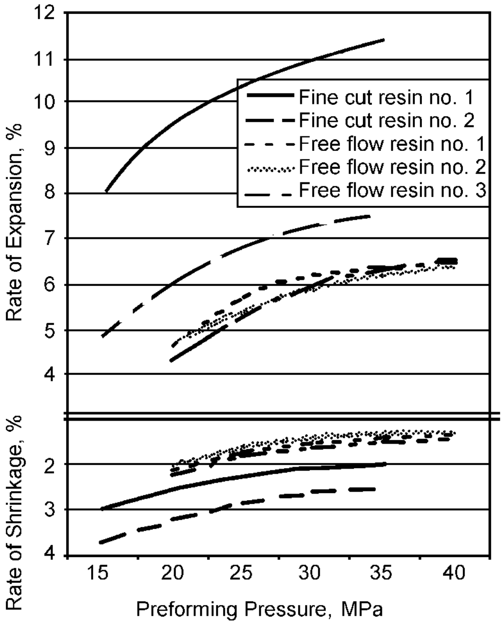


Figure 5.7 Effect of preform pressure on mold shrinkage. *(Courtesy DuPont.)*



Molding Conditions		
Dimensions	**Preforming pressure**	**Dwell period**
100 (O.D.) × 50 (H) mm	15 ~ 40 MPa	5 min (double ended pressing)
Heating rate	**Sintering period**	**Cooling rate**
200°C ~ 300°C, 33.3°C/h, 300°C ~ 370°C, 17.5°C/h	370°C for 5 h	370°C ~ 300°C, 17.5°C/h, 300°C ~ 200°C, 20°C/h

Figure 5.8 Molding pressure and rate of change in dimensions.[3]

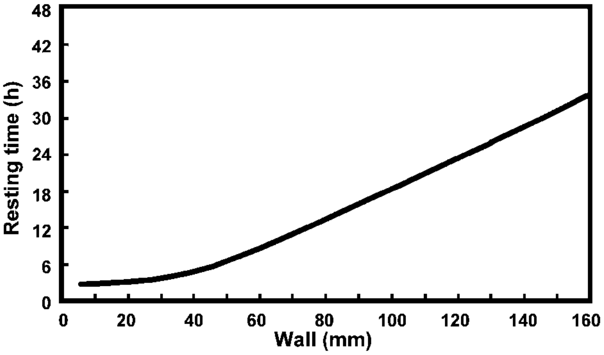


Figure 5.9 Resting time for degassing after preforming. *(Courtesy DuPont.)*

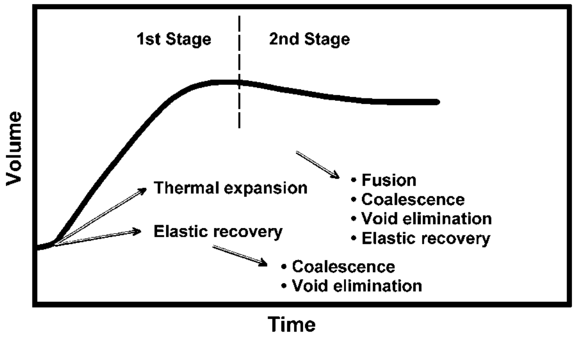


Figure 5.10 Mechanism of sintering Teflon®. *(Courtesy DuPont.)*

Sintering. A preform has limited cohesive strength and is essentially useless; sintering allows coalescence of the resin particles, which provides strength and void reduction. Sintering cycle profiles of time and temperature affect the final properties of the billet. Sintering temperatures exceed the melting point of PTFE (342°C) and range from 360°C to 380°C.

Figure 5.10 shows the various steps of the sintering process. At first the preform completes its elastic recovery and begins to thermally expand past the PTFE melting point. The expansion can reach up to 25%–30% by volume depending on the type of resin, powder, preforming pressure, and temperature. Above 342°C, PTFE is a transparent gel due to the absence of a crystalline phase.

Coalescence and void elimination require time because of the limited mobility of PTFE molecules. Melt creep viscosity of PTFE is in the range of 10^{11}–10^{12} poise at 380°C which severely inhibits any flow similar to that known for thermoplastics. The sintering temperature is held for a period of time to allow fusion, coalescence, and void elimination to proceed and maximize properties in the part. Property development should be balanced against cost in selecting a sintering cycle. Figure 5.11 shows the effect of sintering temperature on the specific gravity and tensile strength of the billet. Specific gravity increases with temperature while tensile strength decreases. Degradation of PTFE above 360°C leads to a lower molecular weight material, which crystallizes more easily and has decreased tensile strength.

The maximum heating rate for small parts is 80°C–100°C/hr. A typical heating rate is no more than 50°C/hr up to 150°C, 30°C/hr up to 300°C, and 6°C–10°C/hr at higher temperatures. Only very small preforms can be subjected to faster rates.

The optimum hold time at the maximum temperature is determined through repeated trials. Figures 5.12 and 5.13 show the effect of sintering time and temperature on tensile strength, and elongation and dielectric strength of skived film. It is clear in this example that 12 hrs hold time at 377°C–382°C results in the best properties. Beyond this point properties generally decline.

The rule of thumb for determining the sintering time is 1 h/cm of wall thickness of solid billets and 1.5 hrs/cm of thickness for billets with a hole in the middle. Small parts need 0.8 hrs/cm of time sintering temperature.

Cooling. Cooling plays two important roles: crystallization and annealing of the sintered billet. Many of the properties of PTFE (similar to other semicrystalline polymers) are governed by the crystalline phase content of the part. Crystallinity is determined by the cooling rate. At 320°C–325°C, the molten resin reaches the freeze point and crystallization begins to take place. Polymer chains, which were randomly distributed in the molten state, begin to pack in an orderly manner during the crystallization process. The slower the cool down, the higher the number of crystalline structures will be. This means that controlling the cooling rate can control the properties of the part.

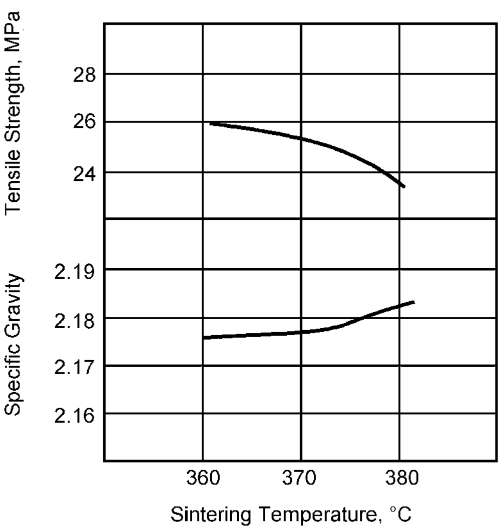


Figure 5.11 Seven-hour sintering: sintering temperature and product quality.[3]

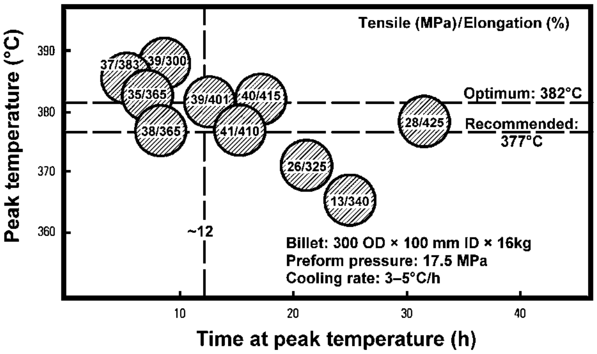


Figure 5.12 Peak temperature/time effect on properties (TS/EL). *(Courtesy DuPont.)*

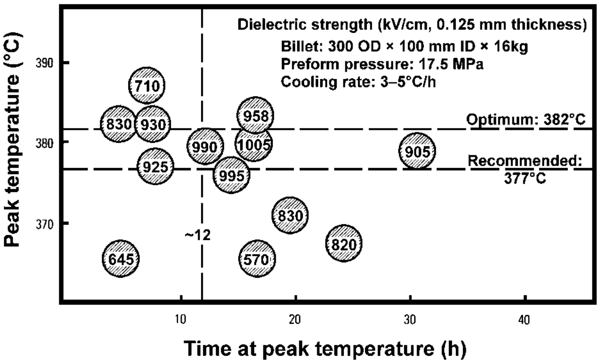


Figure 5.13 Peak temperature/time effect on properties (DBV). *(Courtesy DuPont.)*

Slow cooling, especially for thick parts, is necessary to avoid large thermal gradients, which can cause cracking of the part. This is especially important during the freezing transition because of the large volume decrease that the polymer experiences while going from melt to solid phase. Large stresses are generated in the part, which can fracture the melt if the cooling rate is not sufficiently slow.

Annealing refers to removal of residual stresses in the billet by holding it for a period of time between 290°C and 325°C during the cooling cycle. It also minimizes thermal gradients in the billet by allowing the wall interior to catch up with the exterior surface. The crystallinity of the part depends on the annealing temperature. A part which is annealed below the crystallization temperature range (<300°C) will only undergo stress relief. Annealing at a temperature in the crystallization range (300°C–325°C) results in higher crystallinity (higher specific gravity and opacity) in addition to stress relief.

5.1.3 Automatic Molding

Automatic molding is a process for automatic charging of resin into the mold followed by compression. It is usually utilized for mass production of small parts with a fairly simple geometry. The main requirement of the resin is good flow for easy and complete filling of the mold and part-to-part uniformity. Consistent resin shrinkage is mandatory to obtain consistent size parts. The combination of high productivity and low labor requirements of automatic molding render this process highly desirable for production of rings, seals, spacers, valve seats, etc., where large numbers of relatively inexpensive parts are needed.

Figure 5.14 presents a schematic diagram of the four stages of automatic molding. In the first step, the free flowing resin is charged into the mold cavity formed by the lower ram (punch) and the outer mold. Pressure is actuated during step 2 and the upper ram compresses the resin for a few seconds. In step 3 the upper ram is retrieved. Finally, the lower punch pushes the preform up out of the cavity during step 4, also known as *de-molding*. These operations take place automatically according to preset conditions.

A higher pressure than ordinary compression molding is required for automatic molding because of the short duration of the compression cycle. The effect of pressure on the specific gravity of the preform has been shown in Fig. 5.15 which shows that the specific gravity increases with increased pressure independent of the dwell time.

5.1.4 Isostatic Molding

This technology was originally invented for ceramic and powder metal processing early in the twentieth century. It has been adopted to produce parts from granular PTFE powders. Isostatic molding (sometimes called *hydrostatic molding*) is another technique for producing PTFE preforms by the application of hydrostatic pressure to the powder. The powder is loaded in a closed flexible mold. Compaction of the powder into a preform takes place by pressure applied through the flexible part (bladder) of the mold. The bladder is usually made of an elastomeric material such as polyurethane. This method allows molding of complex shapes by the placement of mandrels inside the flexible bladder.

5.1.4.1 Introduction to Isostatic Molding

Isostatic molding is a suitable alternative to compression and automatic molding techniques for the production of PTFE parts with complex shapes in a wide range of sizes. Compression molding can supply a stock shape which can be machined to obtain the desired shape. The drawback to this option is the extensive machining and material cost which can drive up the cost of the part. Isostatic molding requires relatively low-cost tooling and allows significant savings in machining and material costs. Complicated parts in the exact or nearly exact shape and size, requiring some finishing, can be molded and sintered by this method. A bellows is an example of a part which can be directly molded by isostatic molding, while extensive machining is required to achieve the curved contour of the bellows. Isostatic molding is the method by which all shapes of preforms can be made.

Figure 5.16 shows the principal steps for isostatically molding a simple solid cylinder. The mold cavity is formed inside an elastomeric membrane shaped like a hollow cylinder. In this case, it does not include any mandrels and is completely filled with the powder. The elastomeric bag is closed, sealed and placed inside a pressure vessel. The vessel containing a fluid is sealed, pressurized and held for a dwell period during which the powder is compacted by the action of a pressurized fluid. At the end of the dwell time, the vessel is depressurized and the mold is removed and disassembled for the removal of the preform.

The flexible nature of the bag renders the definition of its volume difficult when compared to a metallic mold. The shape of the bag may also change during the filling step unless it is supported while being charged. The change in the shape of the bag depends on several factors:

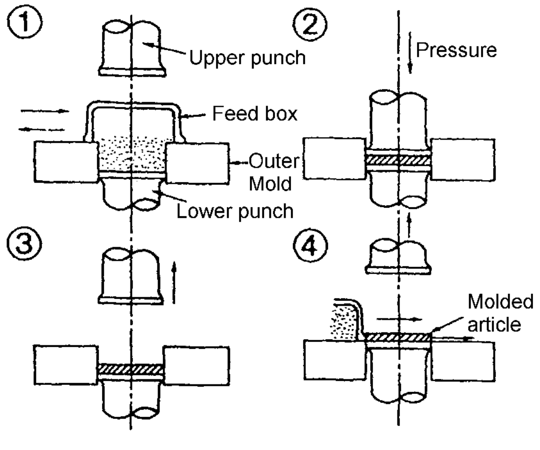


Figure 5.14 Automatic compression molding diagram.[3]

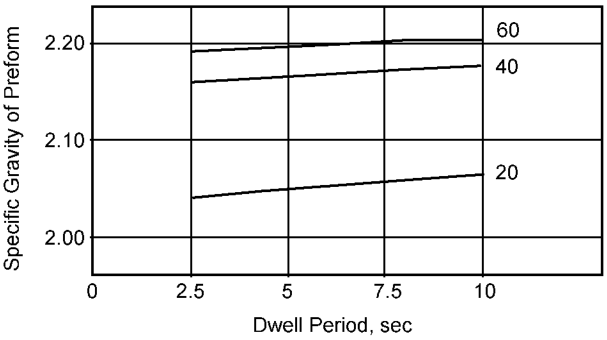


Figure 5.15 Relationship of molding pressure/dwell period and specific gravity of preform.[3] Note: The numbers in the graph indicate the molding pressure (MPa). Dimensions of the molded article: 64 (O.D.) × 52 (I.D.) × (length) mm.

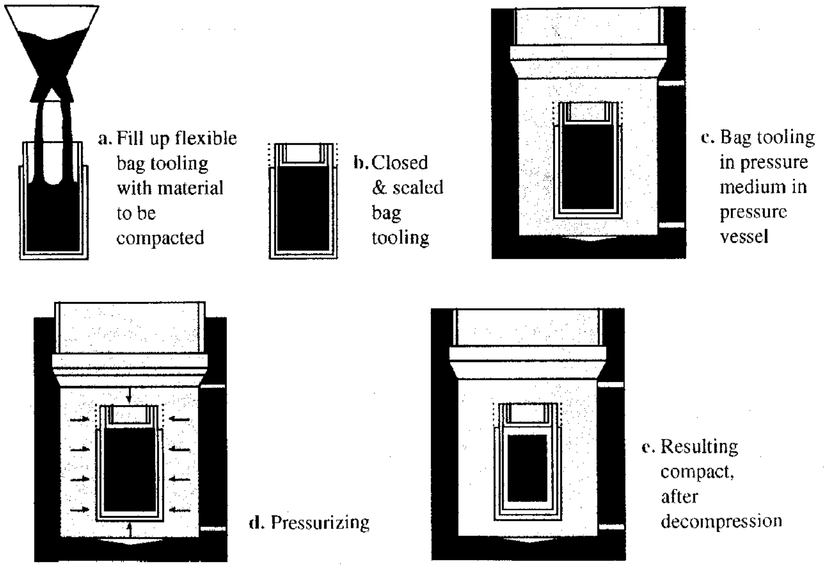


Figure 5.16 Principal steps of isostatic molding.[4]

- The original mold shape.
- Fill uniformity.
- The geometry and wall-thickness of the flexible segments.
- Elastic properties of the bag.
- The fastening of the rigid and elastic sections of the mold.
- The extent and the rate of powder compaction.
- The residual stress in the bag.

Exertion of pressure on the bag is multidirectional which conforms the resin powder to all patterns and nonuniformities in the bag. Consequently, the surfaces adjacent to the bag are less smooth than those adjacent to the smooth metallic surfaces. The importance of surface formation is one of the considerations that determines the selection of the type of molding process.

Isostatic molding is ideal for manufacturing thin long objects from small tubes (5 mm diameter) to very large diameter thin wall tubes (30 cm diameter). Examples include pipe liners, liners for valves and fittings, flanged parts, closed end articles, and a host of other shapes which would require extensive machining. Table 5.3 offers examples of isostatically-molded parts and their applications.

5.1.4.2 Comparison of Isostatic with Other Fabrication Techniques

Very little pressure decay occurs during isostatic compaction because of the absence of die wall friction. The absence of pressure decay permits making a great range of shapes, complexity, and sizes. This process yields a stress-free homogenous preform that exhibits uniform shrinkage during sintering. It results in a component free of distortion with uniform physical properties. The even and constant application of pressure throughout the cycle time results in a preform with lower void content. This is why shrinkage is lower, and specific gravity and physical strength are higher than those obtained by other techniques. The high extent of compaction allows the use of lower pressures in isostatic molding.

A drawback of isostatic molding is that the bag cannot produce sharp and perpendicular corners. Furthermore, the bag follows the contours of the resin particles and produces a less smooth surface than

Table 5.3. Examples of Isostatically Molded Parts

Isostatically Molded Part	Applications
Thin Wall Objects	Pipe liners: 2.5–30 cm diameter, 2.5–50 mm wall thickness, up to 6 m length
	Pump, valve, and fitting liners
Flanged Articles	T pieces, spacers, elbows
Closed End Articles	Cups, nose cones, radomes, bottle and caps, test tubes, crucibles and laboratory ware
Encapsulation	Magnetic stirrers, butterfly valve flaps and thermocouples
Textured Objects	Beehive insulators, embossed articles, valve gate covers vessel covers and threaded parts
Solid Parts	Pyramids, balls and stopcocks,
Parts with Embedments	Reinforced mesh or sheet, bolt head or stud, conductor

compression or automatic molding methods. Some machining will be required to achieve sharp corners and a smooth surface. The lower cost of isostatic molds, labor, and material render the finishing machining affordable without upsetting the economics of this process. Simple parts such as straight tubes can be made with tight tolerances, better than ±2%.[5]

Isostatic cycle times as short as 12 seconds are possible for small simple parts. The length of the cycle increases with the complexity and size of the article. In such instances, this technique is often the only available method for the fabrication of those parts. An example is *in situ* formation of a PTFE liner inside a fitting such as a T-piece.

5.1.4.3 Wet- and Dry-Bag Isostatic Molding

Wet- and dry-bag are two techniques for isostatic molding which are principally identical but operationally different. The *wet-bag* process is similar to the basic molding procedure in which the mold is submerged in the pressurization fluid. In the dry-bag technique, the mold and the bag are fixed in place and the functions of the mold and the pressurization vessel are combined. The pressurization fluid is introduced through a high-pressure liquid supply system behind the flexible bag (Fig. 5.17). The mold assembly is designed to withstand this pressure. The term *dry-bag* contrasts the absence of submerged mold and wet mold assembly.

The dry-bag process has advantages over the wet-bag process. The operation of placing the mold in the pressure vessel has been eliminated. Sealing and unsealing of the mold and the pressure vessel have been reduced to just sealing and unsealing the mold. In addition to cycle time reduction, the risk of contamination of the preform with the pressurization fluid has been eliminated. The dry-bag process can be automated and is an excellent method for the large-scale production of parts. The disadvantage of this process is the large cost differential of the dry-bag and the wet-bag molds. Dry-bag molds must be able to withstand high pressure and in effect act as a pressure vessel. These molds must not be modified without reviewing the mold design because of safety considerations.

5.1.5 Ram Extrusion

Ram extrusion is the only continuous process for fabrication of parts from granular PTFE powders. All the required steps of granular processing are performed in one machine called a *ram extruder.* The most common shapes are solid round rods and tubes. Rectangular rods, L-shaped cross sections, and other ram extrudable profiles are occasionally fabricated.

5.1.5.1 Introduction to Ram Extrusion

There are three basic steps for processing granular resins:

- *Compaction* of the powder to make a preform.
- *Sintering* the preform, which consists of heating the preform above its melting point.
- Air *quenching* or slow *cooling* the sintered part to allow controlled crystallization of PTFE.

These steps are carried out inside the ram extruder continuously using a free flowing resin which is often a special presintered ram extrusion grade or a general purpose free flow powder (Fig. 5.18). These resins behave differently during extrusion. The commercial presintered resins have been specially designed for ram extrusion over a wide range of extrusion conditions and can be converted into a wide range of parts such as round rods with a diameter 2 mm to 400 mm. These parts have excellent physical properties and have high resistance to fracture at the interface of charges (or doses) called *poker chipping* in the industry. Presintered resins can undergo much higher pressures during extrusion than ordinary free flow granular powders, making them especially suitable for small diameter rods and thin wall tubes. General purpose free flow granular powders are more suitable for larger rods (>2 cm diameter) and thick wall tubes.

5.1.5.2 Ram Extrusion: Basic Technology

Two types of common commercial equipment are vertical and horizontal extruders where the direction

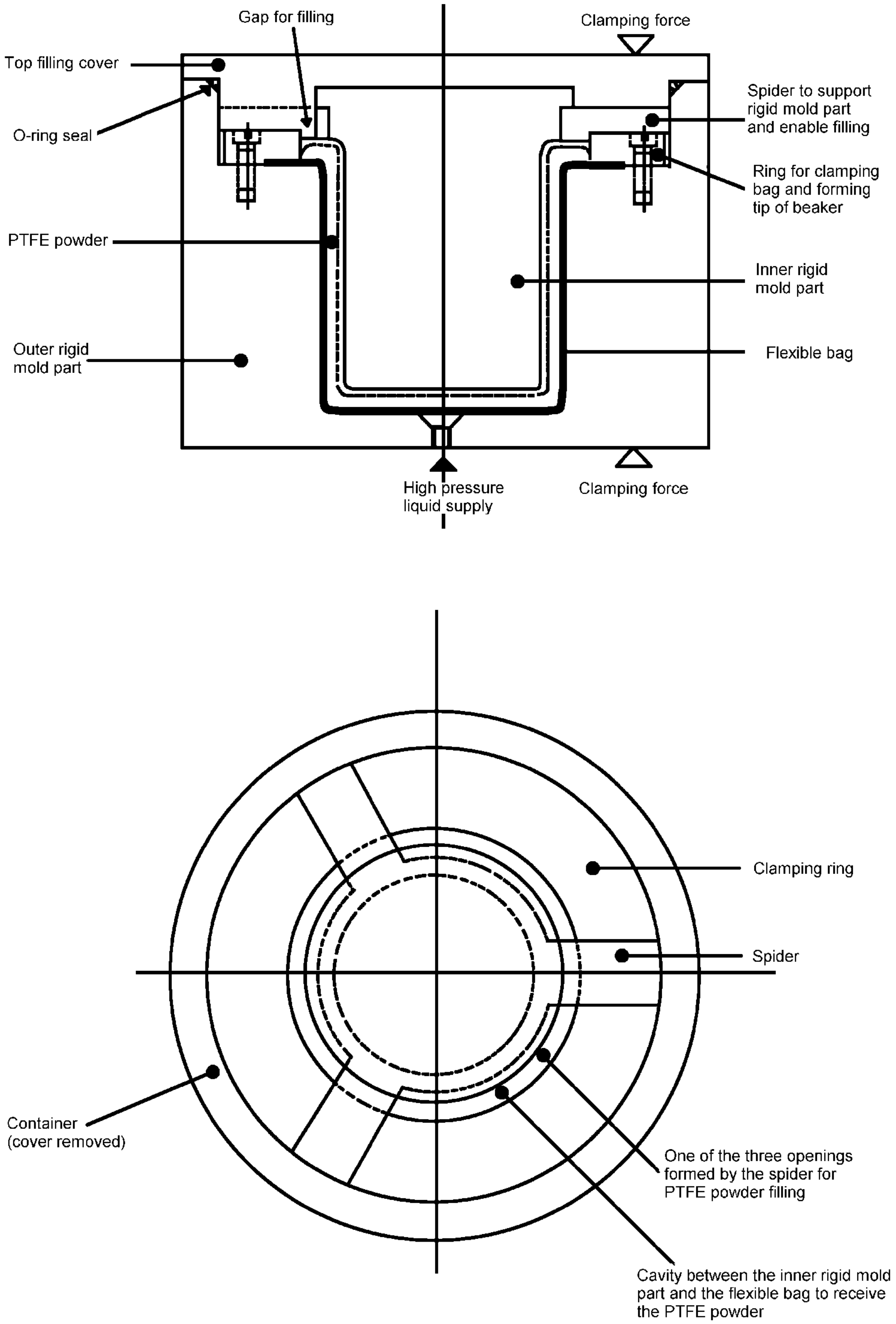


Figure 5.17 Mold for the production of a beaker using an outer flexible bag and inner rigid part.[5]

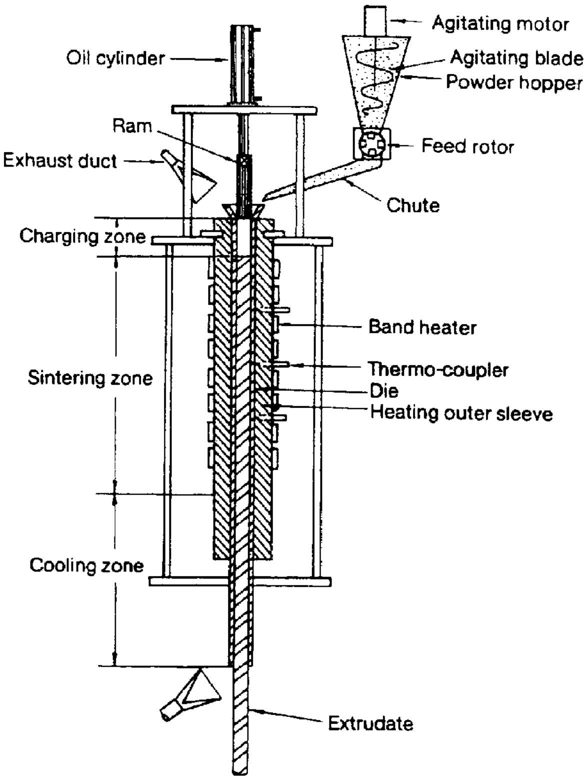


Figure 5.18 Ram extruder.[5]

of the ram motion and the extrudate are, respectively, vertical and horizontal. The fundamental working principles of the two pieces of equipment are the same. The key difference between them is the method of extrudate support. In horizontal ram extrusion, a tray or other similar means can support the extrudate. In ram extrusion, especially a vertical machine, a mechanical *brake* may be needed to protect the extrudate and provide backpressure for coalescence. This brake is usually a chuck, collet or a gland that grips the extrudate and applies a controlled amount of pressure.

In both vertical and horizontal machines, a metered quantity of granular powder is charged to the feed section of the die. This end of the die is cooled to allow easy flow of the resin into the die. PTFE particles and agglomerates become sticky and powder flow suffers when heated above 25°C. The next step is compacting the powder and pushing it into the heated segment of the die by the forward action of the ram. Repetition of these steps advances the compacted resin through the heated length of the die where sintering of PTFE takes place. The adjacent charges of the resin are welded to each other under pressure while sintering is taking place.

Examples of parts made from granular PTFE resins are shown in Figs. 5.19–5.23.

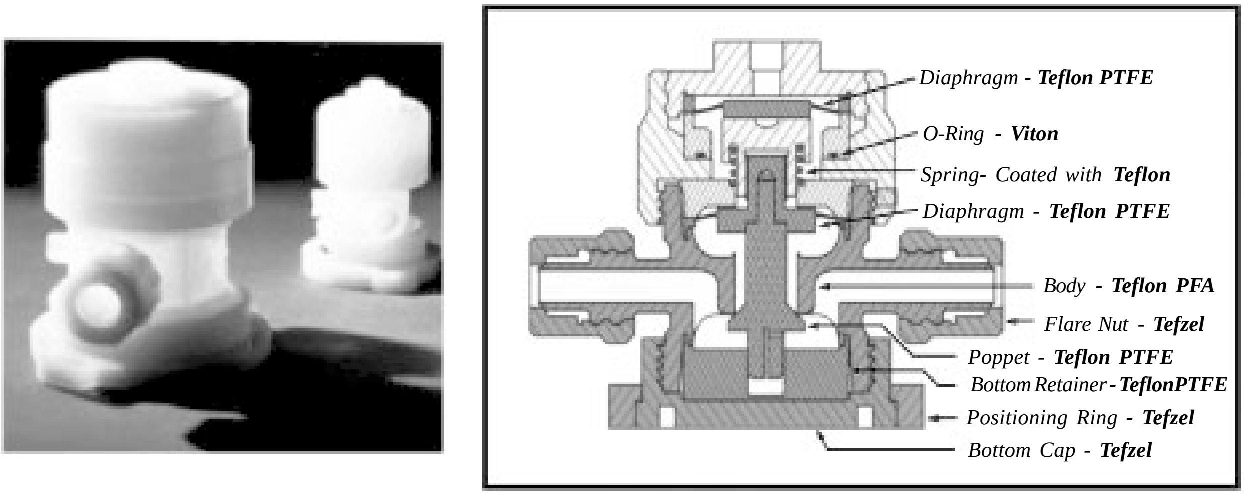


Figure 5.19 High purity fluid flow regulators. *(Courtesy Furon Fluid Handling and DuPont Companies.)*

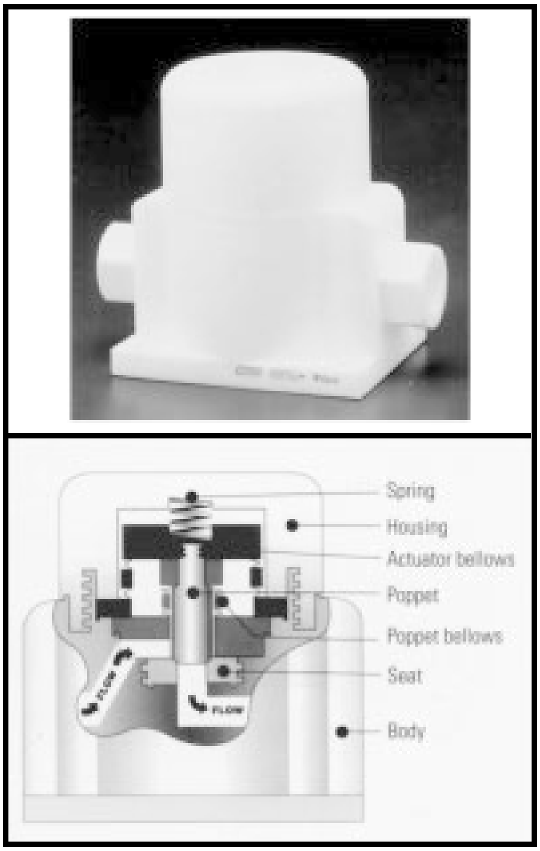


Figure 5.20 Poppet valves of PTFE for high purity applications. *(Courtesy Mace Products and DuPont Companies.)*

Figure 5.21 High purity flow controller and buret. *(Courtesy Mace Products and DuPont Companies.)*

Figure 5.22 PTFE lined pipe. *(Courtesy Crane Resistoflex and DuPont Companies.)*

Figure 5.23 Examples of PTFE lined components. *(Courtesy Crane Resistoflex and DuPont Companies.)*

5.2 Fine Powder Resin Processing

This section discusses the fabrication of PTFE, known as *fine powder* or *coagulated dispersion powder,* into shapes and articles. The most common fabricated commercial forms include rods, tapes, wire insulation, tubing, sheeting, and other profiles. Tube diameters range from a fraction of a millimeter to almost a meter with wall thicknesses of 100 µm to a few millimeters. Rods up to 5 cm diameter can be produced and calendared, prior to sintering, to produce tapes. Unsintered tapes are broadly applied as thread sealant tape in pipe fittings. Unsintered PTFE can be fabricated into cable, sheeting (Figs. 5.24 and 5.25), and pipeliner by wrapping the wire and mandrels followed by sintering.

Fine powder PTFE is fabricated by *paste extrusion*, where PTFE powder is first blended with a hydrocarbon lubricant (hence the term *paste*) which acts as an extrusion aid. It is then formed into a cylindrical preform at a fairly low pressure (1–3 MPa) and placed inside the barrel of a ram extruder where it is forced through a die at a constant ram rate. The extrudate is passed through multiple ovens and a cooling device where it is first dried, then sintered, and finally cooled. The lubricant can also be removed by extraction in a hot solvent bath.[6]

A major requirement of paste extrusion is that, up to the point of sintering and coalescence, the extrudate must possess sufficient strength to withstand the extensive handling that takes place during the process. The tendency of fine powder to *fibrillate* (form a web of strong filaments between particles) when extruded provides the needed strength and the unique characteristics of fine powder articles.

Reduction ratio, the ratio of the cross sectional surface areas of the preform and the extrudate, is an important variable in paste extrusion. For a given extruder barrel, the smaller the cross section of the final product, the higher the reduction ratio. The size of the preform can be varied in a fairly limited range, therefore, resins must be able to undergo the reduction during extrusion. Different fine powder grades have been developed by suppliers to accommodate the wide range of reduction ratios of commercial operations.

5.2.1 Resin Handling and Storage

Fine powder PTFE is susceptible to shear damage, particularly above its transition point (19°C). Handling and transportation of the containers could easily subject the powder to sufficient shear rate to spoil it if the resin temperature is above its transition point. The phenomenon called *fibrillation* (Fig. 5.26) occurs when particles rub against each other, in which fibrils are pulled out of the surface of PTFE particles. Uncontrolled fibrillation must be prevented to insure good quality production from the powder. Premature fibrillation leads to the formation of lumps which cannot be broken up easily.

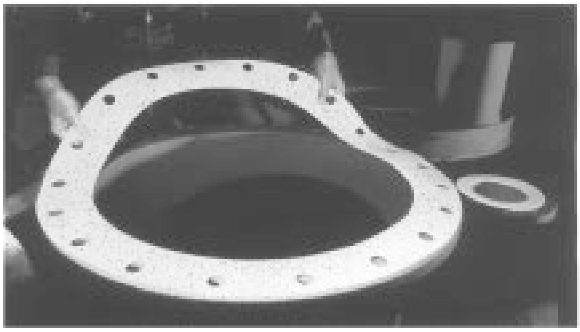


Figure 5.24 A Gore-Tex GR® sheet gasketing. *(Courtesy W. L. Gore and DuPont Companies.)*

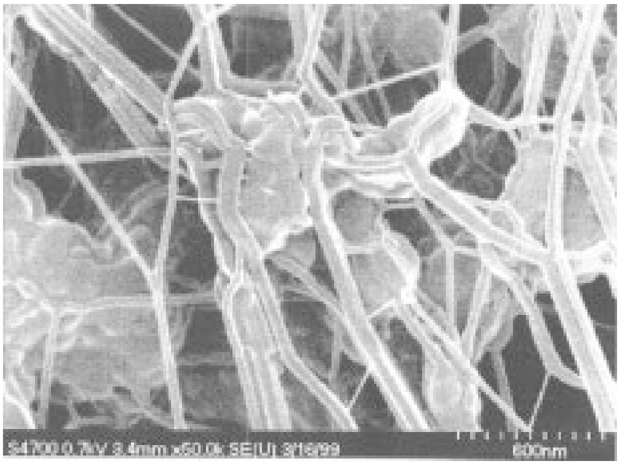


Figure 5.26 An example of biaxially oriented fibrillated PTFE structure. *(Courtesy of Mr. Clay Jones, DuPont Fluoroproducts.)*

To ensure that the resin does not fibrillate, it should be cooled below its transition temperature prior to handling and transportation. A typical commercial container (20–30 kg) should be cooled 24–48 hours to <15°C[7] to assure temperature uniformity throughout the container. In practice, drums of resin are stored and transported at <5°C. Specially designed shallow cylindrical drums are used to minimize lump formation, compaction, and shearing of the resin.

Individual particles of PTFE form agglomerates which are roundish and average several hundred microns in size.

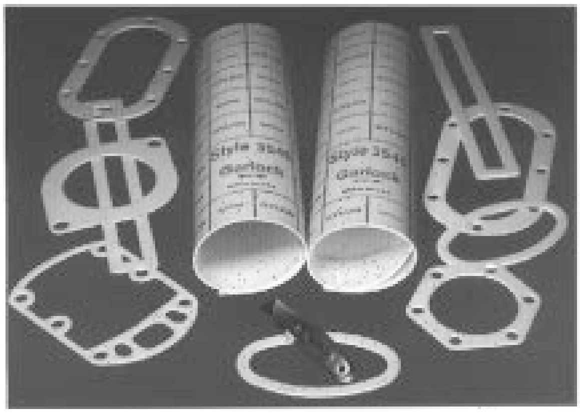


Figure 5.25 A Gylon® sheet gasketing material. *(Courtesy Garlock and DuPont Companies.)*

5.2.2 Paste Extrusion Fundamentals

The principals for fine powder processing can be summarized as:

- Fine powder PTFE is sensitive to mechanical shear, especially above its 19°C transition point.
- Shear stress causes fibrillation of fine powder particles. Resin fibrillation increases when extrusion pressure is raised.
- All transportation, storage, and handling of the powder must take place below its 19°C transition temperature.
- Paste extrusion should take place at above 30°C which is another transition temperature of the polymer.
- A hydrocarbon lubricant is added to PTFE to aid in processing. It is removed prior to sintering the article.
- The extrudate develops strength in the direction of extrusion as a result of fibrillation, permitting its handling in the process.
- Extrusion pressure is a function of the molecular weight of the polymer and lubricant content of the preform for a given reduction ratio. The higher the molecular weight, the higher the extrusion pres-

sure will be. The higher the lubricant content, the lower the extrusion pressure will be.

- Extrusion pressure is a function of several variables which are listed below:
  - Resin Type
  - Reduction Ratio
  - Lubricant Content
  - Lubricant Type
  - Die Cone Angle
  - Die Land Length
  - Extrusion Speed
  - Temperature

5.2.3 Extrusion Aid or Lubricant

The extrusion aid must easily coat the resin yet be readily removable from the extrudate. It should also not leave a residue which could alter the color of the product. The volatilization temperature of the lubricant should be lower than the sintering temperature of the polymer. The other requirements of lubricants include high purity, low odor, low polar components, high auto-ignition temperature, low surface tension, and low skin irritation. Common lubricants are synthetic isoparaffinic hydrocarbons available in a wide boiling range. Some of the commercial lubricants include Isopar® solvents (available from Exxon Corp.), mineral spirits, and VM&P Naphtha (available from Shell Corp.).

The amount of lubricant in the compound depends on the type of product, equipment design, and the desired extrusion pressure. Its content should be as low as possible but not so low that the extrusion pressure would be excessively high. A less volatile extrusion aid is often recommended for the manufacture of an unsintered tape.[8] The range of lubricant content is 15%–25% of the total weight of the compound.

5.2.4 Wire Coating

One of the important applications of fine powder polytetrafluoroethylene is wire insulation primarily for automotive, aerospace, and industrial applications where high temperature rating and resistance to chemicals are required.

5.2.4.1 Blending the Resin with Lubricant

Blending is performed most frequently by two methods: bottle or jar blending and motorized blenders. Neither technique has a clear advantage over the other. The bottle process is suitable for modest scale manufacturing. Large scale blending is usually done in a V-cone blender (see Fig. 5.27) such as the units offered by Patterson-Kelley Corporation, East Stroudsburg, Pennsylvania, USA.

The bottle or jar method (see Fig. 5.28) requires a wide mouth polyethylene or polypropylene bottle for easy (low shear) powder loading. The jars must be sealed tightly to prevent the loss of the lubricant by evaporation.

5.2.4.2 Preforming

This step, which usually takes place at room temperature, shapes the compound into a billet with the same shape as the barrel of the ram extruder. The rule of thumb is to compact the resin to one third of its initial height.[7][9] Preforming removes air from the PTFE powder by compaction.

Preforms are made in a cylinder equipped with a mandrel and a pusher. The mandrel is positioned in the center of the cylinder and the resin is charged in the annular space. The diameter of the preform and the center hole are designed to the following guidelines:

1. The outer diameter is 0.2–1.3 mm less than the inside diameter of the barrel.
2. The core diameter is 0.25 mm larger than the extruder wire guide (mandrel).

The aged lubricated resin without lumps is loaded into the preform cylinder and is evenly distributed around the core mandrel to ensure uniform compaction throughout the preform. The pusher is put on top of the cylinder and compaction commences. Resin compression can begin at a fairly rapid rate but has to be reduced at the latter stages of compaction. This rate reduction is size dependent (Table 5.4) and is aimed at the prevention of air entrapment, otherwise the preform may crack.

Figure 5.27 Patterson-Kelley twin-shell liquid solids blender. *(Courtesy Patterson-Kelley Co., Div. of Harsco Corp.)*

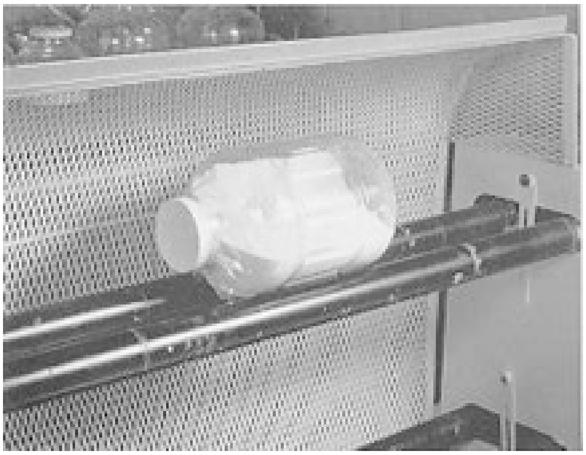


Figure 5.28 Blending fine powder PTFE by bottle rolling. *(Courtesy DuPont.)*

Low pressure should be used to compact the powder in the cylinder. At the initial stage, 0.5–1 MPa pressure is applied which should be increased to 2 MPa by the end of the compression cycle. The criteria for pressure selection is to compress the resin at a sufficiently high pressure to push the air out and prevent preform cracking.

The preform is quite weak and can easily break or deform, therefore it requires care during removal from the cylinder.

5.2.4.3 Extrusion Equipment and Process

Table 5.4. Preforming Compaction Rate (cm/min)[7]

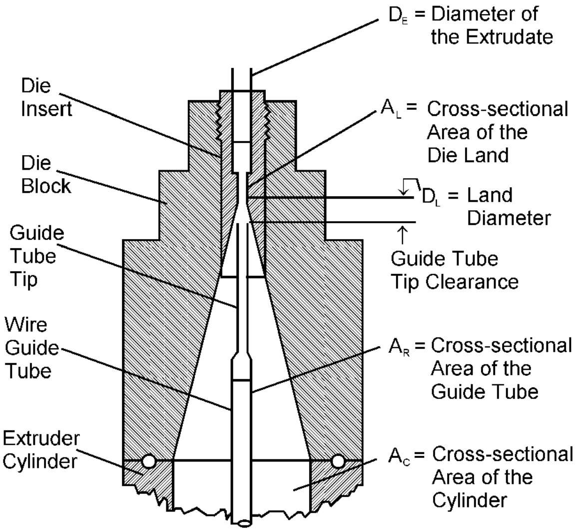
Compression Stage	Preform Diameter, cm	
	< 8 cm	> 8 cm
Initial	25	25
Middle	5.0	5.0
Final	5.0	1

In a paste extrusion line for wire insulation, the wire is passed through the paste extruder where it is coated with PTFE while moving through the die. It then enters a vaporizing oven where it is stripped of the lubricant by evaporation. Next, the dried and coated wire goes into the sintering zone, which usually consists of several individual ovens placed in series. Temperatures of the ovens are set to quickly heat the polymer above its melting point. After leaving the ovens, the wire is cooled and passed through a *spark* tester where the insulation is subjected to a voltage for the detection of flaws. The last step is winding the wire on a spool, which is done by a motorized take-up system and sometimes a concentricity meter.

The ram extruder for this process is a special unit and can be either horizontally or vertically oriented, which refers to the direction of the ram movement. The extruder consists of a heated barrel where the preform is loaded, and a hydraulic or screw-driven ram. The conductor is drawn by a power system through a hollow mandrel located at the center of the barrel. The mandrel terminates in a wire guide tube.

The preform fibrillates in the die under ram pressure and forms an extrudate, which should have the right thickness and smoothness. The preform is pressed through the extruder cylinder (barrel) with little pressure development until it reaches the die, where the cross section area for the passage of the preform decreases by the angular design of the wall (Fig. 5.29).

There are two configurations of drying ovens: internally heated with tubular design, and horizontal heated console design; both are vented to remove the vapors. A typical tubular oven is about 3 m long with a diameter of 150–200 mm. One or two 3 m ovens are required for complete drying. Temperature at the oven entrance is 150°C and at the exit 300°C. In the heated console type oven, several meters of the wire are wound around multiple sheaves which allows longer residence time in this oven than the tubular kind. Temperature is lower in console ovens and ranges between 90°C and 200°C.



$$\text{Reduction Ratio} = \frac{A_C - A_R}{A_L - A_{Wire}}$$

Figure 5.29 Details of master die.[7]

The polymer must be heated to above its melting point of 342°C for a brief period of time for melting to occur. The oven temperatures are typically set at 400°C–600°C, based on a number of variables including the speed of the wire and thickness of the coating. Heat transfer to the polymer accelerates at these temperatures, but care must be taken to prevent exposure of PTFE to temperatures above 380°C where degradation begins to speed up.

The wire is usually allowed to cool by natural convection in the ambient air. Blowers can be installed to move the warm air away from the area.

Tables 5.5 and 5.6 show examples of manufacturing process variables for coating of wires, which comply with US Military (MIL) Standards, using two commercial resins.

Higher reduction ratio increases the extrusion pressure, which can be reduced by the type of lubricant used and increasing its content. Figure 5.30 illustrates the effect of reduction ratio on extrusion pressure for two commercial resins. The relationship is close to linear, e.g., a doubling of reduction ration nearly doubles the extrusion pressure.

5.2.5 Extrusion of Tubing

The majority of tubes made from PTFE by paste extrusion have fairly thin walls (<8 mm) and are produced in a wide size range from a fraction of millimeter to several centimeters in diameter for applications ranging from fluid transfer in healthcare to fuel and hydraulic transfer in jet engines. Tubing is divided into three categories based on the size and wall thickness, for various applications. Table 5.7 summarizes the size and applications of each type. Pressure hoses are composite devices of one or two layer PTFE lining reinforced with over-braiding, usually metal wire, to increase its pressure rating.

5.2.5.1 Spaghetti Tubing

A small vertical paste extruder can be used to manufacture spaghetti tubing. The small size of this kind of tubing eliminates most of the handling problems associated with larger ones. A vertical machine can extrude upwards or downwards.

Extrusion conditions are quite similar to those used in wire coating.

5.2.6 Pressure Hoses

This class of tubing serves critical purposes in a number of industries. The normal size range is from 6 to 50 mm in diameter. The tube sizes in the United States have a special designation. In the industry parlance, they are called by a dash number, such as – 4 (dash four) or –12 (dash twelve). To obtain the diameter of the tube in inches, the number must be multiplied by 1/16, thus, – 4 is equal to 1/4 inch and –12 is equal to 3/4 inch.

PTFE tubes form the inside liner component of these hoses and come in contact with the fluid. Chemical resistance and durability at extreme temperatures are supplied by polytetrafluoroethylene but mechanical integrity has to be fortified. The reinforcement of the tubing results in significantly higher operating pressure than can be achieved with the tube alone. Figure 5.31 represents one example of braiding by which the tube is fortified. Stainless steel wire (filament) is braided in the pattern seen in the Fig. 5.31a. Braiding can be done in double or triple layers using other fibers such as glass or high

Table 5.5. Recommended Tooling and Processing Conditions for Extruding E223 Constructions of Teflon® CFP 6000 Fluoropolymer Resin[7]

Variable	Unit	Barrel Size, in (mm)		
		1.75 (44.5)	2.0 (50.8)	2.5 (63.5)
Mandrel, O.D.	in (mm)	0.625 (16.9)	0.625 (16.9)	0.75 (19)
Conductor, O.D.	in (mm)	0.0296 (0.75)	0.0296 (0.75)	0.0296 (0.75)
ISOPAR G Concentration	wt%	16.5	18.0	18.5
Die Size	in (mm)	0.056 (1.42)	0.056 (1.42)	0.056 (1.42)
Tip, I.D. × O.D.	in (mm)	0.032 × 0.042 (0.81 × 1.06)	0.032 × 0.042 (0.81 × 1.06)	0.032 × 0.042 (0.81 × 1.06)
Tip Clearance	in (mm)	0.08–0.10 (2.03–2.53)	0.08–0.10 (2.03–2.53)	0.08–0.10 (2.03–2.53)
Blow-up, O.D.	in (mm)	0.057–0.058 (1.45–1.47)	0.058–0.059 (1.47–1.49)	0.058–0.059 (1.47–1.49)
Finished O.D. (hot)	in (mm)	0.050 (1.26)	0.050 (1.26)	0.050 (1.26)
Wire Speed	ft/min (m/min)	260 (79)	260 (79)	260 (79)
Pressure	psig (MPa)	8,000 (57.6)	9,000 (64.8)	11,000 (79.3)
Reduction Ratio	—	1250:1	1700:1	2500:1
Vaporizer	°C (°F)	177 (350)	177 (350)	177 (350)
Sintering Oven Zone	°C (°F)			
1		482 (900)	482 (900)	482 (900)
2		538 (1,000)	538 (1,000)	538 (1,000)
3		566 (1,050)	566 (1,050)	566 (1,050)
4		593 (1,100)	593 (1,100)	593 (1,100)
5		482 (900)	482 (900)	482 (900)

Table 5.6. Examples of Electric Wire Insulation Molded from Daikin PTFE[10]

Item	F-201		
	I	II	III
Core wire structure (no. of strands/diameter mm)	7/0.320	19/0.127	7/0.127
Wire plating	Silver	Silver	Silver
Wire outside diameter (mm)	0.96	0.64	0.38
Insulation thickness (mm)	0.25	0.25	0.15
MIL standard	E-20	E-24	ET-28
Extruder:			
Cylinder diameter (mm)	38	38	38
Mandrel diameter (mm)	16	16	16
Die angle (degree)	20	20	20
Die tip diameter (mm)	1.60	1.321	0.762
Guide tube diameter (mm)	1.067	0.686	0.406
Reduction ratio (R.R.)	732	899	2751
Amount of extrusion aid blended (weight part)	19.0	21	22
VM&P Naphtha (% by wt)	15.9	17.3	18.0
Preforming pressure and time (kg$_f$/cm^2 × min)	25 × 5	25 × 5	25 × 5
Guide tube/guide tip clearance	0.8	0.6	0.3
Calculated value (mm)	(0.78)	(0.76)	(0.62)
Die temperature (°C)	50	50	50
Extruder ram speed (mm/min)	18.3	19.0	11.0
Haul-off speed (m/min)	8.2	14.0	18.2
Extrusion pressure (kg$_f$/cm^2)	615	500	1015
Oven temperature:			
#1 drying (°C)	95	95	95
#2 drying (°C)	205	205	205
#3 sintering (°C)	400	400	400
Molded product dimensions			
Outside diameter (mm)	1.52	1.10	0.68
Insulation thickness (mm)	0.28	0.23	0.15
Number of sparks	None	None	None
Test voltage (kV)	(3.4)	(3.4)	(1.5)

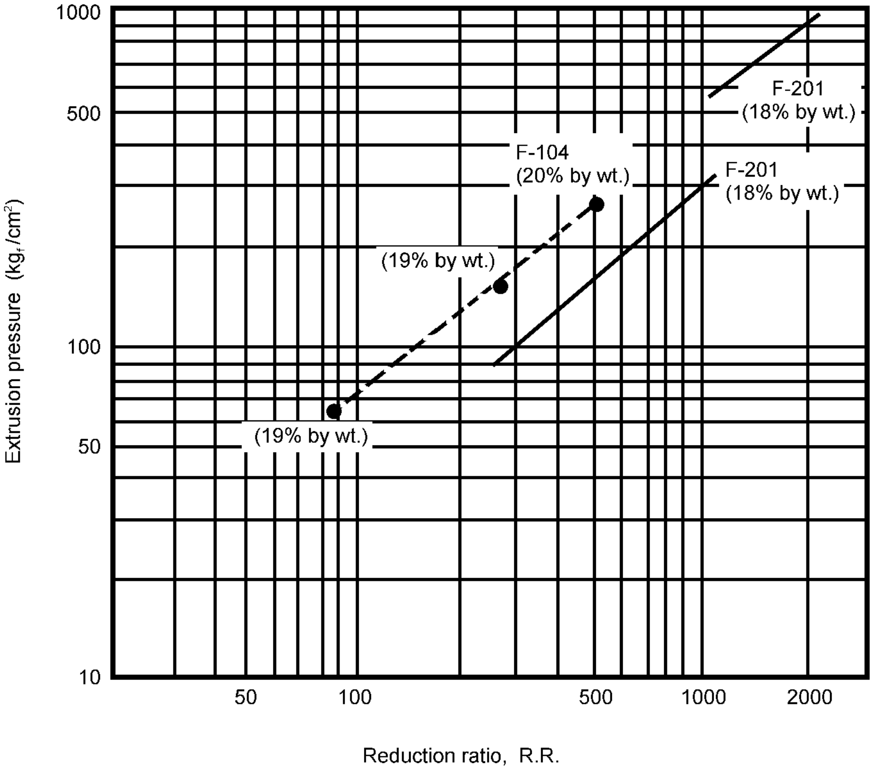


Figure 5.30 Relation of reduction ratio and extrusion pressure.[10] Note: Extrusion aid used: Super VM&P Naphtha (Shell); Extruder used: Jennings extruder.

Table 5.7. Types of Tubing and Applications Made from Fine Powder PTFE

Type of Tubing	Diameter, mm	Wall Thickness, mm	Applications
Spaghetti Tubing	0.2–8	0.1–0.5	Electrical Insulation, Fluid Handling in Medical Equipment and Chemical Applications
Pressure Hose	6–50	1–2	Fuel and Hydraulic Transfer in Aerospace, Chemical and Gas Transfer in Chemical Processing
Pipe-liner	12–500	2–8	Lining Metal Pipes and Fitting for Chemical Processing

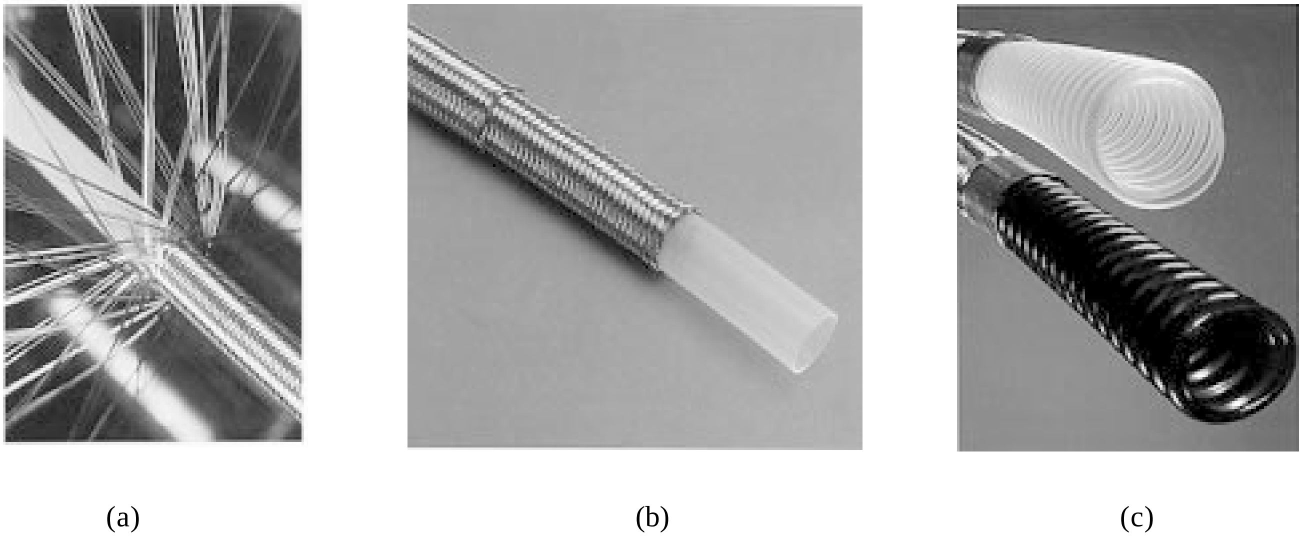

(a) (b) (c)

Figure 5.31 Reinforcement of PTFE tubing: *(a)* braiding of PTFE tubing with stainless steel, *(b)* hose in TEFLON 62 with double braiding for high pressure applications, *(c)* overbraided convoluted tubing—natural and antistatic.[11]

performance polyaramid yarns such as Kevlar®. Figure 5.31b illustrates an example of a double braided tube with stainless steel filament. The tubes are fitted with metal inserts and fittings for connection.

Some applications require flexibility to bend and curl the hoses. To accomplish this, the extruded and sintered tubes can be convoluted in a separate step. The tube is passed through a heated die, which melts the PTFE and creates a spiral peak and valley pattern into the tube. A key requirement of the convolution process is to assure that the wall thickness remains uniform, in other words, the tube is not stretched. Any thinning of the wall will weaken and reduce the burst pressure of the hose. Figure 5.31c shows an example of convoluted tube, which is partly braided with stainless steel.

Another issue in high velocity transport of hydrocarbons such as jet fuel is the build up of static charge on the interior layer of the PTFE tube. The discharge of static charge in the absence of oxygen can lead to a failure in the form of a pinhole in the wall of the tube and subsequent leakage. In the presence of oxygen, static discharge could act as an ignition source. To overcome this problem, the inner layer of the tube is made from a 1%–2% carbon-filled PTFE, which would then allow surface drainage of static charge through the metal fittings. The inside part of the preform is made of carbon-filled PTFE by essentially partitioning the mold.

Pressure hoses find applications where corrosive liquids and gases are transported. Examples include:

- Hydraulic fluid and fuel transport in aerospace industry
- High pressure air, fuel, and hydraulic transfer in automotive industry
- Chlorine, steam, acids, and organic compounds in the chemical processing industry
- High purity transfer lines in the pharmaceutical industry

The hose must meet numerous requirements in the various high pressure applications:

- Low permeability
- High flex life
- Good mechanical properties
- Chemical resistance
- Service at extreme temperatures
- High purity

The stiffness of the hose increases because of the larger content of the amorphous phase PTFE. Flex life increases while flex modulus, which is a measure of the ease by which the tube can be bent, decreases (see Table 5.8).

Table 5.8. Stiffness as a Function of Crystallinity[11]

% Crystallinity	Specific Gravity	Flexural Modulus, psi	Flex Life (cycles to failure)
50	2.14	40,000	4×10^6
53	2.15	54,000	$1–4 \times 10^6$
75	2.22	150,000	6×10^4
85	2.25	170,000	1×10^3

5.2.6.1 Blending Lubricant and Pigment and Preforming

Resin lubrication, pigmenting, and preforming should be done similarly to preparations described for wire coating.

5.2.6.2 Extrusion Process for Pressure Hoses

The process of choice for larger diameters (2–5 cm) has been continuous vertical extrusion where the preform is extruded in a downward direction without subjecting the tube to any bending prior to the completion of the cooling step. The problem with bending a preform or even a partially sintered tube is that mechanical damage (e.g., cracking) to the part done by bending cannot be corrected by the sintering process.

The ideal cooling technique is to quench the tube instantly in very cold water to minimize crystallinity. Practically speaking, modified PTFE can be quenched in cool water without a sizable increase in its crystallinity. The adequacy of sintering and cooling can be determined by measuring the heat of fusion by differential scanning calorimetry (DSC). Unsintered polymer will manifest itself by a peak at or above the first melting point of PTFE (342°C). Oversintered polymer can be detected by the large value of the second heat of fusion (approx. >28–30 J/g). The intensity of quenching is observed by the value of first heat of fusion (approx. 20–23 J/g).

5.2.6.3 Quality Control of Pressure Hoses

Stress cracking is the main reason that high pressure overbraided hoses fail. The variables include mechanical stress at fittings, the type of chemical environment, process variables and the polymer type. A number of industrial and military aerospace specifications have addressed themselves to the questions of testing and requirements of pressure hoses. An example is MIL-H-25579, which is used by the United States Air Force for military aircraft hose specification. The types of measurements required by such specifications are lengthy and time consuming. There are a number of rapid tests which simplify the task of assessment of hose quality.

A tube which meets requirements of the simplified tests is highly likely to meet formal specifications:

a. *Stretch Void Index (SVI):* This test is an indication of the number of voids present in the PTFE tube.

b. *Weep Test:* This method is used to determine the minimum pressure (WP) at the onset of a leak of military fuel through the tube.

c. *Orientation Index (OI):* This index is a measure of the degree of orientation in the machine direction (longitudinal) versus that of the cross direction (transverse).

A high quality aerospace hose should meet the following criteria:

Total SVI <2%
WP >0.70 burst pressure
OI <0.1

The tests to measure these indices are described in the following paragraphs.

Stretch void index (SVI). SVI provides an indication of the number voids in the part. It indicates how well the sintering and coalescence have eliminated small voids, which can be present because of the processing technique or the properties of the resin. Voids directly affect the performance of a tube in the end-use. For example, a void free or low void content part will have a longer flex life and greater flex fatigue resistance than a part containing more voids.

This index relies on the change in the specific gravity of a specimen that has been elongated in an *extensometer*. The procedure for measuring SVI can be found in ASTM D4895. It basically consists of preparing a microtensile bar and stretching it to 200% of its initial length in 1–1.5 minutes. Next, the specific gravity of both stretched and unstretched samples are measured and the SVI is calculated from Eq. (5.1).

Eq. (5.1)

$$\mathrm{SVI} = \frac{\mathrm{SG}\left(\text{unstretched}\right) - \mathrm{SG}\left(\text{stretched}\right)}{\mathrm{SG}\left(\text{unstretched}\right)} \times 100$$

SVI should be measured in both machine and transverse directions to determine the extent of isotropy in the tube. If the SVI values are very low (<1%) in both directions or equal, the sample is isotropic. This means that the sample has been adequately sintered and stresses have been relieved. If the values are both high, sintering has been poor. If the transverse value is high and the machine direction value is low, then orientation is primarily in the machine direction and it is unbalanced.

Weep test. In this test, unbraided samples of the tube are pressurized by filling them with a military fuel (MIL-S-3136, Type III and MIL-H-25579) consisting of 70% isooctane and 30% toluene. A 15 cm length of the tube is filled with the fuel with a small amount of red dye added to it to improve the visibility of the leak. The tube is pressurized to an initial pressure calculated from Eq. (5.2).[11]

Eq. (5.2) $$\text{Initial pressure} = \frac{16.9t}{d}$$

where t = wall thickness (mm), and d = outside diameter (mm).

The factor 16.9 is the standard burst strength in the peripheral direction in MPa units. At this point, the pressure is increased in 0.035 MPa increments until seepage is observed. The results are recorded as the weep pressure and calculated as a percentage of the peripheral burst pressure.

Orientation index (OI). This factor is concerned with orientation of the polymer in the machine and transverse directions which builds strength in the tube. In the majority of paste extruded tubes, tensile strength is higher in the machine direction than in the transverse direction. OI provides a numerical value to monitor the disparity of the tube strength in the two directions.

If a thin-walled cylinder is subjected to a given pressure, P, Eqs. (5.3) and (5.4) can be used to calculate the stress in the longitudinal and peripheral direction.[11]

Eq. (5.3) $$P_l = P\frac{d-t}{4t}$$

Eq. (5.4) $$P_t = P\frac{d-t}{2t}$$

where P_l = stress in the longitudinal direction (MPa), P_t = stress in the transverse direction (MPa), d = outer diameter of the tube (mm), and t = wall thickness of the tube (mm).

A comparison of the formulas shows that the stress experienced by the tube in the transverse direction is twice as large as that in the longitudinal direction. It is desirable, ideally, for the tube to have twice as much tensile strength in the transverse direction than in the machine or longitudinal direction. The orientation during paste extrusion, however, takes place predominantly in the machine direction, that is, the direction of extrusion, of the unsintered tube. Sintering the tube properly closes the voids (35%–40% of the volume occupied by the lubricant) and eliminates the pre-sintering orientation. After sintering, molecular orientation is much more random in the molten phase. To freeze the orientation, the molten tube must be quenched rapidly in cold water. Slow cooling will allow the crystalline phase to orient itself back in the direction of extrusion because of the memory of the polymer molecules.

Orientation of the tube can be measured by x-ray diffraction. Practically, a comparison of the tensile yield strength of the tube in the two directions provides a measure of the orientation. The orientation index is, thus, defined as:

Eq. (5.5) $$\mathrm{OI} = 1 - \frac{\gamma_t}{\gamma_l}$$

where γ_t = yield strength in the transverse direction (MPa), and γ_l = yield strength in the longitudinal direction (MPa).

It can be seen that an orientation index of zero means that tube is randomly oriented, which is ideal. A value of one indicates that all orientation is in the longitudinal direction, which is the worst case.

5.2.7 Unsintered Tape

Major applications of unsintered polytetrafluoroethylene are as tape in thread sealing and wrapping electrical cables, and as rod and tape in packings. Important properties of PTFE like chemical resistance, broad service temperature, low friction, flexibility, high machine direction strength, and deformability in the cross direction make unsintered fine powder PTFE ideal for these applications.

Thread sealant tape is used in pipes and fittings in a variety of industries including water pipe, chemical, pharmaceutical, semiconductor manufacturing, food processing, and others.

Electrical grade tape is wrapped around the cable or wire, and then the construction is sintered to obtain good insulation and electrical properties. The same concept is applied to produce pipe liners, by tape wrapping a cylindrical mandrel. After sintering, the mandrel is removed and the liner is fitted into metal pipe casing.

Some tape is sintered, treated to impart adherability, and then coated with pressure-sensitive adhesive for wrapping objects to reduce friction or provide quick-release properties.

Another important area is oriented tapes and webs which are used in the fabrication of porous fiber, fabric, tube, and sheet. These porous articles find applications for protective clothing, waterproof and weatherproof fabrics, gaskets, filter bags, and many other items.

The unsintered tape is not directly produced in the final thickness and width. Rather, it is made by the extrusion of either a round or rectangular bead (thick ribbon) followed by calendaring which converts it to a thin tape. Calendaring is necessary to obtain tapes that are thin enough to be conformable to the pipe threads. Normally, the lower limit of thickness is 50–75 µm, but 25 µm thick tape can be made by calendaring. The important properties of electrical wrapping tape include adequate physical properties for handling, appropriate thickness, and excellent layer-to-layer adhesion.

Thread sealant tape, on the other hand, must perform after it has been applied to the pipe thread. Lower density enhances the drapability (deformation) of the tape around the threads. A balance between the tensile strength in the machine and transverse directions in the range of 15:1[12] is required to achieve the desirable deformability. Elongation of 100–200 in the transverse direction and better than 800% in the machine direction are desirable. The amount of fibrillation determines the tensile properties and deformability of the tape. Too little fibrillation will yield a tape with insufficient tensile strength while too much fibrillation will create a hard tape lacking enough deformation.

Examples of parts made from fine powder PTFE resins are shown in Figs. 5.24 and 5.25.

5.3 Fluoropolymer Dispersion Processing

This section discusses the coating of surfaces using dispersions and powders of fluoropolymers. A majority of the dispersions consumed are PTFE based; some FEP, PFA, PVDF material are also coated on different substrates. Powder coating resins are all melt processible fluoropolymers. Most of the parts used in the chemical processing industry are fabricated by powder coating which is covered in Ch. 8 of this volume. Liquid coatings are used in the rare cases in which powder cannot reach areas of a part with complex geometry.

This section does not cover the topic of coatings and finishes. These finishes are usually highly formulated and are applied as multiple-pass coatings which include special primers and intermediate layers. They may include pigments, additives, other resins, and more than one fluoropolymer. The main applications of fluoropolymer finishes are in cookware and industrial anticorrosion and high-temperature uses. A separate volume, *Fluorinated Coatings and Finishes*, a Plastics Design Library (PDL) volume in the *Fluorine Handbook Series* published by William Andrew, Inc., covers the topic.

One can think of the PTFE dispersion coating process as impregnation of fibrous or porous materials such as glass fiber, woven glass cloth, and polyaramide fibers and fabrics. The composite product combines the properties of PTFE and substrate. The polytetrafluoroethylene coated or impregnated products are characterized by a number of common attributes, Table 5.9.

Polytetrafluoroethylene dispersions are aqueous milky dispersions consisting of very (<0.25 µm) small particles of resin suspended in water.

The most common articles coated using PTFE dispersions are glass fabrics for architectural and industrial applications such as stadium roofs, valve and pump packing, flexible circuit boards, and conveyer belts. Formulating its dispersion into a form that can be spun through spinnerets can produce polytetrafluoroethylene fibers. Coatings and fibers of PTFE are usually sintered to improve mechanical properties. Other examples of applications of dispersions include cast films, packing, gaskets, bearings, and polymer additives. PTFE dispersions have high utility due to their fluid nature. This is especially important because polytetrafluoroethylene does not flow after melting and does not dissolve in solvents, therefore cannot be processed by melt or solution techniques.

5.3.1 Dispersion Applications

The end uses of polytetrafluoroethylene dispersions are numerous due to the convenience of coating techniques. They can be classified in different ways based on the point of view of product attributes or processing techniques. Table 5.10 is a product type summary of dispersion applications. The focus here is on the shape and form of the part, which influences the process by which they are fabricated.

Table 5.9. Attributes of Polytetrafluoroethylene Impregnated/Coated Material

Attribute	Source
Good Sliding without adding lubricants	PTFE
Non-stick properties	PTFE
High service temperature	PTFE and substrate
Water repulsion	PTFE
Chemical resistance	PTFE
Greater mechanical strength than natural PTFE	Substrate

Another advantage of dispersions is their capability for accepting larger amounts of fillers than PTFE powders. The process of incorporating the fillers is called co-coagulation. The main application of these compounds is in the fabrication of special bearings. There are a number of other smaller uses of PTFE dispersions in fuel cells, batteries, de-dusting, and chloralkali processing.

Another approach to the classification of the applications of polytetrafluoroethylene dispersions is the nature of thermal treatment of the fabricated part. Some articles are sintered, some are not sintered but heated to remove the water and surfactant. In some application, the parts are neither sintered nor heated high enough to remove the surfactant. Table 5.11 summarizes the process-based categorization of dispersion applications.

5.3.2 Storage and Handling of Dispersions

Most polytetrafluoroethylene dispersions should be stored at temperatures between 5°C and 20°C. Freezing the dispersion must be avoided due to its irreversible coagulating effect on PTFE particles. Maximum shelf life for dispersions is one year, although some dispersions may have shorter useful lives. Once a month, drums of stored dispersion should be rolled or gently agitated to rejuvenate them. Coagulation of PTFE particles can occur if the storage temperature is too high, if it is subjected to vigorous agitation or shearing, if shelf life is exceeded, monthly rejuvenation is not done, and if chemicals are added to the dispersion.

Microscopic examination of PTFE dispersion can reveal coagulation of particles. Under magnification, numerous white lumps indicate coagulation or spoilage of the dispersion. A normal dispersion, while it may contain an occasional coagulum, appears uniform and free of lumps.

Polytetrafluoroethylene dispersions may contain one or more surfactants (and other additives) such as perfluoroammoniumoctanoate, also known as “C8” in parlance of the industry. There are health hazards associated with some of the surfactants such as C8.

Table 5.10. PTFE Dispersion Products and Applications

Products	Applications
Coated woven glass cloth and fiber	Architectural fabrics, gaskets and laminates, electrical insulation, release sheets, hoses
Impregnated flax, polyaramides and PTFE yarn or yarn constructions (asbestos in the past)	Packings, seals, and gaskets
Dispersion cast PTFE film	Diaphragm and dielectric insulation in small capacitors, composite laminates
Coated material surfaces	Low friction and non-stick surfaces
Fabric and fiber finishes	Yarns, industrial fabrics, and filter cloth
Blends with polymeric and nonpolymeric materials	Flame non-drip plastics

Table 5.11. PTFE Dispersion Application Categories Based on Fabrication Processing

Sintered	Unsintered, Heated	Unsintered, Unheated
Coated woven glass cloth	Filtration cloth	Packings
PTFE yarn	Batteries	Gaskets
Cast films	Blends with polymeric and non-polymeric materials	Batteries (sometimes heated)
Coated metals		Dedusting
Co-coagulation products		Paint additives
Chloralkali processing		
Fuel cells		

Thorough review of the material safety data sheet for each surfactant must be made and protection measures taken to avoid/minimize exposure and emission.

5.3.3 Dispersion Formulation and Characteristics

This section reviews properties of dispersions and characteristics, which are important to the formulation and application of dispersions. They include solids content, pH, stability, and critical cracking thickness.

Dispersions of polytetrafluoroethylene are colloidal emulsions of small polymer particles (<0.25 µm) in water which are negatively charged. They contain relatively high concentrations of PTFE, which increases their specific gravity. An estimate of solids content can be obtained from the specific gravity (Table 5.12).

PTFE dispersions are supplied with a basic pH to prevent bacterial growth during storage, particularly when it is hot and humid. Bacteria feed on surfactant in the dispersion. Breakdown of the surfactants generates a rancid odor and brown discoloration in the dispersion. The pH can be reduced by adding acids, if necessary. It is important to control the amount of acid added to the dispersion because the increase in ionic strength of the dispersion can lead to coagulation of PTFE particles. As a matter of fact, increasing the ionic strength of polymer dispersion is one of the common methods for coagulation of dispersion to remove and dry the resin.

Ionic strength of a PTFE dispersion affects its conductivity. Conductivity is a very important characteristic of PTFE dispersions and can be a good indicator of its shelf life. It can be measured by a conductivity meter quickly and easily. Conductivity can also influence the viscosity and shear stability of the dispersion. Very high conductivity can destabilize the dispersion.

Stability of dispersion is important to its storage. It will partially settle during extended storage and when it is exposed to elevated temperatures (>60°C). A softly settled dispersion can be re-dispersed by gentle agitation. Freezing of the dispersion will lead to irreversible coagulation. Addition of water-soluble organic solvents or inorganic salts

Table 5.12. Specific Gravity of PTFE Dispersions[14]

Solids Concentration, %	Specific Gravity	Density of Solids, g/l
35	1.24	436
40	1.29	515
45	1.34	601
50	1.39	695
60	1.51	906

and other compounds will also destabilize the PTFE dispersion, and polymer coagulation will occur irreversibly.

The thickness of the wet coating affects the quality of the final sintered coating. An excessively thick layer will result in cracking after the polymer is dried. A *critical cracking thickness* is defined as the maximum thickness which can be coated in a single layer without formation of cracks. Layers in the thickness range of 5 µm to 25 µm can usually be cast without cracking concerns. The exact thickness is dependent on the formulation and type of dispersion, application process parameters, and the geometry of the article being coated. Multiple passes may be used to obtain higher thickness.

5.3.3.1 Formulation

Polytetrafluoroethylene dispersions usually contain nonionic surfactants which promote the wetting tendency of the dispersion. Triton® X-100 is an example of a common surfactant (supplied by Dow Corp.).[13] This type of surfactant does not survive the sintering temperatures of PTFE and decomposes. The products of surfactant degradation are mostly gaseous and evolve during the sintering of the coating, leaving little residue behind.

Many applications of dispersions require a number of properties in the end use which can be achieved by the addition of fillers, pigments, leveling enhancement additives, flow improvement additives, and other additives. For example, cold flow (creep) properties of the coating can be reduced by the addition of fillers such as fiberglass. Additives should be mixed only by mild stirring to avoid coagulation of PTFE.

There are applications where the viscosity of the dispersion must be increased to maintain uniform wet thickness in the process. Addition of water-soluble thickeners such as acrylic polymers is one way of increasing the viscosity of the dispersion. For example, the addition of 1% of Carbopol 934 (supplied by B. F. Goodrich Co.) can increase the viscosity of a dispersion containing 60% solids by 30 times to about 6 poise.[14] Other examples of thickeners include Acrysol® ASE acrylic polymers, by Rohm & Haas, and Natrosol® hydroxyethyl cellulose polymers, by Hercules Corporation.

Another method is the addition of nonionic surfactants (Fig. 5.32), which can be added without increasing the viscosity to unacceptably high levels. Anionic surfactants are less desirable and the cationic type is unacceptable due to their coagulating or flocculating effects. Thickeners and surfactants degrade and evolve off during the sintering of the coating.

5.3.4 Glass Cloth Coating by Dispersion

In this process, glass cloth is coated with PTFE dispersion, which is subsequently sintered in an oven. Typically, the glass fabric is supplied from a payoff roll and is passed through a trough filled with dispersion, followed by a drying and sintering oven. The glass cloth is then collected by a take-up roll. In some instances, the sintering step is omitted on the first few passes. The fabric is calendared to press any broken filaments into the soft PTFE coating and to “heal” mud cracks. The PTFE is then sintered in the remaining passes.

Glass cloth is woven from glass fibers. The fibers are coated with a “sizing” agent to act as a lubricant during the weaving process to prevent the fiber bundles from fraying. The sizing agent degrades and chars during the sintering process and leaves a color ranging from cream to brown. The color can be prevented by removal of the sizing chemically or, more economically, by heat.

Glass cloth has a smooth surface and is porous. It does not ionize in water or absorb the polytetrafluoroethylene dispersion. It picks up a small amount of dispersion per pass, therefore requiring multiple passes (up to a dozen) to obtain a smooth surface, if that is required.

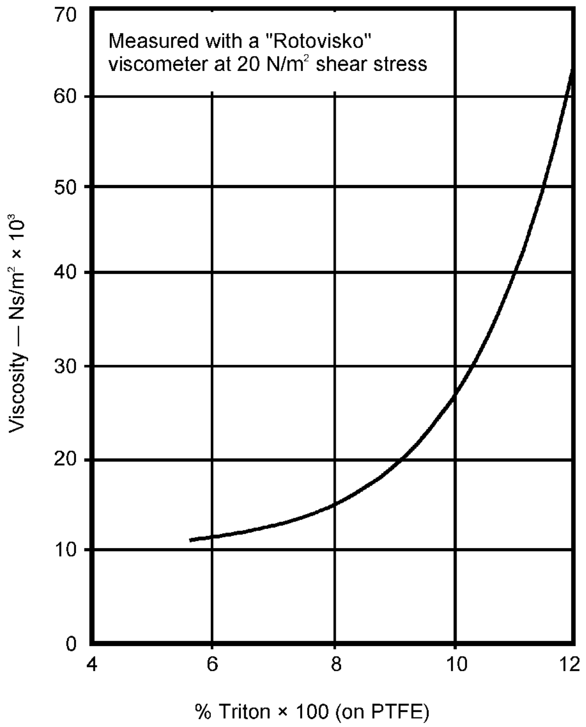


Figure 5.32 Viscosity measurements of a Fluon dispersion (60% PTFE) at 20°C (68°F) for various percentages of Triton X-100.[14]

5.3.4.1 Equipment

The equipment for glass cloth coating is shown in Fig. 5.33 which includes dip tank, oven for drying and sintering (tower), and payoff and take-up rolls. The dip tank should be made of stainless steel and equipped with a submerged roll or slide rod to allow advancing of the glass cloth through the tank. Multiple rolls help improve uniformity of side-to-side dispersion pickup. A partially submerged roll can help increase pickup by thick fabrics by forcing the dispersion through the cloth. Some considerations for the equipment are listed below:

- To minimize foaming, the tank should be shielded from air current and filled from the bottom, gravitationally.
- The equipment must be capable of constant speed to insure uniform dispersion pickup.
- A dip tank water jacket is sometimes necessary to maintain the dispersion temperature at 20°C to 25°C.
- The dip tank should be designed with a minimum exposure to ambient air to avoid evaporation of water which would change the resin concentration, thus wet coating thickness.
- The oven should have three zones consisting of drying, baking, and sintering.
- Drying zone should be capable of 100°C.
- Baking zone should reach 250°C.
- Sintering zone should be capable of 400°C.
- An annealing chamber is sometimes installed at the exit of the sintering oven to prevent the coated glass from cooling too rapidly to avoid wetting difficulty during the second pass coating.
- Finally, it is vitally important to exhaust the fumes of the ovens properly, thus avoiding exposure to the by products of the decomposition of surfactants, additives, and polytetrafluoroethylene.

5.3.4.2 Processing

The processing steps include immersion in the dip tank, removal of excess dispersion, drying, baking, calendaring (sometimes), and sintering.

The dispersion should be gently stirred by an agitator for several minutes or its drums rolled, then filtered through a fine (5 µm to 20 mesh opening, depending on the application) filter. It should be next loaded into the dip tank and allowed to reach a constant temperature before beginning to coat the glass cloth. The coating speed is limited by some practical parameters such as the rate of return of excess dispersion to the dip tank, foam formation in the dispersion, and oven length and capacity.

Excessive coatings may be wiped from the glass cloth by applicators. They include, in the order of decreasing effectiveness, sharp-edged knives *(doctor blade),* round-edged knives, wire-wound rods, and fixed gap horizontal metering rolls. Coating thick-

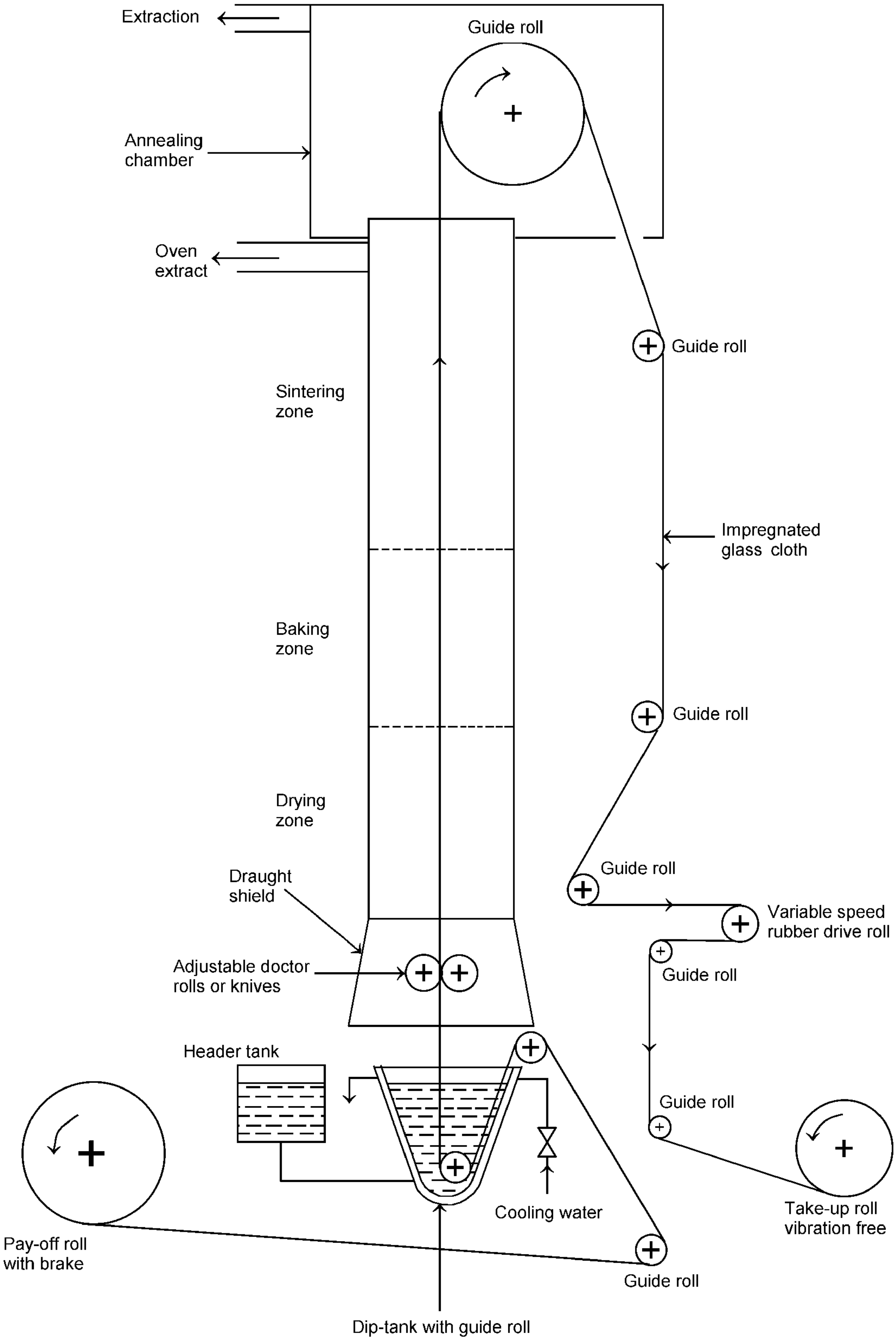


Figure 5.33 Glass cloth coating equipment.[14]

ness should be below critical cracking thickness. Sometimes multiple unsintered layers are coated on the glass cloth. The coated web must first be heated to remove the surfactant and then calendared before sintering to cure the cracks. Calendaring has the added benefit of flattening the fabric and tucking in the broken glass filaments in the coating. Broken filaments create defect point and wick moisture into the glass cloth which may affect its electrical properties.

The thickness and quality of the final coating, the type of glass fabric and the formulation will determine the number of passes that must be made. Typical process conditions for dispersions containing 45%–60% PTFE are shown in Table 5.13. Glass fabric must reach the temperatures shown. Water is removed in the drying zone and the surfactant in the baking zone. It is preferable to extend the baking zone to complete the removal of surfactant as opposed to increasing the sintering temperature due to the reduction in the mechanical properties of glass fabric.

5.3.5 Dispersion Impregnation of Flax and Polyaramide

Flax and polyaramide are used to fabricate packings and gaskets. They are available in a number of forms, which can be coated. The process described below was used in the past to impregnate asbestos and may be used to process flax and polyaramides. The common forms of asbestos included yarn, cord, braid and cloth. Spun yarn could contain up to 5% cotton for production industrial packing. Extruded asbestos yarn had a smoother surface than spun yarn. Packing was produced by braiding and cloth by weaving from spun or extruded yarn. Asbestos packings have two major drawbacks: permeability and high coefficient of friction. Impregnation of asbestos with polytetrafluoroethylene reduced permeability and friction coefficient.

5.3.5.1 Processing

Impregnation of asbestos begins by dipping it in the PTFE dispersion followed by drying and baking. In general, each step is similar to the corresponding step for coating glass cloth. Asbestos is partly ionized in water and assumes positive charge, which promotes coagulation of the negatively charged dispersion on the surface of asbestos yarn. This inhibits the penetration of resin into the interior bulk of asbestos article.

Equipment for impregnating asbestos is conceptually similar to those used for glass cloth coating. Asbestos readily picks up PTFE dispersions and the amount of uptake depends on the concentration of PTFE in the dip tank. The dispersion may be diluted moderately with deionized water or substantially using a dilute aqueous solution of a nonionic surfactant such as Triton® X-100. The speed of the asbestos yarn movement through the dip tank has little effect on the amount of uptake. The length and capacity of the oven determines the maximum throughput of the process.

After dipping, the asbestos is dried in an oven (80°C–90°C) followed by calendaring to smooth the surface.

5.3.6 Coating Metal and Hard Surfaces with Dispersion

Metal and ceramic surfaces are coated with polytetrafluoroethylene dispersions to protect them from

Table 5.13. Process Conditions for Glass Cloth Coating[14]

Number of Passes	Dispersion Concentration, % PTFE	Added Surfactant	Web Speed, m/min	Web Temperature,ºC		
				Drying	Baking	Sintering
1,2,3	45-50	No	1-2	90-100	200-250	380-400
4,5,6	55-60	Yes	1-2	90-100	200-250	380-400

corrosion and create nonstick surfaces. These objectives can be accomplished by using filled or unfilled coatings. Examples of applications include household and commercial cookware and industrial equipment. Each coating type has advantages and disadvantages. Unfilled PTFE forms a surface entirely made of polytetrafluoroethylene which is smoother and less porous than the coated filled resin. The filled formulation generates a harder surface, which wears at a slower rate than the unfilled coating. Unfilled PTFE coatings generally adhere to the surface mechanically, while pigmented dispersions adhere by priming the surface chemically. The middle layers of the coating usually contain the pigment.

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6 Manufacturing Parts from Melt-processible Fluoropolymers

6.1 Introduction

Melt-processible fluoropolymers can be processed by the same methods as other thermoplastics: extrusion, injection molding, transfer molding, compression molding, blow molding, and rotational molding/lining. This chapter describes the fabrication of parts from fluoropolymers using these techniques. Each process has its own characteristics yet they all depend on melt and flow of the polymers. For example, unlike injection molding, extrusion usually results in a semi-finished or an intermediate article that needs further processing to arrive at an end product. This chapter begins with a brief coverage of topics that are common to all processes: material of construction, rheology, and thermal stability.

6.2 Materials of Construction

Products of the degradation of molten fluoropolymers are highly corrosive, often containing hydrofluoric acid. The parts of the machine that come in contact with molten fluoropolymers must be constructed from corrosion-resistant metals that are significantly more expensive than lower grades of steel. Corrosion of process surfaces can result in the contamination of the finished product and deterioration of its physical properties.

For PFA, FEP, and ETFE injection molding machines, materials like Xaloy 309 and Bernex C240 can be used for construction of barrels and Hastelloy C-276 for the screw, adapter, and nozzles.

6.3 Rheology of Fluoropolymer Melts

Rheology of the molten fluoropolymers is of critical importance in processing these polymers. Fluoropolymers, and generally thermoplastic materials, must be processed below the velocity at which *melt fracture* occurs, referred to as the *critical shear rate*. Melt fracture in molten plastics takes place when the velocity of the resin (in flow) exceeds the critical velocity, the point where the melt strength of the polymer is surpassed by internal stresses. Critical velocity of most fluoropolymers is usually much lower than other thermoplastics. Typical symptoms of melt-fracture include a rough surface (*shark skinning*), and frosty or cloudy surface. Parts molded in a process where critical velocity is exceeded exhibit typical symptoms of melt fracture; that is, they may have a frosty or cloudy surface. In some cases, a part may have a smooth and shiny surface but is internally fractured.

There are a few possible ways to eliminate melt fracture, such as reducing the velocity of melt, increasing the critical velocity, and reducing heat losses (see Table 6.1). These remedies are limited in the way that they affect the design of the mold, fabricated part properties, and degradation of the polymer.

Knowledge of flow of the melt at different temperatures and shear rates is required in the fabrication processing of the resins. Melt viscosity of these polymers is a function of shear rate. For example, polymer viscosity changes as extrusion rate is varied. In addition to melt viscosity, melt flow rate (MFR), also known as melt flow index (MFI), is a customary flow characteristic of resins. MFR is defined as the mass of molten polymer (in grams) that flows through the die/orifice of a rheometer in ten minutes and is inversely proportional to the melt

Table 6.1. Techniques for Eliminating Melt Fracture

Remedies	Preventive Actions	Possible Drawbacks
Reduce the velocity of melt	Enlarge runners, gates, or cavities. Slow ram speed.	Polymer degradation. Premature melt freeze.
Increase the critical velocity	Increase melt and/or mold temperature.	Polymer degradation. Ejectability of the part.
Reduce heat losses	Shorten the travel distance of the melt to the gate, i.e., multiple gates.	Complication of design.

viscosity of the polymer. Typically, to measure MFR, a melt indexer is used that consists of a heated, insulated, and temperature controlled cylinder equipped with a weighted piston capable of forcing molten resin through an orifice/die at the bottom of the cylinder. The data are sometimes labeled with the amount of weight and the duration of the measurement of MFR (or MFI).

Thermal degradation of fluoropolymers is time-dependent, similar to other polymeric material, resulting in a decrease in the molecular weight of the polymer. Melt viscosity of lower molecular weight polymer is less than the higher molecular weight material, thus affecting the flow rate of the molten polymer. A useful method of monitoring thermal degradation is by measurement of the flow rate of the polymer being processed. Varying degrees of increase in flow rate occurs with all fluoropolymers, which can be altered by process changes. Usually, an increase in flow rate does not cause a significant change in the tensile properties of the part.

Fluoropolymer manufacturers and suppliers have developed time–temperature–shear-rate data for melt viscosity or melt flow rate (index) to provide an assessment of the thermal stability of these polymers. Figures 6.1 and 6.2 show the melt viscosity of a few commercial grades of polyvinylidene fluoride as a function of temperature at a fixed shear rate. The relationships between melt viscosity and shear rate, and shear stress versus shear rate, are presented in Figs. 6.3–6.5. Melt flow index/rate and its relationship with melt viscosity of polyvinylidene fluoride are given in Tables 6.2 and 6.3.

Similar data for perfluoroalkoxy (PFA), fluorinated ethylene propylene (FEP), ethylene tetrafluoroethylene (ETFE), and perfluoromethyl vinyl ether (MFA) polymers are presented in Figs. 6.6–6.9.

6.3.1 Characterization of Rheology of Fluoropolymers

There are two approaches to characterizing fluoropolymers for injection molding.[6] The more fundamental methodology centers around the measurement of physical properties such as melt viscosity and thermal diffusivity to generate data for mathematical modeling (simulation) of injection molding processes. Careful measurement of these physical properties allows reliable predictions by modeling. The alternative methodology is experimental simulation of injection molding processes, yielding empirical results that are dependent on the type of apparatus.

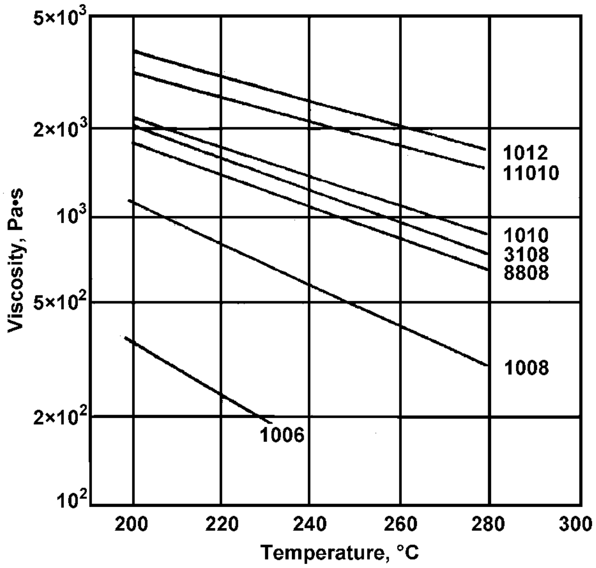


Figure 6.1 Apparent melt viscosity of PVDF vs temperature at 100 l/sec.[1]

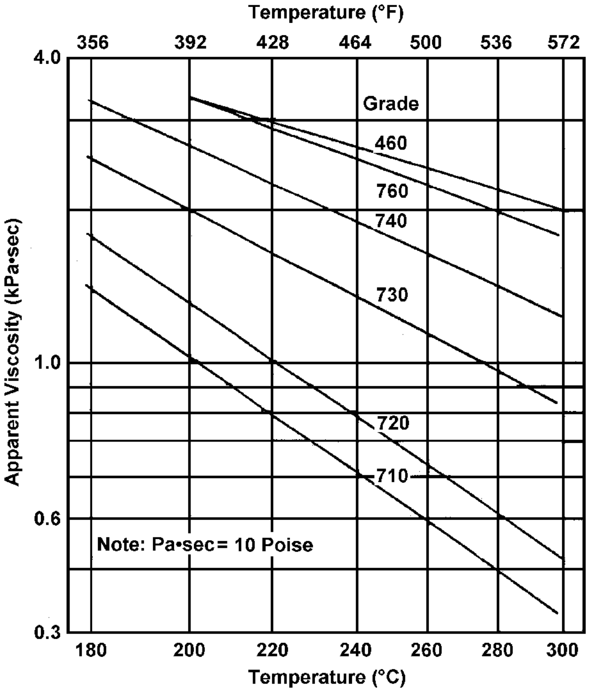


Figure 6.2 Apparent viscosity of PVDF homopolymer vs temperature at 100 l/sec.[2]

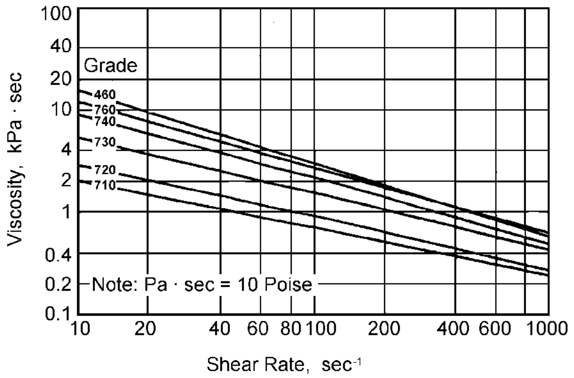


Figure 6.3 Apparent viscosity of PVDF homopolymer vs shear rate at 232°C.[2]

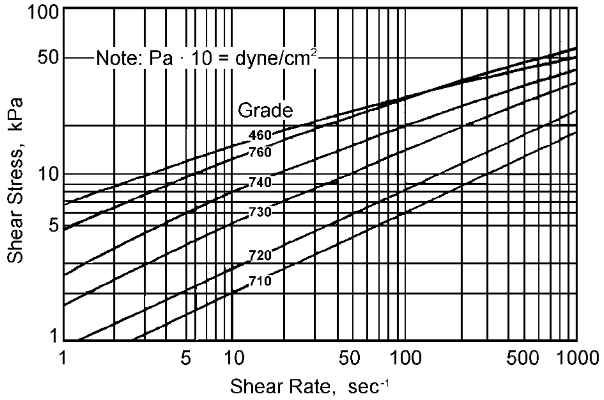


Figure 6.5 Shear stress vs shear rate of PVDF Kynar® homopolymer at 232°C.[2]

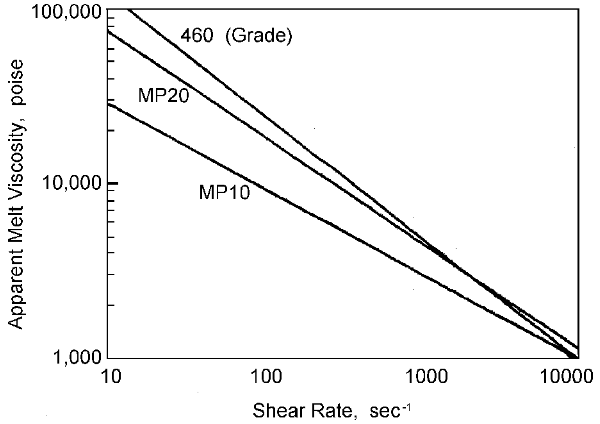


Figure 6.4 Apparent viscosity of PVDF vs shear rate at 232°C.[3]

Table 6.2. Melt Flow Index of PVDF vs Rheometer Load[1]

SOLEF® PVDF	MFI at 230°C Under Loads of:		
	2.16 kg, g/ 10 min	5 kg, g/ 10 min	10 kg, g/ 10 min
1008	6	18	50
1010	1	4	13
1012	0.2	1	4
3108	1	6	17
8808	5	19	52
8908		16	38
11010		5	22

Table 6.3. Melt Flow Rates for Various Grades of PVDF Homopolymer[2]

KYNAR® Grade	Standard Melt Viscosity[a] Range at 232°C (450°F), Pa·s[b]	Melt Flow Rate per ASTM D1238, g/10 min		
		Load (kg)	Range for 232°C (450°F)	Typical Values at 265°C (509°F)
710	600–800	5.0	8–48	
720	800–1050	5.0 12.5	11–30 49–123	190
730	1350–1650	12.5 21.6	14–24 51.85	41
740	1950–2250	12.5 21.6	6–9 23.33	15
760	2500–2900	12.5 21.6	3–4.5 12–17	7
460	2550–3050	12.5 21.6	0.9–2.3 4–11	2

[a] – Per ASTM D3838. Determined at 100 sec^{-1} shear rate using 15/1:L/D capillary having a 120° cone entrance angle. [b] - × 10 = poise.

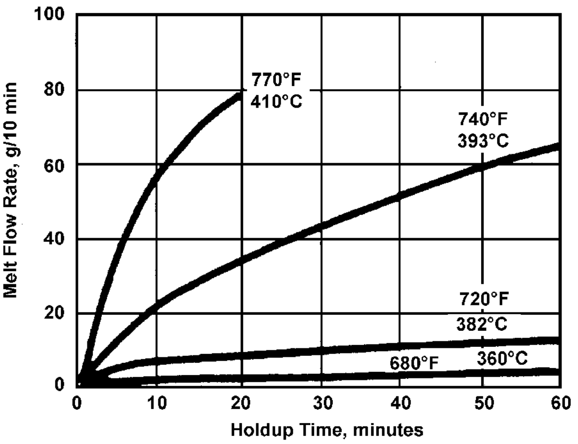


Figure 6.6 Increase in flow rate of Teflon® FEP with thermal exposure.[4]

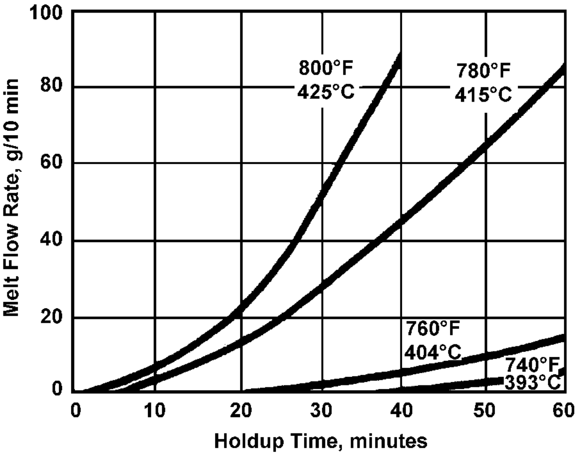


Figure 6.7 Increase in flow rate of Teflon® PFA 340 with thermal exposure.[4]

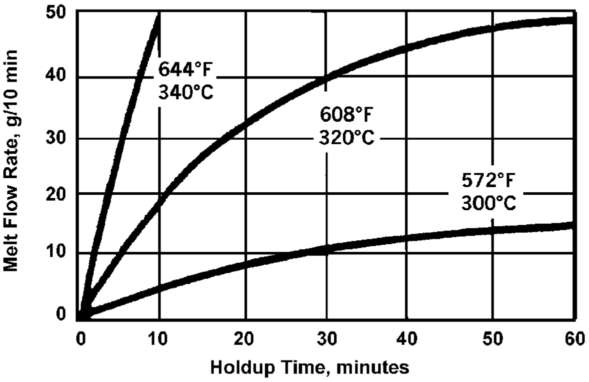


Figure 6.8 Increase in flow rate of Tefzel® ETFE 200 with thermal exposure.[4]

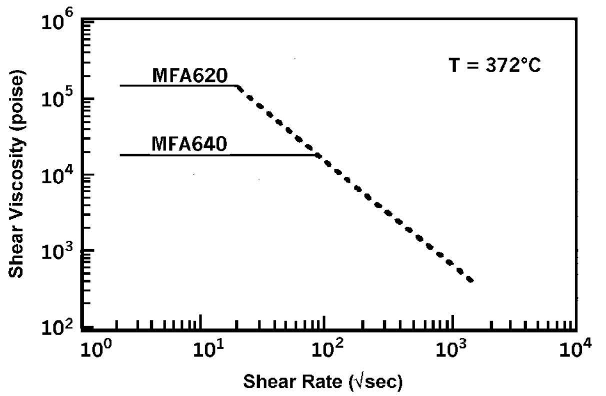


Figure 6.9 Viscosity of Hyflon® MFA vs shear rate at 372°C.[5]

Thermal and rheological characteristics of fluoropolymer melts are important in general melt processing and specifically in injection molding. The single most important property with respect to filling the mold is the viscosity of the melt. It is important for the reader to possess a basic understanding of the subject of rheology in order to be able to interpret the viscosity data. A number of references can be consulted to gain a working knowledge of rheology. Some of the available helpful books include *Transport Phenomena* by Bird, Stewart, and Lightfoot, *Melt Rheology and its Role in Plastics Processing: Theory and Applications,* by J. M. Dealy and K. F. Wissbrun, and *Polymer Melt Rheology: A Guide for Industrial Practice,* by F. N. Cogswell.[6]–[8] The discussions in the following section assume the reader has a modest knowledge of rheology.

Commercial resins are routinely supplied with melt flow rate information that is indicative of the fluoropolymer viscosity at a single temperature, often at a low shear rate. ASTM D1238 is the recognized universal measurement procedure. In this technique, a known weight is applied to a melt reservoir to force the melt out of a nozzle for a predetermined length of time. The results are reported as the mass per unit time of melt that has been discharged through the nozzle (g/10 min). This number provides an easy technique for comparing a number of samples in a relatively short time.

While melt flow rate information is helpful, it is insufficient for complete characterization of viscosity since it is a function of temperature, pressure, and shear stress for a given polymer, for example, melt flow during mold filling and in the runners at or above the melting point of the resin and at shear rates in excess of 1000 sec^{-1}. The viscosity behavior as a function of shear rate depends on the polymer structure (e.g., branching), molecular weight, and molecular weight distribution. Viscosity of most thermoplastics decreases with an increase in shear rate; this effect is also known as *shear thinning*. The viscosity of two resins with similar molecular structures and different low stress viscosity values ($\mu_a > \mu_b$) is likely to have the same order ($\mu_{a1} > \mu_{b2}$) at high shear rates (Fig. 6.10). The ratio of viscosity values at high shear rates (μ_{a1}/μ_{b2}) will be much smaller than the ratio at low shear stresses (μ_a/μ_b).

There are different methods for direct measurement of viscosity in contrast to the indirect procedure of ASTM D1238. They include two types of devices with different kinematics: capillary and rotational viscometers. In capillary viscometers, melt flow is developed in an annular gap or in a slit flow duct. Pressure drop takes place throughout the length of the capillary or the duct. Flow is initiated by the application of a force (pressure) to the polymer melt. There is close resemblance between the way a capillary rheometer and an injection molding machine (during filling) work. In contrast, rotational viscometers generate a drag flow. Examples of rotational devices include cone-and-plate viscometer, plate-plate viscometer, and a Couette viscometer.

In a capillary viscometer, a piston of known weight presses the melt through a capillary with a specific diameter and length. The flow of a Newtonian fluid in a capillary obeys the Hagen-Poiseuille equation.

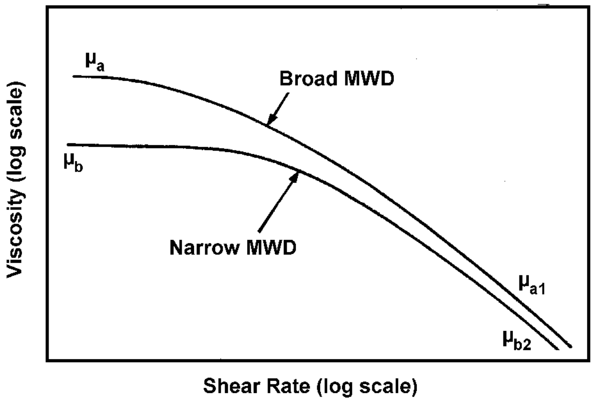


Figure 6.10 A comparison of the rheology of two polymers.

Eq. (6.1)
$$\dot{V} = \frac{\pi R^4}{8L}\frac{1}{\eta}\Delta P$$

where $\dot{V}$ is the volumetric flow rate, R is the radius of the capillary, L is its length, η is the melt viscosity, and ΔP is the pressure drop.

Of course, polymer melts are non-Newtonian due to their shear-thinning behavior. The value calculated from Eq. (6.1) must be corrected[9] for the shear rate at the wall, which is higher for a polymer melt than that calculated by Eq. (6.1). This method is known as the Rabinowitsch correction and is based on determination of viscosity at a location inside the flow channel as opposed to the wall. At a representative location, Newtonian and non-Newtonian shear rates coincide. This location is at $r = \pi R/4$, where the pressure transducer should be located to measure the pressure drop. Another correction has to be made for other pressure losses; it is called the *Bagley correction*.[9]

The *cone-and-plate viscometer* is one of the rotational methods of measuring the polymer viscosity. It consists of a flat horizontal plate and a cone with an obtuse angle. The cone touches the plate at its tip and rotates at a constant speed. The melt is charged into the gap forming between the horizontal plate and the cone. The rotational velocity determines shear rate and the torque applied gives shear stress. Shear rate is constant across the gap, thus it eliminates the need for non-Newtonian behavior of the melt. In a *plate-plate viscometer*, the cone is replaced by a second flat plate. The *Couette viscometer* is comprised of two concentric cylinders where one can be rotated at a constant speed.

There are empirical moldability tests in which the melt is injected into a standard mold with simple geometry. The path of flow is usually long, allowing measurement of flow length as the index of moldability. Flow length is defined as the length of the mold that is filled before resin freezes under defined filling conditions. A variety of mold shapes such as snakes, spirals, discs, and tensile bars have been tried in these tests, the most popular of which is ASTM D3123. It describes a spiral flow mold for assessing thermosetting molding compounds.

The advantage of ASTM D3123 is that it is simple to perform and provides direct evidence of the mold-filling capability of the polymer. The disadvantage of this method is that the basic variables such as temperature, shear rate, and pressure are not constant during the test. The moldability index is a function of thermal and rheological properties of the melt, therefore limiting the scale-up applicability of this test. This test is most useful for comparing various polymers of the same family having similar molecular weight distributions but different average molecular weights. Dealy and Wissbrun[8] present further discussion and models for empirical moldability tests.

6.4 Thermal Stability of Fluoropolymers

Fluoropolymers require fairly high processing temperatures due to their high melting point and/or high melt viscosity. Perfluoropolymers are generally more stable than the partially fluorinated fluoroplastics. PVDF and PVF can generate highly corrosive hydrofluoric acid if they are overheated. In addition to minimizing the processing temperatures, incorporating thermal stabilizers is helpful in reducing the degradation of partially fluorinated fluoroplastics.

Polyvinylidene fluoride [(—CH_2—CF_2—)$_n$] grades have sufficiently low melting points (135°C–170°C) to allow extrusion at 210°C–290°C.[10] Molding PVDF requires lower temperatures (180°C–240°C) than does extrusion. Degradation can be avoided if temperature does not exceed 315°C for extended periods of time, otherwise the polymer is degraded into primarily hydrofluoric acid and carbon (char). PVDF temperature should be reduced to less than 175°C if it is going to be left in the processing equipment for any length of time.

Ethylene-tetrafluoroethylene copolymers [(—CH_2—CH_2—CF_2—CF_2—)$_n$] with ethylene to tetrafluoroethylene molar ratio of about 1 have a melting point of 218°C–280°C. The processing window of ETFE ranges from 280°C–340°C. ETFE decomposes to oligomers above 340°C by cleavage of the main chain at the diads or higher runs of ethylene,[11] especially in the presence of oxygen. Most commercial ETFE copolymers contain copper stabilizers. Various stabilizers have been attempted with ETFE such as the addition of a 0.001% to 2% by weight mixture of metal salt of phosphorous acids.[12] Examples of these acids include phosphorous acid (H_3PO_3), diphosphorous acid ($H_4P_2O_5$), and hypophosphorous acid (H_3PO_2). The metal in the salt is a metal, such as zinc or manganese, in the first to the third main groups of the Periodic Table of Elements.

Copper and copper oxides have been found to improve the thermal stability of ETFE when incorporated at 50–10,000 ppm.[13] The addition of the stabilizer prevented discoloration, embrittlement, and foaming when the polymer was held at 340°C for 1.5 hours. These oxides become effective at higher concentrations in the range. The drawbacks to the relatively high level of copper oxide were pigmentation of the resin (cupric oxide is black), surface roughening, haziness, and electrical flaws. These problems were resolved by replacing small amounts (0.05–500 ppm) of cuprous chloride or iodide for the oxide.[14] Including cuprous halides in ETFE resins also improved stress crack resistance in high-temperature applications. Color formation also remarkably slowed. For instance, ETFE that contained 5 ppm of cuprous iodide retained 90% of its room temperature elongation after it was aged for 215 hours at 230°C. The control ETFE and ETFE containing 50 ppm of metallic copper could be respectively aged for 27 and 70 hours at 230°C before 90% elongation retention was reached.

Commercial ethylene-chlorotrifluoroethylene copolymers [(—CH_2—CH_2—$CClF$—CF_2—)$_n$] have ethylene to chlorotrifluoroethylene molar ratios of about one. The melting point of these ECTFE plastics[15] is higher than 220°C, requiring melt fabrication temperatures in the range of 260°C–330°C. At these high temperatures, rapid degradation of the polymer occurs resulting in discoloration and loss of mechanical, electrical, and chemical properties. Specifically, degradation of these properties occurs during extrusion and injection molding operations.

Thermal stabilizer packages that are effective for ECTFE have been reported. One such composition[16][17] was comprised of a phosphite of an organic polyhydric phenol, a salt of carboxylic acid, and a metal of Group II of the Periodic Table and a thiopropionic acid ester or alkali metal salt. This thermal stabilizer was satisfactory for melt fabricating techniques. For very large parts, a more effective system has been developed.[15] The package contained a product of transesterification of an organic polyhydric phenol and an organic phosphite triester free from phenolic hydroxyl groups, a polymer of a salt of a monocarboxylic acid and metal of Group II of the Periodic Table and polymer of the ester of a (4-hydroxyl-5-alkylphenyl)-alkanoic acid. An example of a thermal stabilizer package was constituted of 0.1%–0.5% by weight of a phosphite of 4,4-*n*-butylidene-*bis*(6-*tert* butyl-*m*-cresole) or 1,1,3,-*tris*(2-methyl-4-hydroxy-5-*tert*-butylphenyl) butane, 0.1%–0.3% by weight of zinc-2-ethylhexylate and 0.1%–0.5% by weight tetrakis [methylene 3-(3',5'-di-*tert*-butyl-4'-hydroxyphenyl) propionate]. Commercial diphosphites have been used as thermal stabilizers for ECTFE[18] as have been blends of a phosphite ester and an oxamidoester.[19] A preferred phosphite ester was *tris* (2,4-di-*tert*-butylphenyl) phosphite (0.5%–2% by weight) and a preferred oxamidoester is 2,2'-oxamidobis [ethyl 3-(3,5-di-*tert*-butyl-4-hydroxyphenyl) propionate] phosphite (0.25%–1% by weight).

Polyvinyl fluoride can be thermally stabilized with mixtures of phenyl phosphites (e.g., triphenyl phosphite) and low molecular weight epoxy resins. Other methods include the addition of the dolomite series and the zinc salt of an organic acid[20] or a dialkyltin *bis*(3-sulfolanylmercaptide).[21]

6.5 Melt Extrusion

Extrusion is one of the most popular processes for fabricating parts from fluoropolymers. Fiber and filament account for a relatively small share of all fluoropolymers extrusion. The principal end products are wire insulation, tubing, film, and sheet. Fluoropolymer films are widely used in release, surface protection, and packaging. Sheet and profile extrusions account for a small share of fluoropolymers' consumption.

The products of degradation of molten fluoropolymers are highly corrosive, often containing hydrofluoric acid. It is important that the surfaces of machines that come in contact with molten fluoropolymers are constructed from special grades of corrosion-resistant metals. These metals are significantly more expensive than lower grades of steel. Corrosion of process surfaces can result in the contamination of the finished product and deterioration of its physical properties.

Extrusion is a continuous process that involves forming a product in two dimensions. These x-y dimensions determine the cross-sectional form of the extrudate, and this can be almost unlimited in scope, ranging from a simple tube to a very complex extruded profile. The third (z) dimension is the length of the extrudate. In principle, it can be infinite. In fact, it is limited by practical considerations governing winding, reeling, storage, and transport. The essential point is that extrusion always produces an object of constant cross section.

The product cross section is formed in a die; the extrusion process consists of raising a thermoplastic above its melt temperature and forcing it through the die. The heating and pressurizing device involves one or more screws operating in a heated barrel, and is known as an *extruder*. Downstream of the die, the extrudate is calibrated, cooled, and packaged by an array of ancillary devices including vacuum calibrators, air cooling chambers, water tanks, cooling rolls, haul-offs, cutters, and winders. Upstream of the die, a melt pump may be interposed between the extruder and the die. The exact selection and arrangement of these components of an extrusion system will depend on the end product. The specific processes for production of different extruded products are discussed in detail in the following sections.

6.5.1 The Extruder

The function of the extruder is to heat the plastics material to a homogeneous melt and to pump it through the die at a constant rate. Because plastic extrusion is a continuous process, the melt preparation device must be capable of a constant output. Ram devices are essentially batch devices, and although it is possible to achieve a constant output by sequentially operating two or more rams, the method is of virtually no importance for the extrusion of thermoplastics such as fluoropolymers. Another possibility is the rotary extruder, a device in which rotating discs or rotors are used to generate shear. Thermoplastic extrusion depends almost entirely on the rotating screw as a melt delivery device. Thermoplastics such as fluoropolymers are characterized by low thermal conductivity, high specific heat, and high melt viscosity, so the preparation of a uniform melt and its delivery at adequate pressure and a constant rate pose considerable challenges. These have been countered by the introduction of various types of extruders.

The principal variants are the single-screw and the twin-screw types. Of these, the single-screw extruder is by far the most popular. The twin-screw extruder may have parallel or conical screws, and these screws may rotate in the same direction (co-rotating) or in opposite directions (counter-rotating). Extruders with more than two screws are known, for example, as the quad-screw extruder, but are not widely used. Twin-screw extruders are normally used when mixing and homogenization of the melt is very important, and in particular where additives are to be incorporated. Fluoropolymers are normally extruded using a single-screw machine (Fig. 6.11).

The output rate of the extruder is a function of screw speed, screw geometry, and melt viscosity. The pressure developed in the extruder system is a function of melt viscosity, screw design, and barrel and die resistance. Extrusion pressures are lower than those encountered in injection molding, and are typically less than 35 MPa.

The key determinant of extruder performance is the screw. The screw has three functions to perform: feeding and conveying the solid thermoplastic pellets; melting, compressing, and homogenizing the material; and metering or pumping the melt to the die. The typical extruder screw (Fig. 6.12) takes the form of a single constant-pitch flight that decreases in depth from the input end to the output end. The pitch is usually equal to the screw diameter. This is sometimes known as a square pitch screw; the resulting helix angle is 17.8°. The screw features three sequential zones, corresponding to the three functions of feeding, compression, and metering.

Flight depth is usually constant in the feeding and metering zones, and decreases at a constant rate over the compression zone. The feed zone occupies about 50% of the screw length, the compression zone takes up 25% to 30%, and the metering zone accounts for the balance. The ratio of the flight depths in the feeding and metering zones is known as the compression ratio, and it affects the mixing and shear heating characteristics of the screw. The ratio of the screw length to its diameter is known as the *L/D ratio*; this has a bearing on mixing and uniformity of output. Most conventional screw designs perform satisfactorily for fluoropolymers. Extrusion screws for wire insulation should have an L/D ratio in the range of 24:1 to 30:1. A screw with a long feed section with approximately a 3:1 compression ratio (core progressive profiles that do not subject the resin to excessive shear) is preferable.

The mixing performance of a single screw can be improved by the addition of mixing elements in the metering zone (Fig. 6.13). These are sometimes teamed with or replaced by static elements such as pins in the barrel, although pins have not proven effective with FEP and PFA. Attention to the barrel can also improve the material conveying performance at the inlet, stepping up the output rate. A series of axial grooves in the barrel wall (Fig. 6.14), extending for at least three screw diameters, is effective.

Variants on the single screw include the barrier or melt extraction screw (Fig. 6.15) and the vented screw. Barrier screws have separate input and output flights that overlap in the midsection of the screw where the plastics material is only partially melted. The barrier flights are slightly smaller in diameter than the main flights. Molten material passes through this clearance and proceeds to the metering zone while solids are retained for further heating. The barrier screw offers the potential for lower melt temperatures or higher output rates, but is difficult to design and optimize. Vented screws, sometimes known as decompression screws or two-stage screws, are effectively two screws placed in series, with the second or downstream screw having a higher transport rate than the first. The upstream end of the screw is provided with conventional feeding, compression, and metering zones, but these are followed by a sudden increase in flight depth, and then by further compression and metering zones. The mid-screw increase in flight depth causes a sudden pressure drop in the molten plastic, and this allows any dissolved volatile matter to boil out. The lack of compression at this point, coupled with the differential transport rates of the two screw sections, makes it possible to extract the volatile material through a port in the extruder barrel without the plastics melt emerging at the same time. Vented screws typically have an L/D ratio of greater than 30:1 and suffer from some instability in pumping output. Operating conditions are also constrained by the need to ensure that the vent does not plug with plastics melt. For these reasons, the use of vented screws is usually confined to materials likely to contain moisture, volatile matter, or entrained air. Fluoropolymers are not prone to these problems so vented screws are not normally used in their processing.

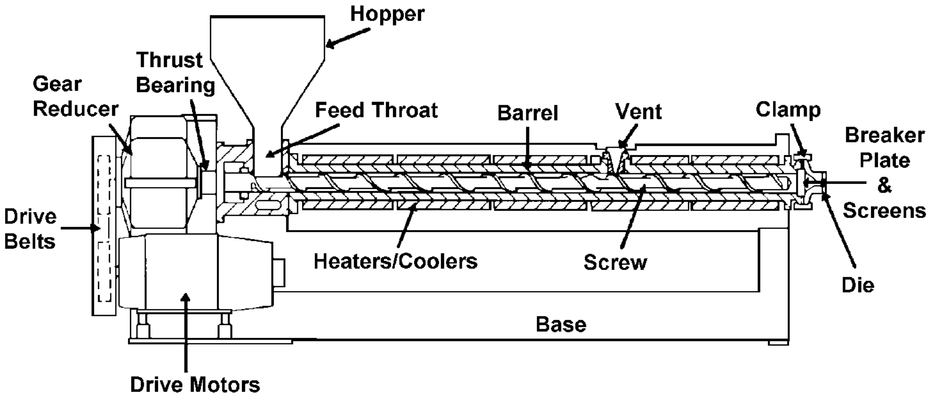


Figure 6.11 Typical single-screw extruder with a vented barrel.

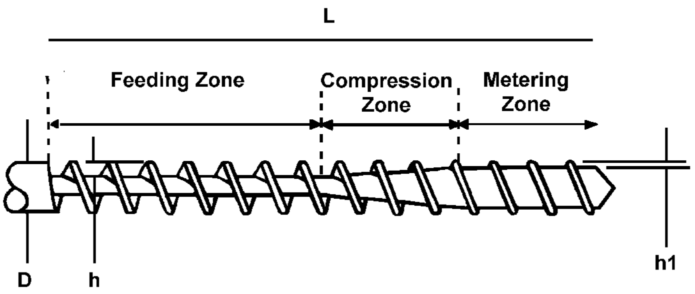
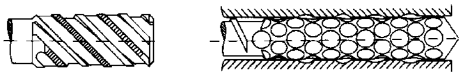


Figure 6.12 Features of a typical extrusion screw. Key: L = screw length, D = diameter, h = initial flight depth, h1 = final flight depth. L/D = length/diameter ratio, h/h1 = compression ratio.

Maddox Mixer

Pineapple Mixing Head



Egan Mixing Section

Cavity Transfer Mixing Section

Figure 6.13 Mixing elements for thermoplastic extrusion.

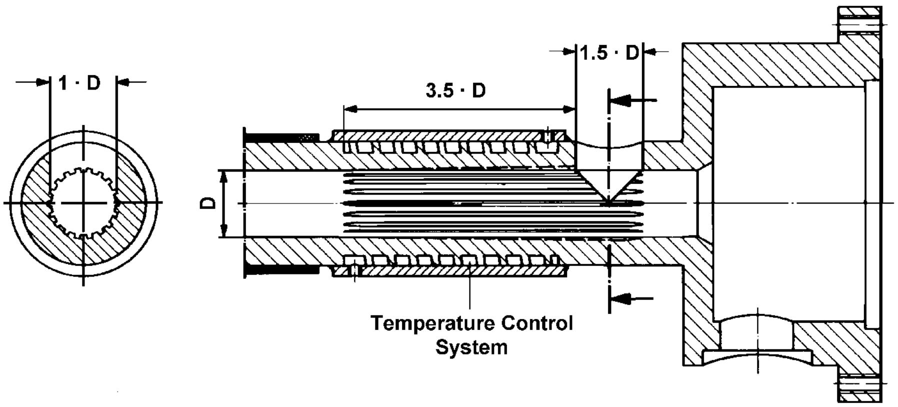


Figure 6.14 Grooved feed section of barrel.[22]

Figure 6.15 Section of barrier screw.

6.5.2 Film Extrusion

Fluoropolymer film can be produced either by extrusion casting or extrusion blowing processes. Each has its advantages and disadvantages. These basic processes result in film with a molecular orientation predominantly in the machine direction. Superior optical and physical properties can be developed by orienting the film in two orthogonal directions. The process is known as biaxial orientation and it can be applied to both tubular and sheet film. Regardless of process, film production lines include common downstream equipment such as haul-off, tensioning, and reeling stations. A high-purity melt, free of inclusions, is essential for film production. This is achieved by filtering the melt through a screenpack upstream of the die.

6.5.3 Sheet Extrusion

A *sheet* is usually defined as thicker than 0.25 mm (0.01 in); anything thinner is classified as *film*. Polyvinylidene fluoride sheet is extruded up to 30 mm thick and in widths up to 2500 mm. The sheet material can be thermoformed, or fabricated by blanking, punching, machining, and welding. The key characteristics of polyvinylidene fluoride sheet are a good ratio of strength and rigidity to thickness, toughness, moisture resistance, resistance to sterilization procedures, good moisture barrier properties, chemical resistance, and non-toxicity.

6.5.3.1 Production

Extruded sheet is produced with a die having a wide slit-like outlet. The internal flow geometry is designed to transform the cylindrical melt flow received from the extruder to this slit form, while at the same time ensuring that the melt flow velocity at the slit exit is constant at all points across the slit width. This is difficult to achieve, particularly in wide sheet dies, and a number of solutions have been devised to deal with the problem. The usual approach is known as the *coat hanger* die, so called because the internal flow passage tapers from the die center to the edges. By offering a greater resistance to flow in the die center, this tends to equalize flow rates across the die. Most sheet dies include two other regulating devices. An internal adjustable dam known as a *restrictor bar* or *choker bar* is positioned in the flow path of the die exit and acts as a coarse regulator. Fine regulation is achieved by adjustment of the die lips at the die exit. The upper die lip includes a thin section that can be flexed elastically by the action of manual or automatic adjuster bolts, so that the die exit gap can be varied across the die width. The die gap should be set in the range of 0% to 10% greater than the desired sheet thickness.

From the die, the sheet passes immediately to a cooling and finishing device in the form of a roll cooling stack. The usual configuration is a three-roll vertical stack with the sheet entering at the nip between the upper two rolls. Variations include up-stack working where the sheet enters between the lower two rolls, a horizontal roll stack used with a vertical die for low-viscosity melts, and a two-roll stack for thinner sheet gauges. The function of the stack is to cool and polish the sheet. Alternatively, an embossed roll may be used to impart a texture to the sheet surface. Close temperature control of the rolls is critical; the temperature variation across the roll should be no more than 1.5°C. Roll temperatures depend on sheet thickness and production rate, and on whether a glossy surface is required. If so, the appropriate sheet surface must be maintained at least at 110°C until it contacts the polishing roll. Table 6.4 summarizes the effect of die and roll variables on sheet characteristics.

6.5.4 Pipe and Tube Extrusion

Tubes and pipes can be extruded from fluoroplastics. These extrusions are usually applied in the transport of corrosive chemicals and, to a lesser extent, as linings.

Table 6.4. Influence of Die and Roll Stack Variables on Sheet Characteristics

Variable	Orientation	Transparency	Gloss	Stiffness	Impact Resistance
Die gap	↑	-	-	-	-
Melt temperature	↓	-	↑	-	-
Roll temperatures	-	↓	↑	↑	↓
Roll speeds	↑	↓	↑	↑	↓

6.5.4.1 Production

Dies for pipe production consist essentially of a female die ring that shapes the pipe's outside diameter, and a male mandrel that shapes the inside diameter. The difficulty is supporting the mandrel in rigid and accurate alignment with the die ring without compromising the product. The spider-type (Fig. 6.16) uses three or four "spider legs" to support the mandrel but these legs cause axial weld lines as the melt flows around them. An alternative is the breaker plate design in which the mandrel is supported by a disc pierced by a multitude of small holes. A better solution, particularly for larger pipe dies, is the spiral mandrel. Here the mandrel is rigidly supported and the melt flow is directed around it in an initially helical pattern which is converted to axial flow by the geometry of the flow channels and lands. Weld lines are eliminated but the difficulty is ensuring an even flow rate at all points of the die outlet.

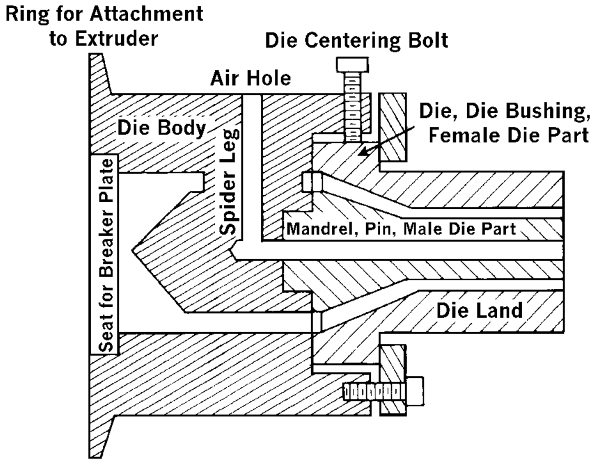


Figure 6.16 Typical spider-type tube die for pipe and tube extrusion.[23]

The outside diameter of the pipe may be calibrated either by an internal air pressure of 1.3 to 2.0 bar, or by external calibration in a vacuum sizing tank (Fig. 6.17) operating at a pressure of 0.3 to 0.5 bar. For calibration by internal pressure, the diameter of the die ring is made approximately equal to the internal diameter of the finished pipe. For vacuum tank calibration, the die ring is made up to 25% larger and the haul-off is set for a wall thickness drawdown of up to 30%.

6.5.5 Coextrusion

Coextrusion is the process of forming an extrudate composed of more than one thermoplastic melt stream. The process came about because some service demands, particularly from the packaging industry, could not be satisfied by a single polymer although they could be met by a combination of polymers. Coextrusion was first practiced in the production of cast film and is now also used in blown film and sheet extrusion. The intention is normally to produce a laminar structure in which each layer contributes a key property to the overall product performance. Coextruded films may be very complex structures composed of many different functional layers, including tie layers whose purpose is to bond neighboring layers of limited compatibility. Five layers are not uncommon. However, side-by-side coextrusion is also possible. Fluoroplastics can be coextruded with other polymers such as ETFE and nylon.

Separate extruders are required for each distinct material in the coextrusion. The process has two variations, depending on the point at which the separate melt streams are brought together. In feed block coextrusion, the streams are merged into a single laminar melt flow in a feedblock (Fig. 6.18) which is positioned immediately upstream of the extrusion die. The process depends on the high viscosity of plastics melts to prevent intermingling of the layers as they pass through the extrusion die. The flow rate of each component layer can be controlled by valves in the feedblock and the capital cost is relatively low. The alternative, die coextrusion, uses a complex die construction in which separate melt path manifolds are arranged to merge at a point close to the die exit (Fig. 6.19). The thickness and flow rate of individual layers can be independently controlled, and it is also possible to handle polymers with substantially differing viscosities and melt temperatures. The capital and maintenance costs of such multimanifold coextrusion dies are high.

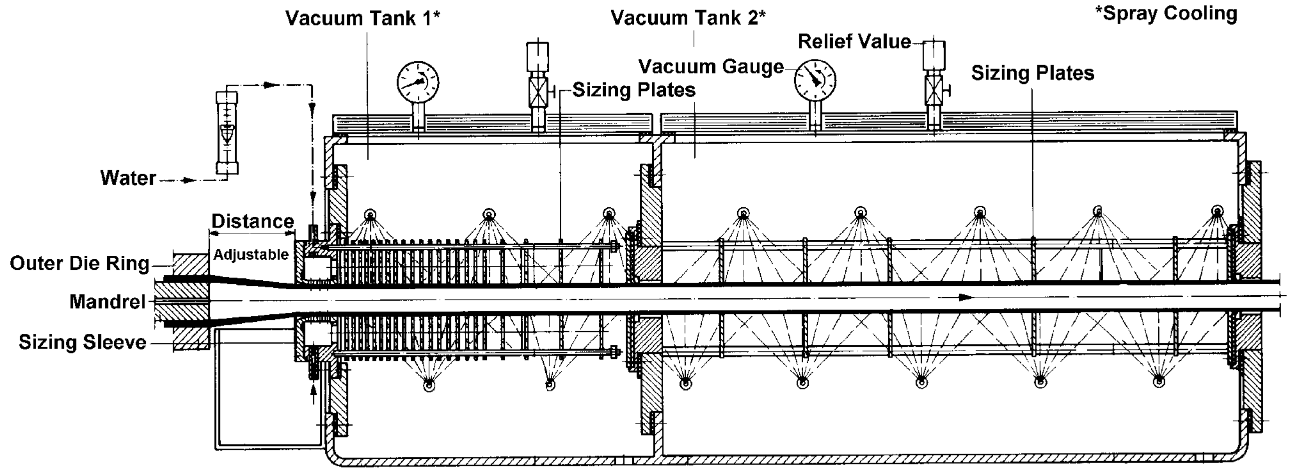


Figure 6.17 Vacuum sizing tank used for pipe and tube extrusion.[24]

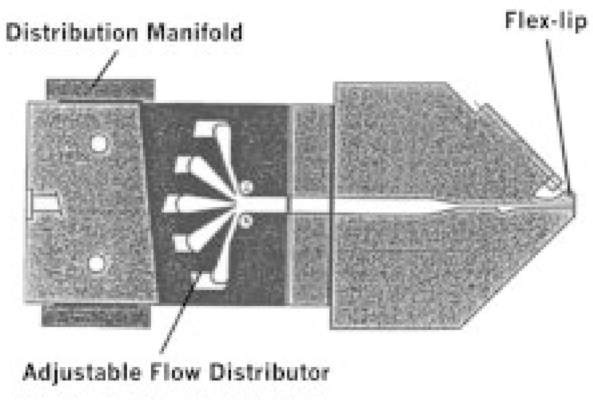


Figure 6.18 Schematic of coextrusion feedblock.[25]

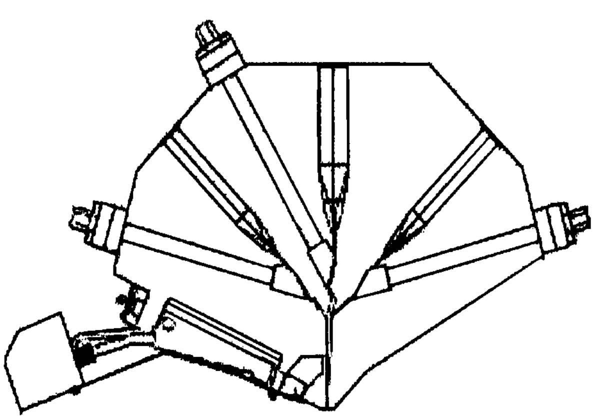


Figure 6.19 Three-layer multimanifold coextrusion die.[26]

6.5.6 Drawdown Ratio (DDR)

The *drawdown ratio*, DDR, characterizes a tubular die and is defined as the ratio of the cross-sectional area of the annular die to the cross-sectional area of the finished insulation, as seen in Fig. 6.20 and Eqs. (6.2) and (6.3). Each resin has a characteristic range of DDR shown in Table 6.5. A comparison of drawdown ratios for a number of polymers is listed in Table 6.6.

Eq. (6.2) $$DDR = \frac{A_D - A_T}{A_{cw} - A_{bw}}$$

where A_D = cross-sectional area of the die cylinder (cm^2), A_T = cross-sectional area of the guide tube (mandrel) (cm^2), A_{cw} = cross-sectional area of wire and insulation (cm^2), and A_{bw} = cross-sectional area of the wire (conductor) (cm^2). Eq. (6.2) can be rewritten in the simplified form given in Eq. (6.3):

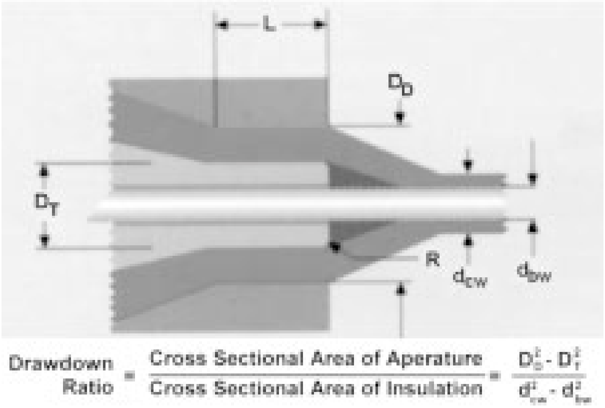


Figure 6.20 Design of a tubular die.[27]

Eq. (6.3) $$DDR = \frac{D_D^2 - D_T^2}{d_{cw}^2 - d_{bw}^2}$$

where D_D = diameter of the die cylinder (cm), D_T = diameter of the guide tube (mandrel) (cm), d_{bw} = diameter of wire and insulation (cm), and d_{cw} = diameter of the wire (conductor) (cm).

An important consideration in designing dies and tips for wire coating is draw-ratio balance (DRB) defined by Eq. (6.4). The ideal value of DRB is 1, which means that the interior and exterior surfaces of the tube are drawn to the same extent. For FEP and PFA, the DRB range is 0.9–1.15. Concentricity suffers at DRB < 0.9 while a DRB > 1.1 can result in tears. ETFE has a more narrow range, 1.04–1.07. Drawdown ratios for large diameter cables may range from 2:1 to 3:1.

Eq. (6.4) $$DRB = \frac{D_D / d_{cw}}{D_T / d_{bw}}$$

Eq. (6.5) $DRB = 1$ (Ideal Ratio)

Figure 6.21 shows an example of a high-temperature wire, insulated with PFA.

Table 6.5. Drawdown Ratio of Fluoropolymers for Wire Insulation Extrusion[28]

Resin Type	FEP	PFA	ETFE
Drawdown Ratio	50–150	50–250	10–50

Table 6.6. A Comparison of Drawdown Ratios for Various Polymers[29]

Resin	Drawdown Ratio	Maximum Drawdown Ratio
Polyethylene	3–4	10
FEP	50–150	200
ETFE	10–50	100
PVDF	2–3	4
PVC	1.5–3	5
Polyurethane	1.5–3	5

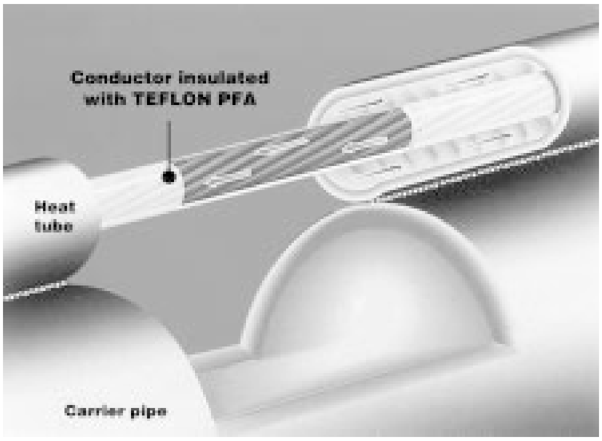


Figure 6.21 High temperature PFA insulated wire. *(Courtesy of DuPont Company.)*

6.6 Fluoropolymer Tube Extrusion

Tube extrusion is quite similar to the wire insulation process. Processing details depend on the size and type of the tube. Tube can be manufactured by both in-line and crosshead dies. FEP tubing can be produced with outside diameters as low as 1 mm to over 20 mm. This range is broken into three processing zones based on the size of the outside diameter: small, medium, and large. The sizing die determines the outside diameter of the extrusion output and the line speed determines the inside diameter. Take-up speed and the die gap, and the difference between the inside diameter of the die and the outside diameter of the tip, set the wall thickness.

6.6.1 Sizing of Tubes

Thermoplastics tube size is set by one of four techniques: the vacuum trough, the extended (internal) mandrel, the sizing sleeve, and the sizing plates (Fig. 6.22). Vacuum trough and extended mandrel are the more common techniques for holding the size of fluoropolymer tubes and pipes in a quench bath. These two methods are described in detail below. In the sizing sleeve method, the outside diameter of the tube is fixed as it comes in contact with a water-cooled metal sleeve (usually brass). This contact takes place by air pressure inside the tube or by drawing a vacuum through the perforated internal surface of the sleeve. The sizing-plate method predates the vacuum trough technique. In this method, the tube takes its size as it is pulled through a series of brass or stainless steel plates, similar to the way that metal wire is drawn from a metal rod. The tube is forced through the plates by a positive internal air pressure.

In the vacuum trough method illustrated in Fig. 6.22a, the tube (or pipe) enters into one end of a closed long trough and is extruded out of the other end. The trough is filled with water which directly contacts and surrounds the tube, providing efficient cooling. Inside the trough, vacuum is drawn over the water, reducing the pressure in the trough thus allowing the soft tube to expand against the collars or rings at the entrance and exit. This mechanism prevents tube collapse and ensures well-rounded sizing of the outside of the tube. The pressure difference between the outside (under vacuum) and the inside of the tube that is open to the atmosphere generates the expansion force. The tube moves through fixed metal collars or rings which give it its size. The first collar at the trough entrance is the most important one. A small stream of water is directed at the pipe just before entrance as a lubricant. The number and positions of the rings and sleeves are usually adjustable. They become slightly smaller as the pipe passes through the trough, taking into account shrinkage that results from cooling and crystallization of the polymer.

The vacuum trough method provides excellent cooling with little frictional drag acting against the tube. The are no theoretical limitations to the production rate. The trough has to be longer for higher output rates, which has a bearing on the available space. Large pipes (>100 mm in outside diameter) are hard to keep submerged under the water without distorting them or marring their surface. In these occasions, the trough is not filled, but water is sprayed and cascaded all around the pipe while it is passing through. The entire inside space of the trough is maintained under vacuum.

The extended mandrel technique, illustrated in Fig. 6.22b, is highly desirable for fluoropolymers because it provides internal cooling and support to the tube. The shrinkage of the plastic as a result of cooling causes a tight contact between the tube and the metal mandrel that can extend up to 30 cm beyond the die. Longer mandrels have been difficult to use due to mechanical difficulties. Surfaces will eventually cor-

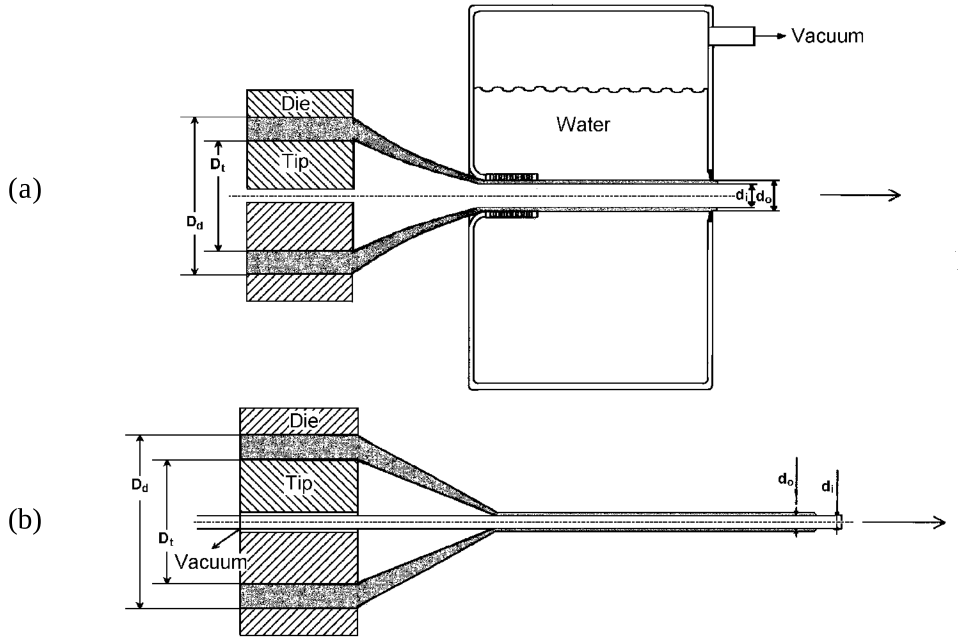


Figure 6.22 Methods of tube and pipe sizing; (*a*) vacuum trough method, (*b*) extended mandrel method.

rode mandrels made of brass, stainless steel, or aluminum. Their surface is roughened to prevent adhesion of the tube as it passes over the surface. The mandrel is tapered with the larger end closer to the die. The diameter difference between the large and small ends is a function of the fluoropolymer type in addition to the variables related to the tube type and size. The end of the mandrel is slightly larger than the final pipe size to allow additional shrinkage. There is a passage for cooling water inside the mandrel. To ensure a constant temperature, the passage must be uniform. Water cascades accomplish additional cooling over the tube. A small split ring is placed around the tube just as it leaves the die to prevent oscillation of the water, which could otherwise cause water marking. Water cascades further cool the tube after it leaves the mandrel. It finally enters a water trough equipped with sizing plates.

6.6.1.1 Small Diameter Tubes

A *small tube* is usually one that has an outside diameter of 5 mm[27] or less and a wall thickness of less than about 1 mm. A free-extrusion technique, similar to the wire coating process, is the method by which small tubing is manufactured. In this case, the desirable drawdown ratio is much smaller than that of a wire insulation process. The draw-ratio balance should be equal to 1. Outside diameter can be controlled by placing a sizing die at the entrance to the quench bath. Air pressure can be employed to expand the tube against the die. The air pressure should be slight due to the low melt strength of the melt cone.

6.6.1.2 Medium Diameter Tubes

The best method of fabricating tubing with outside diameters of 10 mm or more is vacuum trough sizing.[27] This process does not require internal pressurization so that it is convenient for cutting tubes to predetermined length without disturbing the extrusion and sizing processes. The tooling required for medium tubes is similar to that for small tubing. Draw-ratio balance of unity is recommended; drawdown ratios (DDR) of various resins are given in Table 6.7. Generally, a lower drawdown ratio should be considered for higher melt viscosity (lower melt flow rate). A lower DDR reduces the orientation of the melt, thus allowing more precise sizing of the tube. A disadvantage of high orientation is that it limits the formability of the tube in post extrusion fabrication processes such as thermoforming. Elongation of highly oriented tubes is limited, which can result in breaks in the formed part.

6.6.1.3 Large Diameter Tubes

The most common method of fabricating tubing with outside diameters of 12–30 mm and wall thickness in the range of 0.3 to 0.8 mm is the extended mandrel technique.[27] Aside from corrosion concerns, brass is the best choice of construction material for the mandrel and Vespel® for the insulation gasket between the guide and the mandrel. The guide is heated electrically to prevent melt fracture. Mandrel temperature is controlled to allow solidification of the melt and avoid sticking.

6.6.2 Heat Shrink Tubes

Heat shrink tubing provides a convenient method for the application of a protective coating/lining to objects that will be encountering corrosive chemical environments and high temperatures. Basically, a heat shrink tubing molds itself around a substrate by a brief application of heat; it can conform to intricate and irregular designs to form a sealed covering.[2] Heat shrink tubing is deliberately unstable from a dimensional standpoint. Typically, the tubing is expanded during fabrication at elevated temperatures to a diameter that is significantly, say about 100%, greater than the outside diameter of the part onto which it is going to be shrunk. The expanded tubing is then rapidly cooled while under tension. Heat allows relaxation of the tubing back to its pre-expansion diameter.

Desirable polymer for heat shrink tubing must be able to sustain a great degree of elongation and conversely return back to its pre-expansion dimensions by elastic recovery. FEP, PFA, and PTFE are the most common fluoropolymers for manufacturing heat shrink tubing. Typical commercial heat shrink tubing is identified with polymer type and a ratio such as 1.3:1, 2:1, or 3:1,[3] which identifies the relative diameter of tubing before and after expansion. A number of companies that extrude fluoropolymer tubing also supply heat shrink tubing.

Table 6.7. Drawdown Ratio for Medium Size Fluoropolymer Tube[27]

Resin	FEP	PFA	ETFE
Drawdown Ratio	6–10	6–10	3–12

In one example (Teflon® FEP 100),[5] shrink tubing was fabricated by heating the FEP tubing to a temperature in the range of 163°C to 177°C in an oven. Upon reaching the required temperature, a compressed gas such as nitrogen, air, or carbon dioxide, or a pressurized liquid was pumped into the heated tubing. The tube was expanded inside a limiting mandrel to prevent overexpansion. The tube was rapidly cooled while it was held to the expanded diameter under pressure. Pressure depends on the diameter and wall thickness of the tube and the temperature of the expansion process.

FEP shrink tubing is applied to metal mandrels as a protective covering. The tubing is shrunk by first preheating the mandrel, especially for large diameter devices, to reduce the metal's heat sink action that can prevent proper shrinkage of the tubing. FEP is heated to a temperature in the range of 125°C to 205°C. At about 125°C, FEP tubing begins to shrink by relaxation of the frozen stress in its structure and completes its conformation to the metal mandrel at maximum temperature (<205°C).

The theoretical explanation for the formation of shrink tubing centers on the crystalline structure of the fluoropolymers. These plastics are semicrystalline, which means that their microstructure consists of crystalline and amorphous regions. Heating the polymer to near its melting point increases the mobility of the amorphous regions, essentially allowing the polymer to act as an elastic structure. The crystalline regions provide nodes to which the amorphous chains are tied. The crystalline regions "hold" the elastic network together much the same as crosslinking would in elastomers. The length of the amorphous chains (i.e., the degree of crystallinity) determines the degree of elasticity or expandability of the tubing.

Figure 6.23 shows an example of PFA tubing produced by extrusion for a high-purity fluid handling system. Figure 6.24 is an example of a convoluted ETFE tubing.

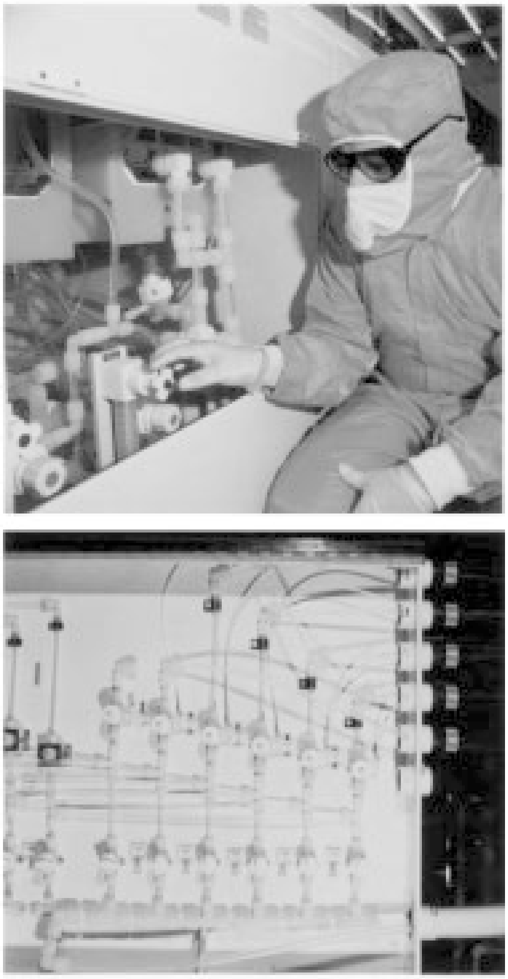


Figure 6.23 Extruded PFA tubes in a high purity fluid handling system. *(Courtesy Advanced Micro Devices and DuPont Companies.)*

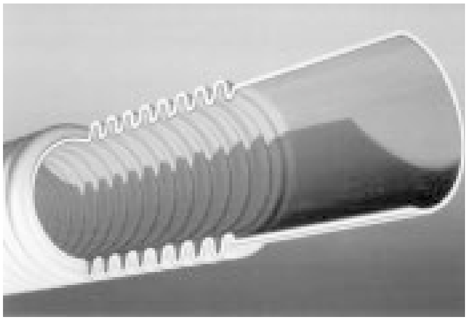


Figure 6.24 Convoluted ETFE tubing for an automotive filling and vapor management system. *(Courtesy Advanced Micro Devices and DuPont Companies.)*

6.7 Fluoropolymer Film Extrusion

Fluoropolymer films have found applications where extreme high and low temperatures and aggressive chemicals are involved. For example, these films are used as release sheets in compression molding of high-temperature parts with epoxy and phenolic resins. Another common application is, in general, as liners. One example is as roll cover to protect metal rolls from corrosion in chemical processing industries such as paper manufacturing. Other applications include glazing for solar collectors, gas and liquid sample bags, and drug and food packaging. Partially fluorinated fluoroplastics provide films with especially excellent tensile strength and modulus for applications where mechanical strength is required.

Monoaxially and biaxially oriented films of fluoropolymer are made by melt extrusion of the resin into flat webs or tubes. The main function of orientation is to enhance the mechanical properties of the film such as tensile break strength and tear resistance.[6] The decision to orient is usually made according to the requirements of the end use for mechanical properties. All process surfaces that contact molten fluoropolymers must be corrosion resistant because of the formation of corrosive compounds such as HF and HCl from the high-temperature degradation of these plastics.

The most common die to extrude a flat fluoroplastic film is the *coat hanger* design. Figure 6.25 shows a schematic of a coat hanger die. The polymer melt enters the die near its lateral center and is redirected towards the two ends of the die. The melt travels through the channels that are angled towards the exit side of the die, thus distributes across the width of the die. The molten polymer flows through the die gap toward the exit slot, also called *die lips*. The gap is formed by two flat metal plates and is named the *land area*, as it is called in other types of dies. The two plates are usually formed by several sections, which can be independently adjusted to increase the control over the thickness of the extruded film/sheet. Today, complex dies are available that are computer-controlled and do not require manual adjustment.[7]

The die is designed such that the channels restrict the melt flow in a way that all the melt experiences the same amount of shear. The distance of travel is equalized by the restraints designed in the flow channels. The net effect is equal flow rates at the

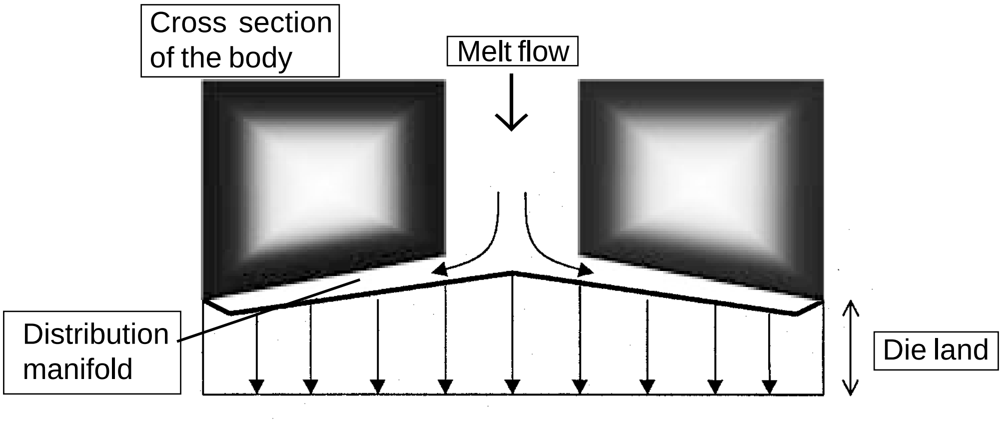


Figure 6.25 Schematic design of a coat hanger die.

center and the far ends of the die, thus a uniform web thickness. This means that the flow in the center of the die is most restricted. One advantage of this approach is the uniformity of residence time in the die. This regime is called *plug flow* in that no internal shear is generated in the melt while flowing through the die. Dies with widths as high as 3 meters have been successfully designed and built, although most commercial dies have widths of less than 1.5 meters.

Films and sheets of various fluoropolymers can be produced by different film formation techniques. Processing methods are described for some of these films.

6.7.1 PVDF Films

In this section, examples of films made from polyvinylidene fluoride (PVDF) are discussed. Although most of the polyvinylidene fluoride film is in the form of coating on metal substrates, stand-alone PVDF films and sheets are produced by extrusion and film blowing.[8][9] Blends of PVDF and a number of other polymers such as polymethylmethacrylate (PMMA) are miscible. Films made from these blends have excellent piezoelectric properties.

Extrusion of PVDF films can be done in a standard single-screw extruder. Gradual transition screws with a length-to-diameter ratio (L/D) of 20:1 and ample metering sections are recommended for PVDF extrusion. Die designs should enhance the proper distribution and homogeneity of the melt. Extrusion temperatures are selected based on the shape of the part and usually vary from 230°C to 290°C. Very thin parts such as high gauge wire require higher temperatures (>300°C) at the extreme tip of the die. PVDF films are cooled by chill rolls operating between 65°C and 140°C. Whether extruded or blown, PVDF films can be uniaxially or biaxially oriented to a thickness of <25 µm.[30][31]

It was discovered that a number of PVDF film properties, including electrical, could be altered by the extrusion and orientation conditions.[32] The relationship between the extrusion and orientation process and the electrical properties of the film are important because of the application of PVDF films in miniaturized capacitors which are used in apparatus such as defibrillators. To compare the properties, extruded film, while in molten state, was brought in contact with chilled rollers at 80°C and cooled rapidly. The oriented film was stretched at 150°C in the longitudinal direction by a stretch ratio of 3.5, that is, its original length was increased by 3.5 times [Eq. (6.6)]. The dielectric constant and dissipation factor were measured as seen in Table 6.8. Orientation increased the dielectric constant and reduced the dielectric loss factor. Altering the stretch ratio only mildly affected the dielectric loss factor (Table 6.9). This means that a degree of orientation was required for a major drop in tan δ and beyond where little change was observed. Similarly, the added impact of biaxial orientation over that of monoaxial orientation was, at best, incremental (Table 6.10).

Eq. (6.6) $$SR = \frac{L_f}{L_i}$$

where SR = stretch ratio, L_f = final length after stretch (cm), and L_i = initial length before stretch (cm).

In another example,[32] unoriented PVDF films were stretched at 150°C in the longitudinal direction at a stretch ratio of 3.5 to 1. A sample of the longitudinally oriented film was stretched in the transverse direction at 60°C at a stretch ratio of 3.4 to 1, thus producing a biaxially oriented film. Dielectric constant and loss factor values were measured for these films (Table 6.10).

Another approach to reduce the loss factor was to heat treat (set) the oriented film under tension after it had been elongated or shrunk by less than 5%. For example, an oriented PVDF film was heat set at a temperature of 140°C–160°C and elongated 5%. Results of loss factor measurements can be seen in Fig. 6.26. Loss factor, in general, decreased with an increase in the time of treatment to less than 1%.

A homopolymer of vinylidene fluoride was extruded[33] using a coat hanger die with a width of 590 mm to produce a sheet at a thickness of 150 µm at a die temperature of 270°C. A chill roll at a temperature of 70°C chilled the hot film. This film was biaxially oriented by four times the original length in the extrusion (machine) direction and six times in the transverse direction (perpendicular to the extrusion direction). The film was at a temperature of 100°C while it was oriented at a stretch rate of 10 mm/min in both directions.

PVDF films have been coextruded[34] to fabricate multilayer films. The specifications of the main and satellite extruders are listed in Table 6.11 and illustrated in Fig. 6.27. In one construction, the top layer consisted of 60% by weight PVDF and 40% by weight of polymethylmethacrylate. The alloy had a melt viscosity of 18,200 poise at a temperature of 232°C and at a shear rate of 100 sec^{-1}, as measured on a capillary rheometer. The bottom layer was an ABS polymer with a melt viscosity of 16,000 poise, measured under similar conditions. The resulting film exhibited no intermixing of the layers. A distinct interface with good interlayer adhesion was obtained, enduring boiling water, organic solvent immersion, and thermoforming tests. Tensile strength and elongation were 33.4 MPa and 64%, respectively.

Equipment for biaxial orientation (also called *tentering*) requires substantial capital investment, more than the blown film process. Tubular extrusion is an alternative process in which the film can be biaxially oriented during the extrusion. The orientation takes place in both longitudinal and transverse directions. This technique requires extrusion of film from a circular die. The tube is oriented in the longitudinal direction by drawing the film. This is accomplished by means of winding up the film at a faster rate than the extrusion rate. The extent of machine direction orientation (or stretch) is expressed by the *drawdown ratio* defined as the ratio of the velocity of the film at the take-up point to the velocity of the extrudate at the die. Orientation in the transverse (loop) direction is achieved by introducing air into the extruded bubble during extrusion and expanding the bubble. *Blowup ratio* is the parameter describing orientation in the transverse direction and is defined as the ratio of the diameter of the bubble to the extrudate. The extent of PVDF orientation in this process[35] is insufficient to impart good physical properties to the film. To enhance orientation, a second stage solid state is applied to the quenched film.

Figure 6.28 shows the double bubble process that includes an extruder, generally in association with a hopper into which PVDF and polymethylmethacrylate (PMMA) were charged. PMMA was added to reduce the crystallinity of PVDF that resulted in tearing and unevenness in the surface of the 100% PVDF film because of “neck” formation. The resin blend was melted in the extruder barrel and was extruded through an annular die. The extrudate was inflated by air that was introduced through an orifice located within the die. The bubble was passed through an annular ring from which a stream of chilled air or water was aimed inwardly so that it impinged upon the bubble. It then proceeded upwards to a hot air ring from which a stream of hot air blew against the

Table 6.8. Effect of Orientation on Electrical Properties of PVDF Films[32]

Frequency,Hz	60		120		10,000		Film Thickness, μm
Film Type	**ε'**	**tan δ, %**	**ε'**	**tan δ, %**	**ε'**	**tan δ, %**	
Unoriented	12.0	4.8	11.8	3.7	11.2	1.8	74
Monoaxially Oriented	13.7	1.7	13.7	1.6	13.2	2.4	25

ε' = Dielectric constant, tan δ = dielectric loss factor.

Table 6.9. Effect of Monoaxial Orientation on Electrical Properties of PVDF Films[32]

Frequency, Hz	tan δ, %			ε'		
Orientation	**60**	**120**	**1,000**	**60**	**120**	**1,000**
I	1.31	1.27	1.31	13.1	13.0	12.8
II	1.08	1.01	1.13	12.6	12.5	12.4
III	1.36	1.47	1.31	12.4	12.3	12.1
IV	1.00	1.07	1.45	14.0	14.0	13.7
V	1.11	1.03	1.04	14.4	14.2	14.1

ε' = Dielectric constant, tan δ = dielectric loss factor.

Table 6.10. Effect of Orientation on Electrical Properties of PVDF Films[32]

Frequency, Hz	60		120		1,000		10,000		Film Thickness, μm
Film Type	**ε'**	**tan δ, %**	**ε'**	**tan δ, %**	**ε'**	**tan δ, %**	**ε'**	**tan δ, %**	
Unoriented	11.7	4.5	11.5	3.8	11.3	1.9	11.0	1.9	120
Monoaxially Oriented	13.2	1.3	13.1	1.5	12.8	1.7	12.7	2.3	36
Biaxially Oriented	13.1	1.1	13.0	1.3	12.8	1.5	12.7	3.2	9

ε' = Dielectric constant, Tan δ = dielectric loss factor.

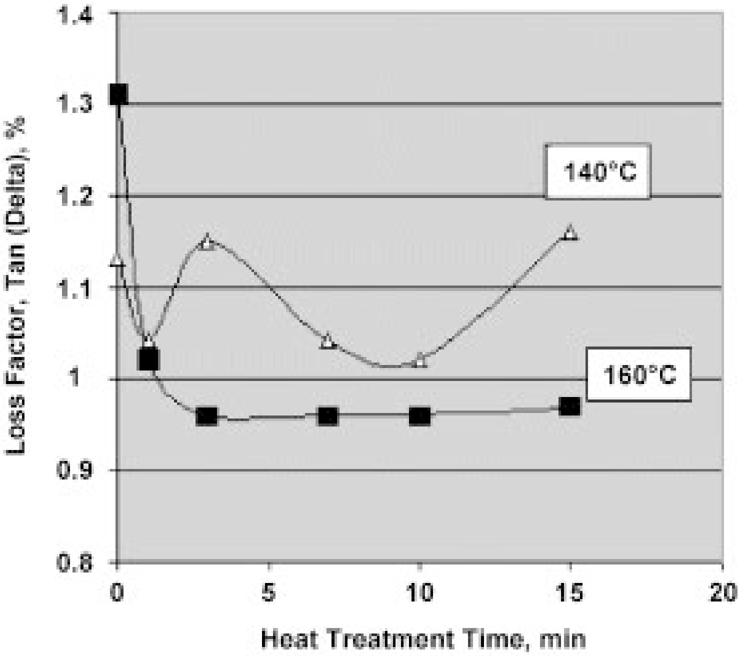


Figure 6.26 Loss factor of PVDF as a function of heat treatment temperature and time.[32]

Table 6.11. Extruder Specifications for PVDF Coextrusion[34]

Extruder	Diameter, mm	Length to Diameter Ratio (L/D)	Compression Ratio	Polymer	Film Thickness, μm
Main	50	24:1	5:1	ABS	378
Satellite	31.5	24:1	3.5:1	PVDF Alloy	75
	Temperature, °C				
Extruder	**Feed Zone**	**Metering Zone**	**Adapter and Coextrusion Block**	**Die Body**	**Die Lips**
Main	177	204	204	207	218
Satellite	177	204	204		

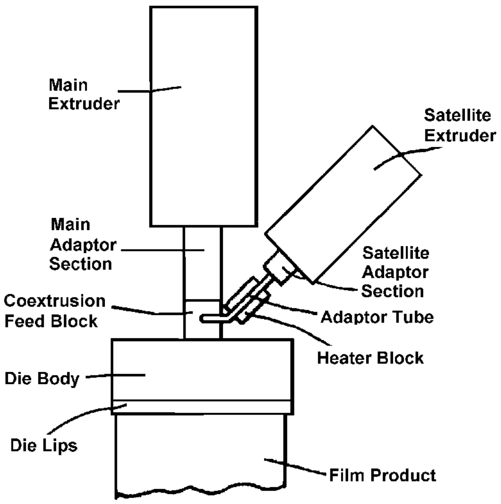


Figure 6.27 Equipment for coextrusion of polyvinylidene fluoride.[34]

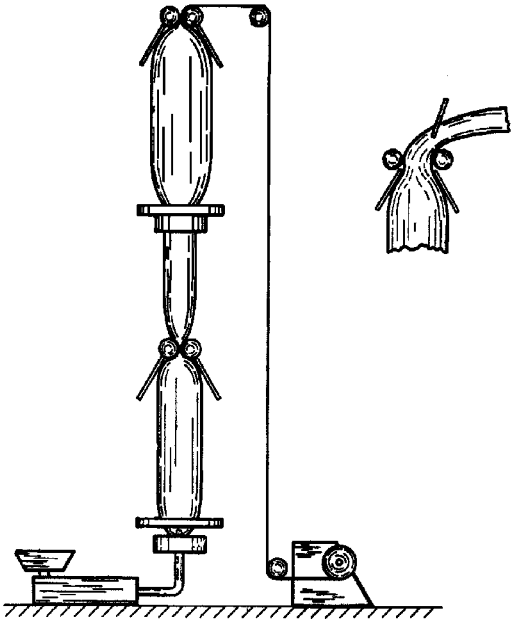


Figure 6.28 Schematic diagram of film blowing process.[35]

second bubble and heated it. The tubular film continued upwards where it encountered a second collapsing frame that directed the bubble through nip rolls. The collapsed bubble was flattened and passed idler rolls and finally wound up on a collection core.

Extrusion temperature of the PVDF/PMMA was in the range of 220°C–240°C. The preferred drawdown ratio of the first bubble was in the range of 10:1 to 15:1, and 2:1 to 3.75:1 for the second bubble. The desirable blowup ratio ranged from 1.5:1 to 1.75:1. A cooling air temperature of 10°C–20°C was required while the hot air temperature, before the second bubble, varied from 120°C–140°C. The film can be dimensionally stabilized by an annealing process at 120°C for 5 minutes.

Others[36]–[38] have described processes to produce filled and unfilled films and sheets of polyvinylidene fluoride in a wide thickness range. In one invention,[37] conductive PVDF films were formed by slitting a thin wall conductive tube by a film blowing technique which had superior uniformity over a conventionally extruded flat film. The conductive film/sheet has found application in heaters and circuit protection devices.

It has been found[38] that by adjusting the PVDF extrusion conditions, light transmission in the 280 to 330 nm (Dorno rays) can be maximized. The percent transmission of light showed little dependence on the film/sheet thickness in the range of 0.02–2 μm, which could not be explained by the conventional Beer's Law. More than 40% transmission was obtained when the spherulite size of the polymer was less than 10 μm in the film thickness range of 0.02 to 2 mm. One procedure to obtain such a film was to extrude polyvinylidene fluoride into a film at 270°C followed by cooling the extrudate on a chill roll maintained at 120°C. The film was next oriented, in two steps, in longitudinal and transverse directions by stretch ratios of 2.8 and 3, respectively.

6.7.2 ETFE and ECTFE Films

Ethylene tetrafluoroethylene (ETFE) and ethylene chlorotrifluoroethylene (ECTFE) copolymers and terpolymers are converted to films using single-screw extrusion similar to other high melting point and melt viscosity thermoplastics. The extrusion conditions for various grades of ETFE and ECTFE are given in Table 6.12. These resins can degrade and evolve hydrofluoric and hydrochloric acid at elevated temperatures. Both of these acids are highly corrosive to metals thus requiring extruder barrel, screw, die, adaptor, and other process surfaces to be constructed from special metal alloys.

Levy[39] has described a process for orienting fluoropolymer films using a combination of two rolls (Fig. 6.29) rotated at different speeds while the film was heated to a temperature above its second transition temperature, typically between 145°C and 175°C. Roll B rotates at a faster speed than roll A, resulting in the stretch, where the ratio of the speed of roll B to roll A is equal to the stretch ratio (SR). The stretched film was cooled below the second transition temperature of the polymer while it was held under tension. Levy reported that orientation in longitudinal direction (LD) imparted improvement in the mechanical property of the film in the transverse direction (TD). Table 6.13 shows the composition of ETFE and ECTFE resins in this study. Tables 6.14–6.16 present the properties of these resins as a function of stretch ratio. A stretch ratio of 0 was indicative of as-cast, unstretched film. Note that in the absence of any stretch in the transverse direction, with an increase in the LD stretch ratio, ultimate strength and TD modulus increased significantly, while creep decreased and shrinkage reached a constant level. Ultimate strength in the transverse direction could be enhanced by more than ten times as a result of longitudinal stretching.

In other reports,[40] a heat shrinkable (oriented) film was described in which the base resin was a copolymer of chlorotrifluoroethylene and up to 5% of another monomer such as vinylidene fluoride. This film could be shrunk by the application of heat (about 2 minutes at 150°C), thus it was useful as a covering. To orient the film, it was wound around a pair of parallel rolls (similar to Fig. 6.26) in which the second roll (B in Fig. 6.26) moved at a faster rate than the first roll (A in Fig. 6.26). Heat was required to assist the stretching process and, to accomplish this, the rolls were heated to a temperature in the range of 85°C to 130°C. The stretched film was cooled below the second transition temperature of the polymer while it was held under tension. Stretching the film in the

Table 6.12. Typical Extrusion Conditions for ETFE and ECTFE Fluoroplastics

Resin	Screw Speed, rpm	Barrel Temperature, °C			Melt Temp., °C
		Rear	Center	Front	
ETFE and ECTFE	5–100	290–370	315–360	325–345	300–345

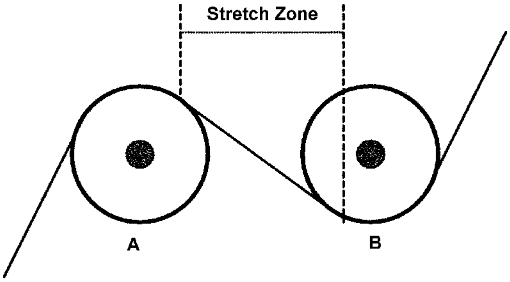


Figure 6.29 Twin-roll stretch device.[39]

Table 6.13. Composition (Mole%) and Properties of ETFE and ECTFE Resins[39]

Characteristic	ETFE Terpolymer	ECTFE	ETFE Quarterpolymer
Comonomer:			
Ethylene	51.5	50	50
Tetrafluoroethylene	46.75	—	46.8–44.8
Chlorotrifluoroethylene	—	50	—
Perfluorobutylethylene	1.75	—	—
Hexafluoropropylene	—	—	3–5
Perfluoropropylvinylether	—	—	0.2
Melting Point,°C	270	245	275
Melt Viscosity, Pa·sec	10,000 (at 297°C)	2,000 (at 275°C)	—

Table 6.14. Mechanical Properties of a Film of a Terpolymer of ETFE as a Function of Stretch Ratio[39]

Stretch Ratio	Shrinkage at 200°C, %		Modulus[1] in Longitudinal Direction, MPa	Ultimate Strength, MPa		Creep, %[2]	
	Longitudinal Direction	Transverse Direction		Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction
0	0.7	0.5	1,104	51.8	15.9	82	229
1	40	-12.5	1,346	93.8	24.2	9	—
2	35.3	-2.7	2,139	129.7	40.7	4.2	—
3	20.8	0	3,381	213.9	69.7	1.9	7.6
4	14.7	0.5	4,547	256.7	94.5	1.5	9.9
5	12.7	1.3	5,575	306.3	140.1	1.5	—
6	12	1.5	6,624	302.9	169.1	0.8	—

[1] ASTM D882 [2] ASTM D674

Table 6.15. Mechanical Properties of an ECTFE Film as a Function of Stretch Ratio[39]

Stretch Ratio	Shrinkage at 200°C, %		Modulus[1] in Longitudinal Direction, MPa	Ultimate Strength, MPa	
	Longitudinal Direction	Transverse Direction		Longitudinal Direction	Transverse Direction
0	1.1	0.8	1,525	71.1	30.4
1	33.8	-11.7	1,891	95.9	32.4
2	26.2	-4.5	2,546	142.1	42.8
3	15.2	1.5	3,899	206.3	66.9
4	9.7	2.3	4,982	279.5	92.5
5	8.7	2.7	5,437	299.5	107
6	8	3.5	6,624	314.6	153.2
7	8.2	2.5	6,914	254.6	164.2

[1] ASTM D882

Table 6.16. Mechanical Properties of Films of a Quarterpolymer of ETFE as a Function of Stretch Ratio[39]

Stretch Ratio	Shrinkage at 200°C, %		Modulus[1] in Longitudinal Direction, MPa	Ultimate Strength, MPa	
	Longitudinal Direction	Transverse Direction		Longitudinal Direction	Transverse Direction
0	1.3	0.05	1,214	53.1	22.1
1	35	-9.7	2,042	75.9	31.7
2	27	-1.3	3,754	142.8	62.1
3	20.2	0.8	5,472	231.2	112.5
4	13.8	1.5	6,100	258.1	151.1

[1] ASTM D882

longitudinal direction imparted strength in both directions of the stretch and transverse direction.

6.7.3 Perfluoropolymer Films

FEP and PFA are the most common resin choices for perfluoropolymer films manufactured by single-screw extrusion. These two polymers have the highest extrusion temperature of all fluoropolymers with PFA processing temperature being the highest. Most commercial grades of PFA have melting points in the range of 300°C to 310°C and have high melt viscosity (low MFR), requiring the highest extrusion temperatures. Another consideration is the relatively low critical shear rate of these resins, which limits the extrusion rate. A typical extruder for PFA and FEP film extrusion would have a length to diameter (L/D) ratio of 31:1 and be equipped with multiple heater zones and a crosshead die. Table 6.17 provides a comparison of extrusion conditions for FEP and polyethylene. Table 6.18 shows a comparison of extrusion conditions for PFA and FEP.

At about 300 sec^{-1}, the extrudate becomes less smooth and exhibits “shark skinning” that limits the extrusion rate. Conditions of the extruded film/sheet of FEP as a function of shear rate are provided in Table 6.19. To overcome this problem, critical shear rate must be increased. This can be done by increasing the melt temperature, which is limited by the degradation of the resin or incorporation of an additive in the polymer. Combinations of a small amount of boron nitride (BN) and calcium tetraborate (CTB) have been found to extend the critical shear rate of FEP and some other resins significantly. This additive package is commonly used as a nucleating agent for foaming these polymers.

Levy[43] has described a process for orienting perfluoropolymer films. Tables 6.20 and 6.21 (see Table 6.22 for resin composition) present the properties of PFA and FEP as a function of stretch ratio. A stretch ratio of 0 was indicative of as-cast unstretched film. Note that in the absence of any stretch in the transverse direction, with an increase in the stretch ratio TD modulus increased significantly, while creep decreased and shrinkage reached a constant level. In effect, stretching the film makes it “stronger” in many ways.

Table 6.17. Processing Conditions for Extrusion of Films[41]

Process Condition	FEP	Polyethylene
L/D Ratio	31:1	25:1
Temperatures,°C: Rear Barrel, Center Rear Barrel, Center, Center Front, Front, Adaptor, Head	371	163
Die Temperatures, °C	371	163
Melt Temperature, °C	374–380	164–169
Screw Speed, rpm	5–100	5–100
Melt Pressure at Crosshead, MPa	Maximum 34.4	Maximum 34.4

Table 6.18. Processing Conditions for Extrusion of FEP and PFA Films[42]

Process Condition	FEP	PFA
Resin Feed Temperature, °C	70	70
Temperatures, °C:		
Zone 1	345	365
Zone 2	350	370
Zone 3	355	375
Zone 4	360	380
Zone 5	360	380
End Plate	360	380
Die Body Temperatures, °C	355	375
Die Lip Temperatures, °C	360	380
Screw Speed, rpm	4	4
Chill Roll Oil Temperature, °C	190	210
Chill Roll Speed, rpm	6.4	6.4

Table 6.19. Appearance and Critical Shear Rate of FEP With and Without Additives[41]

Shear Rate, sec^{-1}	Appearance of Neat FEP (no additive)	Appearance of FEP containing 2,500 ppm BN and 110 ppm CTB	Temperature, °C	Extrusion Rate, g/min
100	Smooth	Smooth	371	5
150	Smooth inside and outside diameter	Smooth	372	8
320	Some sharkskin	Smooth	373	17
620	Sharkskin	Smooth	373	34
1,320	Sharkskin	Smooth	374	75
2,720	Sharkskin	Smooth	374	155
3,650	Gross melt fracture	Smooth	376	208
4,200	Gross melt fracture	Smooth	377	244
4,500	Gross melt fracture	Smooth	377	263

Table 6.20. Mechanical Properties of PFA Films as a Function of Stretch Ratio[43]

Stretch Ratio	Shrinkage at 260°C, %		Modulus,*1 MPa		Creep,*2 %	
	Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction
0	0.2	0.5	518	511	18	15
0.5	24	-9.5	331	518	96	12
1	37	-4	428	649	223	11
1.5	42	0	538	759	150	8
2	34	2	676	856	10	4
2.5	30	3.4	842	932	6	3
3	27	4.4	1,035	994	7	2
3.5	25	5	1,228	1,035	4	3

*1 ASTM D882 *2 ASTM D674

Table 6.21. Mechanical Properties of FEP Films as a Function of Stretch Ratio[43]

Stretch Ratio	Shrinkage at 260°C, %		Modulus,*1 MPa		Creep,*2 %	
	Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction	Longitudinal Direction	Transverse Direction
0	1	0.6	642	511	15	18
0.5	26	-9	462	649	—	6
1	29	-8	511	704	—	4
1.5	40	-2.5	690	828	5	3
2	36	0	925	904	3	2
2.5	31	1.3	1,132	959	—	3
3	29	1.8	—	—	—	—

*1 ASTM D882 *2 ASTM D674

Table 6.22. Composition (Mole%) and Properties of PFA and FEP Resins[43]

Characteristic	PFA	FEP
Comonomer		
Tetrafluoroethylene	98.5	93
Perfluoropropylvinylether	1.1	—
Hexafluoropropylene	—	7
Melting Point, °C	305	275
Melt Viscosity, Pa·sec	20,000 (at 372°C)	30,000 (at 372°C)

6.8 Injection Molding

A significant portion of fluoropolymer consumption is processed by means of injection molding. The process produces a complex finished part in a single rapid and automatic operation. This distinguishes plastics injection molding from most other manufacturing processes, although there are parallels with metal casting, particularly with die-casting. Generally speaking, a whole series of forming, joining, and finishing operations would be needed to replicate an injection molded article in other materials using different manufacturing methods. It is the single operation that makes injection molding economically viable despite the high cost of machinery and molds. Injection molding machines and molds are very costly because of the high pressures required when injecting fluoropolymer melts (thermoplastics, in general) and the complexity of the process controls. The ability to produce a completely finished part at high speed balances the equation with high machine and mold costs and makes injection-molded articles highly cost effective.

6.8.1 Injection Molding of Fluoropolymers

Fluoropolymers can be injection-molded in plunger or ram-type equipment but a screw machine works best with this family of plastics. The screw-type injection molding machines have a number of advantages including those listed in Table 6.23. Various components of screw-type machines for processing fluoropolymers are described in this section.

6.8.1.1 Injection Molding Equipment

A number of factors should be considered in the design of a screw for plastication of fluoropolymers in addition to those considered for conventional injection molding of other thermoplastics. The most significant additional factors are the high processing temperature, corrosive nature, high melt viscosity, and low critical shear of fluoropolymers.

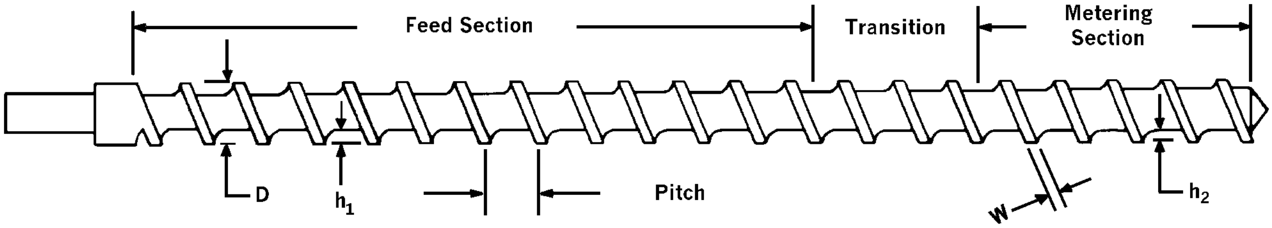
Plastication unit design. The role of the plastication part of the machine is to mix and melt the polymer and the additives, homogenize, pressurize, and feed the melt to the transfer section of the cylinder through the check valve. Plastication takes place at elevated temperatures (230°C–400°C) depending on the type of the plastic. Polyvinylidene fluoride is injection-molded at the lowest end of the temperature range while PFA is processed at the highest.

Figure 6.30 shows the schematic of a screw along with some suggested dimensions for processing PFA, FEP, and ETFE. The metering section of the screw occupies 25% of the length. The screw needs to have a constant pitch. The ratio of the flight depth from the feed section to the metering section should be 3:1 for fluoropolymers. The recommended number of turns of the transition zone for ETFE is three turns, and one-half turn for PFA and FEP.[44]

A conventional nozzle (Fig. 6.31) with a reverse taper can be used with FEP, PFA, and ETFE. The size of the bore should be as large as possible and it should be tapered in order to prevent stagnation and abrupt changes in the melt velocity. The sprue should extend into the nozzle a sufficient length (13–25 mm) to minimize the likelihood of cold slug formation in

Table 6.23. Advantages of Screw-Type Injection Molding Machine

Process	Advantage
Heat Transfer	Uniform melt-temperature and thorough plastication. Higher melt temperature possibility. Less thermal degradation.
Mass Transfer	Better additives and pigments dispersion in the melt.
Material Flow	Shorter hold-up times. Less resin stagnation in the barrel. Efficient pressure transmission to the melt. Efficient mold filling.



Suggested dimensions of screw

Diameter (D) (mm)	Pitch (P) (mm)	Depth of feed section (h_1) (mm)	Depth of metering section (h_2) (mm)	Width of land (W) (mm)
38.1	38.1	6.5	2.159	3.810
44.5	44.5	7.4	2.464	4.445
50.8	50.8	8.4	2.794	5.080
63.5	63.5	10.7	3.556	6.350

Figure 6.30 Schematic of screw design for injection molding FEP, PFA, or ETFE.[44]

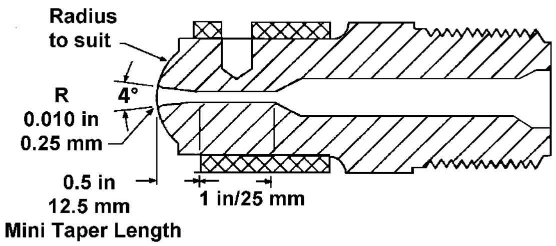


Figure 6.31 Schematic of a conventional reverse tapered nozzle.[44]

the nozzle. To ease the removal of the sprue with the shot, an included angle of 4° has been recommended.[44] The orifice of the nozzle should be rounded at the point of exit (e.g., with a radius of 0.25 mm) to reduce the probability of *peening* (see "Glossary" for description). The nozzle should be equipped with its own heater and temperature controller. The bore and the adapter must match to allow a smooth and uninterrupted path for the flow of the melt**.**

It is important to prevent the melt from returning into the cylinder during the injection process. Part packing and small tolerances can be achieved by using a check ring valve (non-return) to block the back flow as seen in Fig. 6.32. Packing the melt is defined as leaving the ram in the forward position, after the mold has been filled, to reduce sink marks and voids while molding a part with thick sections. Mold packing time is measured from the instant the mold cavity is filled to when the ram is retracted. Excessive packing leads to delamination of the part. Overpacking can be avoided by the use of a smear head. The path between the valve and the screw must be streamlined and smooth to eliminate stagnation and retention of resins in the seams. Streamlining the flow can be achieved by designing a pointed screw tip that also helps reduce the amount of residual melt after the completion of injection.

An alternative to the check ring valve is a smear head (Fig. 6.33), which is based on the use of a small clearance in the diameter over significant land length. This design restricts the back flow of the melt during the injection step. The screw rotates during the retraction step resulting in forcing the melt forward through the narrow annular space. Melt temperature increases as a result of the shear, which helps improve mixing and reduces the packing pressure. There are reasons for choosing a smear head over a non-return valve. They include melt stagnation, less probability of overpacking, less chance of streak formation in the part, and reduced abrasion due to the absence of metal-to-metal contact. Lower viscosity melts may require the use of the check ring valve.

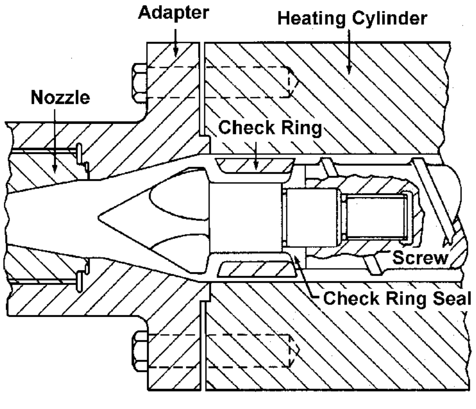


Figure 6.32 Schematic of a combination of a check ring valve and an adapter.[44]

Temperature and speed control in the plastication unit is very important in producing a high quality part. Control of the temperature is achieved by dividing the cylinder into multiple zones, usually three. Separates zones control the temperature of the adapter and the nozzle. Temperature control up to 430°C is required for processing high-viscosity fluoropolymers. This is translated into heater output of up to 6.2 W/cm^2. The hydraulic system must be capable of producing a range of uniform ram speeds from very slow (as low as 60 secs/shot) to high rates of ram speed.

Sizing of the plastication unit should consider the weight of the part and the runner, melt density (Table 6.24), and clamp tonnage. A tonnage of 5 T/in^2 should be sufficient for molding all fluoropolymers.

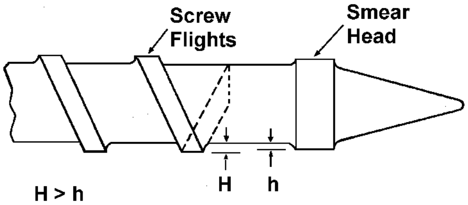


Figure 6.33 A smear head design.[44]

Table 6.24. Melt Density of Fluoropolymers

Polymer	Melt Density, kg/m^3
FEP	1,492
PFA	1,492
ETFE	1,298
ECTFE	1,362
PVDF	?

Mold design. Mold cavities should be constructed from corrosion-resistant metals. When the mold is made of hardened steel or tool steel without protective plating, it should be thoroughly cleaned with a mild alkaline solution. It should be dried and coated with an agent to prevent rusting and pitting while being stored. A thin (0.01–0.03 mm thickness) chrome and nickel plating, free of pinholes, on the steel can increase the longevity of the mold.[44]

The diameter of the sprue bushing should be at least 1.6 mm larger than the diameter of the main runner and slightly larger than the nozzle orifice. A standard taper of 4–6 mm/m is a good rule-of-thumb choice.

An important objective in designing runners is to minimize pressure and heat loss. To achieve this goal, full-round large diameter runners with the shortest length should be specified. Runners with a trapezoid shape cross section are easier to machine and may be used. Connection of runners and gates should be smooth and without restrictions. As the size of the molded part increases, the length of the runners should be reduced and its cross section increased. Generally, parts up to 13 mm thickness require a runner diameter of 6 mm. Runners in the diameter range of 50%–100% of the part thickness are necessary for thicker parts.[44] Runner layout should also be designed to minimize the amount of scrap because fluoropolymers are more expensive than most other thermoplastics.

Attempts have been made[45] to devise sprueless systems for injection molding of fluoropolymers. A hot runner system is necessary for sprueless molding that meets a number of criteria:

- Uniform temperature distribution across the full length of the flow channel.
- Large flow channel and gate size without any residence pocket for the melt.
- All parts that contact the fluoropolymer melt must be corrosion resistant.

These conditions were met by a hot-runner system with the nozzle design in Fig. 6.34 which shows the key part of the system in which the copper-beryllium (Cu-Be) nozzle is heated by a strong spiral heater. Cu-Be is an outstanding thermal conductor which, in combination with a lowering of the heater in the center area, can help produce a uniform temperature in the flow channel. A gap of 1 mm was designed between the body of the nozzle and its head in the gate area to separate the cold mold from the heated nozzle. When the nozzle was set at 300°C and mold temperature set at 30°C, a maximum temperature variation of ±6°C was obtained over the length of the runner.

Gates should be eliminated if at all possible, otherwise they should be as large as practical with the shortest length or land possible. Rectangular tab or fan-type gates are preferable over round gates as long as they are well flared into the mold. These gates are not as easy to remove from the part as the round gates but they help relieve stress in the melt. Round gates do not allow the same degree of independent control of the filling of the cavity as the rectangular gates provide. Generally, the diameter or thickness of the gate should be 0.5–1.0 times the thickness of the part (Table 6.25). No abrupt changes should take place between the runner and the gate.

Diaphragms or ring gates can be used for molding parts where concentricity is important such as cylindrical parts or parts where weld lines can not be tolerated. Pinpoint gates should not be used unless parts (small) are injected rapidly. Tunnel gating can also be used in such cases. Gate location should be at one of the points listed in Table 6.26.

A number of factors should be considered in the design of the mold and the operation of the injection molding machine. These considerations should be given more weight for processing higher melting point and melt viscosity fluoropolymers. Part design considerations include generous filleting, streamlining of angles and intersections, uniform or gradually changing wall thickness, simplicity of design, replacement of pins in the mold with post molding drilling, reduction of the number of cavities for more complex parts, and the avoidance of *jetting*, which is the flow of a rapid, small melt stream into the mold cavity.[44]

6.8.1.2 Process Conditions and Operations

This section covers melt temperature and profile, screw rotation, injection speed and pressure, mold temperature and back pressure, cycle management, clean-out procedure, and shutdown and startup procedures.

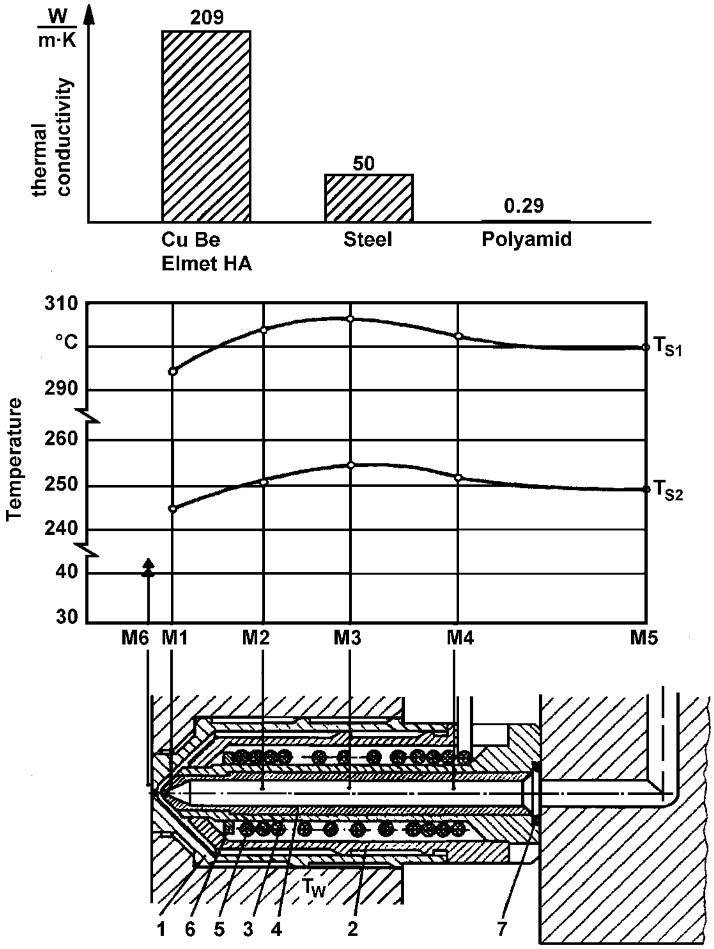


Figure 6.34 Construction and temperature control curve for an externally heated hot-runner nozzle.[46]

Table 6.25. Relationship between Gate Size and the Part Thickness[47]

Thickness, mm	Gate Size, mm
3.2	1.6–3.2
3.2–6.3	3.2–4.7
6.3	4.7–6.3

Table 6.26. Gate Locations in Injection Molding

Consideration	Gate Location
Stress	Where the part would not be stressed by bending or by impact.
Weld lines	Where the line would not be critical.
Finishing	Where finishing the gate site would be inexpensive or unnecessary.
Thickness	Where the part is thickest to minimize sink marks and to avoid pushing the melt through a thin section to fill a thicker one.
Venting	Where the location is consistent with venting requirement such as at the weld lines or at the bottom of blind cavities.
Part shape	At the center of a circular part.

Injection molding conditions for a number of unfilled fluoropolymers have been summarized in Table 6.27. Melt temperature, as measured at the nozzle exit, should be decreased as hold-up time becomes longer. When both hold-up time is long and temperature is high, the rear zone should be set to a lower temperature than the front zone to minimize polymer degradation. Front and rear temperatures should be the same when hold-up time is short. Mechanical work increases the temperature of melt and should be considered. A rear zone temperature which is too high may cause bridging of the feed, while a temperature which is too low results in high torque demand and stalling of the screw. The location of the thermocouples, machine size, screw type and speed, shot size, and cycle time should be considered in the selection of melt temperature.

Table 6.28 lists injection molding conditions for a number of compounds of different fluoropolymers.

It is important to minimize the rotation speed of the screw. High speeds can be used, in conjunction with the appropriate backpressure, to mold thin and/or long parts. Injection pressure should also be as low as possible. Dimensional stability improves when pressure is lowered because of a reduction in the residual stresses in the molded part. Injection pressure may have to be increased if an improvement in the weld line or a reduction in sink marks is desired. Part design and equipment capability should always be considered in the selection of injection pressure. Backpressure should be kept at the lowest possible value. Increasing it can sometimes help increase the stock temperature.

Injection speed should be selected by consideration of the smallest channel through which the melt has to flow. If the injection speed is too fast, the surface of part will turn out frosty or rough. If the injection speed is too slow, the part surface will be rippled. Selection of the injection speed should take into account all other variables in the process such as the melt temperature, shot size, and mold temperature.

Table 6.27. Injection Molding Conditions for Fluoropolymers[44][48]

Process Variable	PVDF	ECTFE	FEP	PFA	ETFE
Cylinder Temperature, °C:					
Rear	193–215	265–277	315–329	315–332	273–302
Center	204–227	271–282	329–343	329–343	302–330
Front	221–232	277–288	371	371	302–330
Nozzle Temperature, °C	232–260	288	371	371	343
Mold Temperature, °C	Ambient to 93	Ambient to 107	>93	149–260	25–190
Stock Temperature,°C[1]		282	343–382	343–399	303–329
Injection Speed, rpm	Slow–fast	Moderately Fast	Slow	Slow	Moderately Fast
Injection Pressure, MPa	6.2	—	21–55	21–55	21–103
Hold Pressure, MPa	3.5	—	—	—	—
Back Pressure, kPa[2]	172	—	—	—	—
Times, sec		—	—	—	—
Injection	3–4				
Hold–up	7–8				
Cooling	25–30				
Mold Shrinkage, % (3.2 mm thick test bar)	2.5–3.0	—	3.5–4.0	3.5–4.0	2.0–3.5

[1] Stock temperature refers to the temperature of the resin as it leaves the nozzle.

[2] Back pressure is the pressure applied by the hydraulic system which the screw must overcome in its backward motion while recharging the melt.

Table 6.28. Injection Molding Conditions for Compounds of Fluoropolymers[45]

Process Variable	PFA	PFA	PVDF	FEP	ETFE	ETFE
Filler	Glass Fiber	Carbon Fiber	Carbon Fiber	Carbon or Glass Fiber	Glass Fiber	Carbon Fiber
Filler Content, weight %	15–30	20–30	10–30	20	10–25	10–30
Cylinder Temperature, °C:						
Rear	316–332	316–332	182–249	316–329	274–302	274–302
Center	329–343	329–343	193–260	329–343	302–329	302–329
Front	338–366	338–366	213–274	366–371	307–335	307–335
Melt Temperature,°C	343–385	343–385	210–288	343–385	293–343	293–343
Mold Temperature,°C	149–232	149–232	82–104	>93	66–149	66–149
Injection Speed Fill:						
mm/sec	13–25	13–25	13–25	13–25	25–51	25–51
Screw, rpm	60–90	60–90	60–90	60–90	60–90	60–90
Injection Pressure, MPa	55–83	55–83	69–103	21–55	69–103	69–103
Hold Pressure, MPa	21–48	21–48	34–69	21–48	34–69	34–69
Back Pressure, kPa^2	0.34–0.69	0.34–0.69	0.34–0.69	0.34–0.69	0.34–0.69	0.34–0.69
Resin Drying:						
Temperature,°C	121	121	121	121	121	121
Time, hrs	2	2	2	2–4	2	2

Mold temperature should be selected with consideration given to many dependent process parameters including the design and geometry of the part, surface finish, ejectability, residual stresses, and shrinkage of the part. Mold temperature also influences the cycle time which is important to the productivity of the machine. Very high mold temperatures should be avoided when the part has thick walls. It can be set higher than normal when the flow path in the mold is long relative to the part's wall thickness. A technique has been reported for molding thin parts in which the mold temperature was raised above the melting point of the polymer before filling began.[49] After the mold was filled, the mold was cooled down below the freeze point of the polymer. An increase in the mold temperature also reduces the likelihood of part delamination.

Thorough cleaning of the injection molding machines is very important. If the parts are made of non–corrosion-resistant metal, cleaning prevents corrosion of the process surfaces. The residual polymer can be removed by purging, which means running the machine on a material capable of pushing the fluoropolymer out of the machine. A purge can be left in the machine when the equipment is constructed of corrosion-resistant metals. The most effective procedure for cleaning is comprised of taking apart the injection molding machine before the molten polymer cools and removing the polymer.

6.8.1.3 Dimensional Stability of Parts

Close tolerances can be achieved provided that operating variables of the process are tightly controlled. Mold design is, however, the other critical factor in obtaining high-precision molded parts. As tolerances become smaller, cost of manufacturing and complexity of the process grow. Almost every variable in the molding process affects the part dimensions. Shrinkage during the molding process is a critical factor in determining the final dimensions of the part.

Shrinkage increases with part thickness (Table 6.29) and mold temperature because in both cases cooling rate decreases. Consequently, crystallinity increases and internal stresses decrease. A number of plastics exhibit direction-dependent shrinkage (Figs. 6.35 and 6.36). The least amount of shrinkage takes place in the direction of flow due to the highest degree of orientation in this direction. The rule-of-thumb that is useful to the design of molds is that the straighter the path, the lower the shrinkage. Table 6.30 shows the effect of various parameters on shrinkage of injection-molded parts. Annealing a molded part, that is, heating and holding it above its performance temperature, can prevent further shrinkage during its use.

Figures 6.37–6.39 are examples of parts fabricated by injection molding processes.

6.9 Rotational Molding

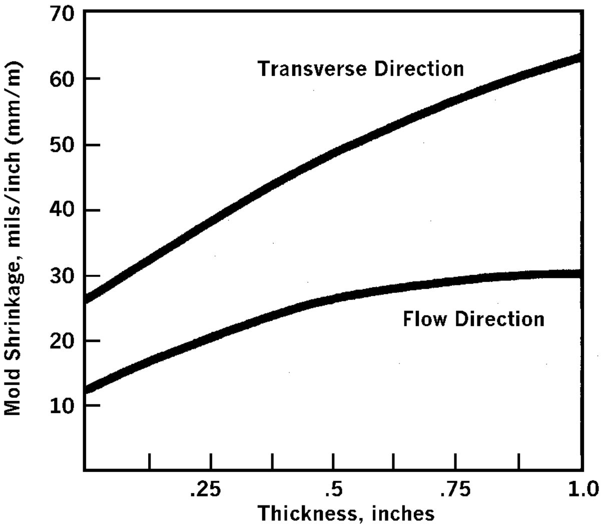
Rotational molding (also called *rotomolding* or *rotational casting*) is a process for manufacturing seamless hollow plastic parts for a variety of applications ranging from liquid storage tanks to containers of various shapes. It (Fig. 6.40) involves the external heating of a thin-walled hollow metal mold containing a polymer powder. Heating occurs while the mold is rotated multiaxially. The powder melts and coats, or sinters, onto the interior wall of the cavity. The mold is then cooled which allows the part to solidify and crystallize in the case of fluoroplastics. Finally, the part is removed and the mold is charged to repeat the cycle.

The rule-of-thumb for selecting rotational molding technology is: part quantities of less than 25,000 per year and sizes larger than 200 liters. In the case of fluoroplastics, smaller parts are also produced by this technology. It allows the production of parts with intricate geometry without imparting significant residual stresses or orientation to the part. These are the advantages of this process over blow molding in addition to its ability to fabricate larger parts. Rotomolding requires significantly smaller capital investment than injection and blow-molding processes, thanks to its low-pressure requirement. Parts made by rotational molding often cost more than those manufactured by more conventional processes because of its relatively long cycle time.

Fluoropolymers can be fabricated into hollow objects by rotomolding. They are, however, hard to mold due to their relatively high melting point and melt viscosity. The most frequently rotomolded fluoropolymers are PFA, FEP, PVDF, ETFE, and ECTFE. Fluoropolymers constitute about 1% of all rotomolded parts.

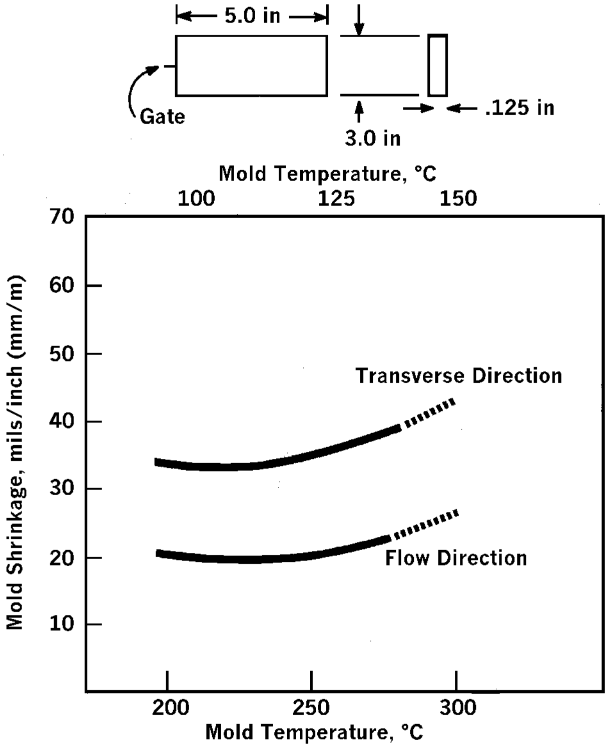
Table 6.29. Shrinkage of PFA and FEP as a Function of Thickness[44]

Part Thickness, mm	Shrinkage	
	mm/m	%
3.2	35–40	3.5–4.0
6	40–45	4.0–4.5
12.7	45–50	4.5–5.0
19.1	50–60	5.0–6.0



Mold Temperature = 200°F/93°C
Melt Temperature = 625°F/330°C
Injection Pressure = 10,000 psi/70 MPa

Figure 6.35 Shrinkage of ETFE (Tefzel® 200) vs thickness in flow and cross directions.[44]



Part Thickness 0.125 in/3.2 mm
Melt Temperature 625–650°F/330–345°C
Injection Pressure 7,000–10,000 psi/50–70 MPa

Figure 6.36 Shrinkage of ETFE (Tefzel® 200) vs mold temperature in flow and cross directions.[44]

Table 6.30. Effect of Various Parameters on Shrinkage

Increase Shrinkage	Decrease Shrinkage
Increased stock temperature	Increased injection pressure
Increased mold temperature	Filler addition
Increased part thickness	Increased polymer orientation
	Straight melt flow during molding

Figure 6.37 High purity flow controller fabricated by injection molding process. *(Courtesy Atlantic Tubing and DuPont Companies.)*

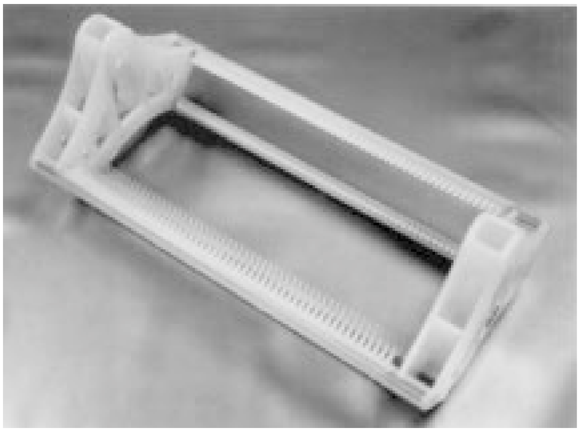


Figure 6.38 A semicon wafer carrier-fusion bonded assembly of injection molded side rails and strengthened by pultruded rods consisting of carbon fiber compounded PFA. *(Courtesy Entegris and DuPont Companies.)*

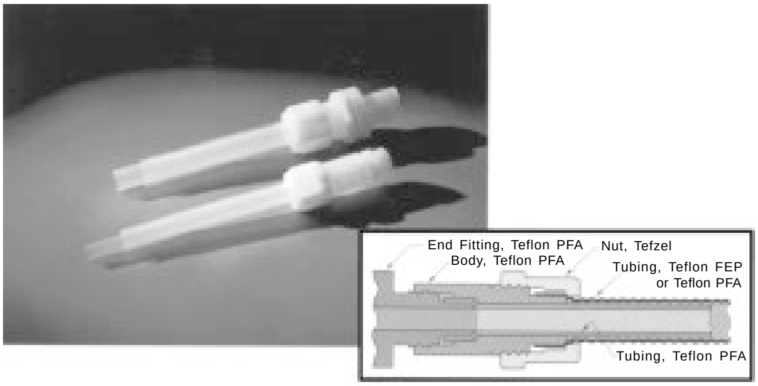
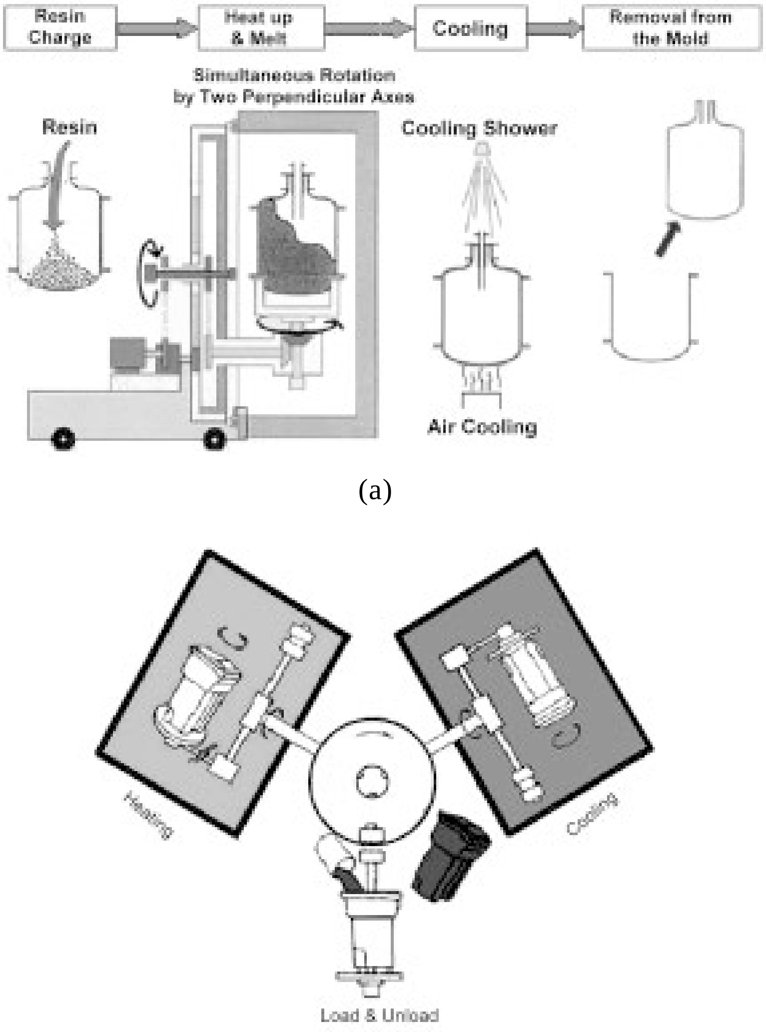


Figure 6.39 A dual containment flare fitting made from PFA by injection molding. *(Courtesy St. Gobain and DuPont Companies.)*



(a)

(b)

Figure 6.40 Schematic diagram of rotational molding. *[(a) Courtesy DuPont Fluoroproducts. (b) Courtesy Glenn Beall Plastics, 32981 N. River Road, Libertyville, IL, 60048.]*

6.9.1 Basic Process Technology

Rotational molding is used to produce a broad array of seamless hollow plastic products. Except for permanent adhesion to the cavity wall, processing considerations in *rotolining* are otherwise identical to those in rotomolding. In this process, a premeasured amount of a plastic powder, granules, or liquid is charged inside a mold cavity. The mold is closed and heated in an oven while being rotated multiaxially (usually two axes). Figure 6.41 depicts a biaxial rotomolding machine. The major axis is the centerline of the arm of the mold. The minor axis rotates the mold perpendicular to the major axis. Typically, the minor axis revolves four times to every one time of the major axis. The basic steps of mold charging, heating, cooling, and part removal are shown in Fig. 6.41. In an alternative design, the molds undergo a "rock and roll" motion, rotating 360° around one axis and rocking about a perpendicular axis. In a majority of cases, the mold is heated by forced hot air. Open flame burners, as well as infrared, conductive, inductive, and dielectric heating techniques, have also been reported. The wall of the mold is usually heated to a temperature above the melting point of the polymer.

Heat transfer, from the hot air in the cavity and from the wall of the mold to the powder, melts the polymer which sticks to the hot cavity (Fig. 6.42). It results in the formation of an even coating on the interior wall of the cavity. The mold is cooled while it is rotated to retain the uniform wall thickness. Finally, after the polymer has solidified, the rigid part is removed from the mold. Volatile material formed during the heating period is removed from a vent port. The rotation rate, temperature, heating rate, and cooling rate are controlled throughout the process.

The rotomolding process is differentiated from *spin-casting* or *centrifugal casting* by its relatively low rotation speed that is usually in the range of 1–20 rpm. Rotation speeds range up to 40 rpm on the minor axis and 12 rpm on the major axis. These speeds are slow enough to prevent development of significant centrifugal forces.

The rotational molding process takes place in two stages. During the first stage the polymer melts, sinters, and densifies, while in the second stage the melt flows on the walls of the mold and fills all channels, undercuts, and other cavities in the geometry of the mold under shear stresses developed during the rotation. The main force acting on the polymer is gravity because, due to the low rotation speed, the centrifugal forces are negligible. The absence of significant shear requires high molding temperatures to reduce the viscosity of the polymer and expedite its mold filling action.

This method is ideally suited to the casting of spherical shapes, but the outer shape may be modified with the use of special techniques. Normally, metal molds are used and plastic is poured into the rotating mold that may spin about a horizontal, inclined, or vertical axis. The centrifugal force, even though minor relative to gravity, improves both homogeneity and accuracy.

6.9.2 Rotomolding and Rotolining Processing Conditions

This section provides examples of temperature and time cycles for rotomolding select fluoroplastics. The most frequently molded fluoroplastics, by this technology, are PFA, FEP, PVDF, ETFE, and ECTFE. Rotation ratios for these resins follow the general guidelines that have been listed in Table 6.31. In summary, the rotation ratio ranges from 1:5 for cylinders to 8:1 for oblongs. A typical rotation ratio for a medium part is 4:1. The exact value of rotation ratio for each resin must be determined experimentally.

Rotomolding can also be used to fabricate liners that are installed in a casing or a cavity in a secondary operation. The main goal is to obtain good adhesion between the liner and the surface of the cavity. One way this can be accomplished is by creating "surface roughness" on the back surface of the liner to mechanically interlock the liner to an adhesive coating on the cavity wall. A number of patents describe this approach of enhancing the liner adhesion.[52]–[54] Sumner[54] unveiled a process in which the two materials were joined together by mechanical interlock created by "chips" at their interface. The chips were composed of a polymer that could be the same as the lining resin or of a different plastic.

The mold was charged with a free-flowing PFA powder comprised of two separate distributions. The fine cut powder had a particle size of 500 µm or lower. The coarsely divided PFA powder, which formed the chips, had a size range of 3.2–6.2 mm. After

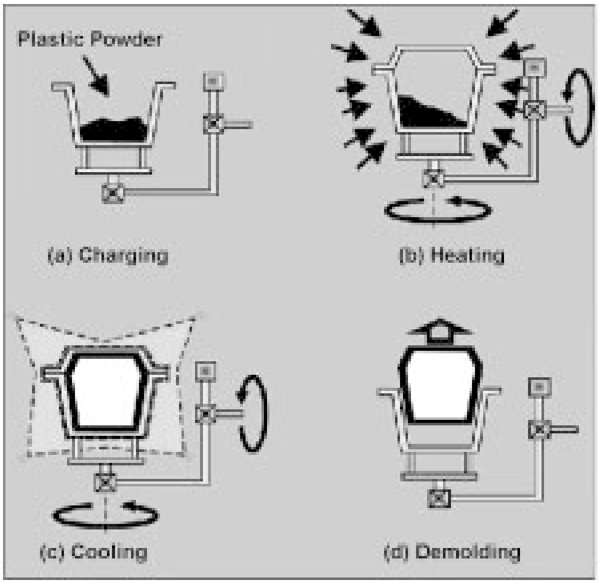


Figure 6.41 An example of a biaxial rotational molding machine.[50]

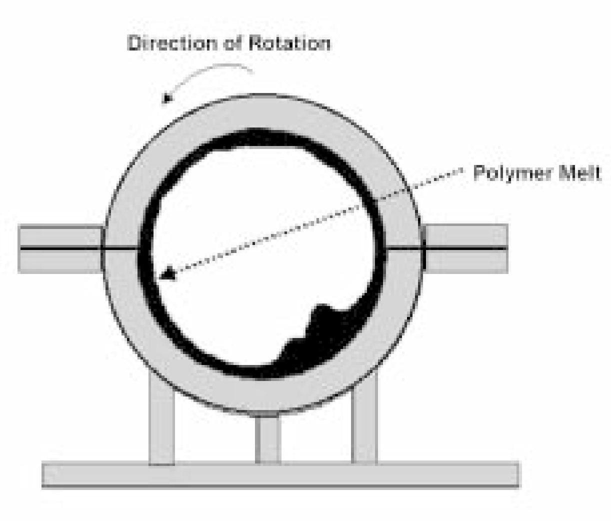


Figure 6.42 Scheme for adhesion of polymer melt to the wall and part formation.

Table 6.31. Typical Rotation Ratio of Various Shapes[51]

Shapes	Rotation Ratio	Rotation Speed of Major Axis
Horizontally mounted oblong articles and straight tubes	8:1	8
Cubes, balls, odd shapes, and rectangular boxes	4:1	8
Rectangular shapes with more than two or thin sides when run at a ratio of 4:1	2:1	8
Flat rectangles such as gas tanks	1:3	4 6 9.5
Pipe angles and curved air ducts	1:4	5
Vertically mounted cylinders	1:5	4

charging, the mold was indexed into an oven preheated to the desired molding temperature of 315°C to 371°C. In general, the molding temperature depends on the type of resin. The mold was rotated biaxially during which the PFA powder melted and built up a molten layer of uniform thickness on the mold surface. The chips remained substantially unmelted after the smaller particle-size fraction of the PFA powder has been melted. Rotation speeds around the major and minor axes were 8 rpm and 10 rpm.

The chips remained loose in the mold until they melted at their surfaces and adhered to the molten PFA layer on the mold wall (Fig. 6.43). At this point the chips became embedded in the viscous melt and were fused to this layer. The chips became somewhat rounded, depending on the temperature and the length of the heating cycle, but they did not lose their basic shape. As soon as the particles have formed the molten coating, and before the chips lost their basic shape, the mold was indexed into the cooling station. Cooling by air or water spray was continued until the molten layer solidified into a liner with embedded chips.

The resulting liner has a smooth front surface and a rough back surface formed by the protruding chips. The remaining angularity of the chips provides overhanging surfaces allowing a suitable material to be tightly anchored to the back surface of the liner by the molding process. The liner was relieved of stress by thermal treatment at temperatures of 95°C to 150°C. The liner was next placed in a compression mold and a glass-fiber–filled epoxy molding compound was molded against the liner to form its casing. The mechanical interlock between the chips and the casing provided a strong bond with peel strength approaching 9–13.5 kg/cm. The liner could also be installed in a pre-made casing where the liner was fastened to the surface of the casing by a layer of an adhesive.

6.9.2.1 ECTFE

ECTFE is a copolymer of ethylene and chlorotrifluoroethylene. This resin is not hygroscopic and does not need to be dried prior to molding.

Conventional molds, such as plaster-cast aluminum, are satisfactory for ECTFE molding. A corner radius greater than 1.25 cm has been recommended to produce a smooth interior surface and uniform wall thickness. To facilitate release from the mold, silicone or fluorocarbon release agents can be sprayed in scant amounts on the mold surface. Venting of the mold is recommended.

Although oven temperatures between 282°C and 357°C have been successfully tried for rotomolding ECTFE, the recommended range is 288°C–315°C.[55] At temperatures above 321°C, small bubbles are formed that are difficult to eliminate from the part. Cycle time has to be determined experimentally. The

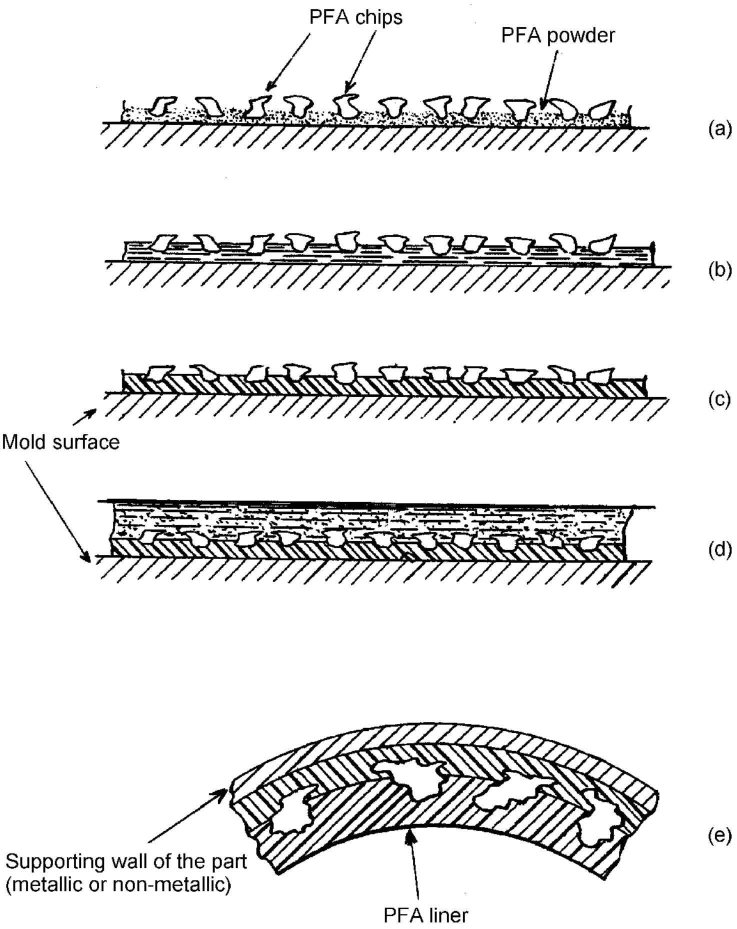


Figure 6.43 Rotational molding of PFA powder.[54]

best approach is to begin with a short cycle and increase it until the optimal cycle has been determined. Specific gravity and tensile property measurements can control the quality of the part. Table 6.32 gives examples of cycles for a few different part designs.

6.9.2.2 ETFE

Rotomolding conditions of ethylene tetrafluoroethylene (ETFE) polymer are generally similar to those of ECTFE. Table 6.33 shows ranges for temperature and oven (fusion) time for processing ETFE.

Bealky, et al.,[57] reported fabrication of fluoropolymer tanks for the storage of high-purity corrosive gases by rotational lining. The tank walls could consist of multiple layers of the same or different fluoroplastics. For example, a D-1 style cylinder with a diameter of 17.6 cm and a length of 22.5 cm was rotolined with ETFE in a carousel-type rotomolding machine. The cylinder walls were cleaned by degreasing and sandblasting, and baked under vacuum (or under inert gas). The cylinder was purged with nitrogen prior to filling it with 1,450 g of ETFE. The gas valve was next installed on the cylinder and it was filled with nitrogen. The assembly was then mounted inside the rotomolding machine. The cylinder was preheated to 252°C for 20 min and rotation was started. The oven temperature was raised to 300°C for 80 min before indexing the machine into the cooling station. Rotation was continued while the cylinder was cooled by forced air and water spray. After cooling was completed, the arm was indexed into the unloading/loading station and the cylinder was removed.

6.9.2.3 PFA

Perfluoroalkoxy (PFA) polymer is the most difficult to fabricate by rotomolding because of its high melt viscosity. Table 6.33 shows the temperature and oven (fusion) time ranges for processing PFA. Some specific examples of rotational molding and lining are described here.

Table 6.32. Rotomolding Heating and Time Cycles for ECTFE[55]

Part	Mold	Wall Thickness, mm	Temperature, °C	Oven Time, min
Hair dryer case	6.3 mm thick aluminum	1.9	315	13
Rectangular tank 45.4 cm × 10 cm × 15.1	1.6 mm thick sheet metal	1.6	296	14
15.1 cm sphere	6.3 mm thick cast aluminum	3.1	296	14
50.4 cm T pipe joint	12.6 mm thick cast ductile iron	3.5	315	25

Table 6.33. Rotomolding Heating and Time Cycles for ETFE and PFA[56]

Resin	Part Wall Thickness, mm	Temperature, °C	Oven Time, min	Rotation rate for boxes, cylinders, and tees, rpm		Rotation rate for spheres and ellipsoids, rpm	
				Major Axis	Minor Axis	Major Axis	Minor Axis
ETFE	1.5–6.25	305–330	25–60	8	9	8	10
PFA	2–3	355–385	90–180	8	9	8	10

In an interesting development, Wolf[58] described rotomolding the liner of a pressurizable vessel designed for storage and dispensation of fluid chemicals. The inner liner was seamless and molded separately from a fluoropolymer. The liner was then encapsulated within the outer overpack. The outer overpack was a metallic casing (preferably stainless steel) that was heat-welded in place around the inner liner. The inner liner was formed with recesses in the areas adjacent to the welds of the overpack. These recesses hold a sacrificial layer of fluoropolymer between the liner and the overpack. The sacrificial fluoropolymer is designed to protect the liner from the heat of welding.

In another case,[59] PFA (with a melt flow rate of 4–9 g/10-min) was first mixed with 0.1% by weight of a tin powder, 0.03% by weight of N-phenyl-α-naphthylamine, and 0.02% by weight of carbon black. This mixture was tumbled in a drum while being heated to a temperature of 304°C–310°C which lightened the color of the mixture. The cooled powder was loaded in the cavity of a carousel-type rotolining machine. Tin helped eliminate the bubbles from the part.

A simple cylindrical shape required a temperature of 371°C for 75 min. Alternatively, a temperature of 357°C for 90 min would produce an equally satisfactory lining. The air and/or water media cooled the mold and the part was removed and inspected. A bubble- and porosity-free lining with a uniform wall thickness was obtained.

A more complex part, such as a pipefitting, was molded from the same PFA powder mixture. A different cycle was required consisting of heating at 385°C for 45 min followed by 45 min at 357°C. A smooth bubble-free lining on the fitting was obtained.

RMB Products, Inc., has developed a tank that has been rotomolded[60] around fins to improve heat transfer to and from the tank. The fins were first electrostatically coated with the resin powder before being placed in the rotational molding machine. The precoating of the fins was found to improve resin adhesion. The polymer of choice for this tank (Fig. 6.44) was PFA or ECTFE, which allows the tank to be used to store aggressive chemicals.

The technique developed by Bealky, et al.,[57] discussed in Sec. 6.9.2.2, required a preheating and heating time of 60–150 min for PFA at a melting temperature of 232°C–316°C. The cylinder was heated from 10 to 65°C above the melting point of the polymer. Wall thickness of the cylinder was in the range of 2–5 mm.

6.9.3 Conclusion

Rotational molding is a complex process and involves numerous related variables and details that must be set correctly to produce quality parts repeatedly. The details concern the design of the part, the choice of the plastic, the design and fabrication of the mold and, finally, the actual rotational molding process. The end use requirements usually provide guidance for specifying the construction material and the design and dimensions of the part. On the other hand, any design must be practical and economical. The cost of mold construction and the operating process are strongly influenced by the design of the part. Fluoropolymers pose additional restraints on the process and part design due to their high melting temperature and viscosity.

A reader who would like to engage in rotomolding must consult other references that have addressed the subject in a thorough and in-depth manner. Complete coverage of this technology can easily occupy a separate volume that is beyond the scope of this book. This task has been most ably accomplished by a number of authors and experts. Figures 6.45–6.47 provide examples of parts fabricated by rotational molding.

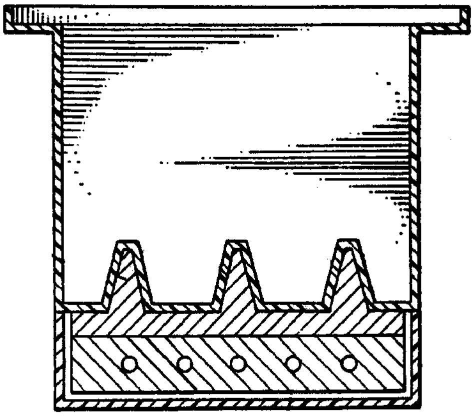


Figure 6.44. Schematic of a finned tank.[60]

Figure 6.45 A rotationally molded storage tank with a capacity of 5,000 liters. *(Courtesy Entegris and DuPont Companies.)*

Figure 6.46 Seamless ETFE-lined vessels fabricated by rotational lining. (*Courtesy RMB and DuPont Companies.*)

Figure 6.47 Seamless ETFE-lined vessels fabricated by rotational lining. (*Courtesy RMB and DuPont Companies.*)

6.10 Other Part Manufacturing Techniques

Historically, thermoplastic polymers have been processed by a variety of molding methods which are usually selected to accommodate the shape, geometry, and other requirements of parts. Each molding process has its own advantages and disadvantages that prevent it from being used to make parts of all shapes and sizes. Table 6.34 lists some of the important benefits and shortcomings of the molding and extrusion techniques for thermoplastics. The second issue is the high viscosity of most molten fluoroplastics, which substantially increases force requirements for moving the melt, and the machine part strength to withstand the high stresses (pressures) generated during the processing.

The rest of this chapter discusses compression molding, transfer molding, blow molding, and vacuum bagging of fluoropolymers.

6.10.1 Compression Molding of Fluoropolymers

The general procedure for compression molding is applicable to thermoplastics molding except that cooling the mold under pressure hardens the article. The length of the heating and cooling cycles is determined experimentally. Thermoplastic compounds can not be pressed into a preformed charge. In contrast, a thermosetting compound undergoes a chemical reaction (crosslinking) during the hardening of the part.

Fluoroplastics generally have high melting points, thus they need to be heated to an elevated temperature (Table 6.35) during compression molding. Heating and cooling make for long cycles and great power consumption in conventionally heated compression molds. Small molds are preferable to larger machines. Separate platen presses are used where one is a hot press that is electrically heated and the other is a cold press that is water-cooled. The article is shaped in the hot press under pressure. The mold is then transferred, as rapidly as possible, to the cold press to chill the article under pressure. The article is removed after it has been cooled to a sufficiently low temperature. To ease the removal of the part from the mold, its surfaces can be covered with aluminum foil that has been sprayed with a mold release agent.

The length of cycle time depends on the mass size of the part and the properties of the fluoropolymer. The hot press is usually preheated to decrease the overall cycle time. For example, a lower melting point or a lower melt viscosity fluoropolymer requires a shorter cycle than one with a higher melting point or melt viscosity. Pressure is gradually increased during the heating cycle. Table 6.36 gives examples of compression profiles of different fluoropolymers at different thicknesses in flat sheet geometry. Thicker parts require significantly longer cycles (many hours) to melt and fuse the resin and eliminate bubbles and voids. Large cylindrical stock shapes (>100 kg) of these have been produced and subsequently skived for film and tape applications.

Another example of compression molding was given by Nichias Corporation.[61] A rectangular plate-like part was formed by inserting a stainless steel plate in the mold at the core of the part and surrounding it with a fluoroplastic resin. PTFE bearers (Nos. 3 and 4 in Fig. 6.48) were positioned between the core material and the mold cavity such that the core was inserted into the mold without contacting the surface of the mold cavity. Essentially, the PTFE bearer resembles a large screw that is threaded (No. 4 in Fig. 6.48) into the metal core plate (No. 1 in Fig. 6.48). Consequently, the fluoroplastic surface layer could be formed around the core. PTFE did not soften and deform during the molding, leading to its complete encapsulation in the core.

In the first molding step, half of the fluoroplastic resin was charged into the mold. Next, the bearer and core assembly was set in the mold. Then the other half of the resin was dispensed into the mold. The hold-down plate was used to compress the contents of the cavity while the mold was heated to a temperature above the melting point of the fluoroplastic resin. After cooling, the part can be removed and machined to the required specifications.

A method has been described[62] for producing a compression molding powder that is a blend of PTFE or polychlorotrifluoroethylene (PCTFE) resins and extra-high molecular weight (EHMW) FEP. This grade of FEP was defined as having a melt viscosity of 10^6 poise or more, MFR of less than 0.8 g per10 minutes, 12%–30% by weight of hexafluoropropylene, a weight average molecular weight of 2×10^5 and a tensile strength of 27 MPa. The blended alloy had melt fabrication characteristics (like FEP) and

Table 6.34. Comparison of Molding and Extrusion Techniques for Thermoplastic Polymers

Molding Technique	Advantages	Disadvantages	Typical Process Shear Rate (sec^{-1})
Injection Molding	The most precise control of shape and dimensions, highly automatic process, fast cycle time; the widest choice of materials.	High capital cost; is only good for large numbers of parts; large mold pressures (140 MPa).	1,000–10,000
Compression Molding	Lower mold pressures (7 MPa); does minimum damage to reinforcing fibers (in composites); large parts are possible.	Requires more labor; longer cycle than injection molding; less shape flexibility than injection molding; each charge is loaded by hand.	<1
Transfer Molding	Good for encapsulating metal parts and electronic circuits.	Some scrap with every part and each charge is loaded by hand.	1–100
Blow Molding	Can make hollow parts (such as bottles); stretching action improves mechanical properties, fast cycle; requires low labor.	No direct control over wall thickness; cannot mold small details with high precision; requires a polymer with high melt strength.	—
Rotational Molding/Lining	Labware that's shatterproof and won't contaminate samples; small to very large lined vessels; valve lining; bellows; items with complex geometry; containers	A slow process; requires labor and involves numerous moving parts. A great deal of cleaning and surface conditioning is necessary.	<100
Extrusion	Used for films, wraps, or long continuous parts (i.e., pipes).	Must be cooled below its glass transition temperature to maintain stability.	100–1,000

Table 6.35. Typical Compression Molding Temperature and Pressure of Fluoropolymers

Fluoropolymer	Temperature, °C	Pressure, MPa
Polychlorotrifluoroethylene (PCTFE)	230–315	13.8–20.7
Polytetrafluoroethylene (PTFE)	370–395	7–138
Perfluoroalkoxy (PFA)	343–380	1.5–10.5
Fluorinated ethylene propylene (FEP)	340–370 290–315*[1]	1.5–10.5
Ethylene tetrafluoroethylene (ETFE)	300–335	1.5–10.5

*[1] Requires extending the holding time at the peak temperature under pressure.

Table 6.36. Compression Profile of Fluoropolymers

Fluoropolymer					
PFA, FEP (3.2 mm thickness)		PFA, FEP (1.6 mm thickness)		ETFE (1.6–3.2 mm thickness)	
Time, min	Pressure, MPa	Time, min	Pressure, MPa	Time, min	Pressure, MPa
0–8*[1]	0.17	0–6[1]	0.17	0–6[1]	0.26
8–10*[1]	1.7	6–8[1]	1.7	6–10[1]	0.69
				10–12[1]	1.72
0–5*[2]	3.45	0–5[2]	1.7	0–5[2]	3.45

*[1] In hot press. *[2] In cold press.

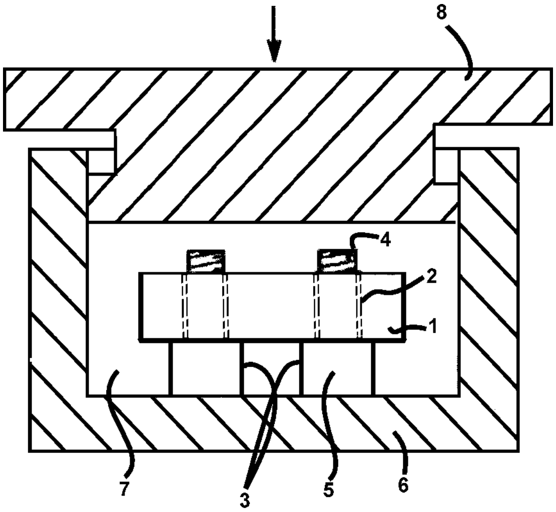


Figure 6.48 A schematic diagram of a rectangular compression mold.[61] 1: - metal core plate; 2: threaded section; 3, 4: PTFE bearers; 5: bearer head; 6: mold; 7: resin space; 8: hold-down plate.

cold compression molding and sintering properties similar to PTFE. Parts made from the blend had a combination of the properties of the two polymers such as the freedom from voids and creep resistance of FEP, and stress crack resistance and high tensile strength at elevated temperatures.

The process for preparing a blend of PTFE and extra-high molecular weight fluorinated ethylene propylene copolymers included grinding each polymer separately, mixing the proper ratios, and mixing and grinding again until the separate phases were thoroughly mixed. The powder was sieved through a 40–80 mesh screen before molding. A typical composition comprised of 0.1%–60% by weight EHMW-FEP and 40%–99.9% PTFE. The alloys made by this procedure could be melt-processed at 300°C–350°C and 5–20 MPa. They could also be compression molded at 5–20 MPa and sintered at 300°C–390°C. The melt processing and sintering temperatures of the alloy depended on its PTFE content; the higher the PTFE content, the higher the processing temperature. High PTFE content alloys were more difficult to mold by melt-processing methods.

Table 6.37 shows the properties of parts made by compression molding alloys of EHMW-FEP/PTFE. PTFE content ranged from 0%–100% by weight and molding took place at a pressure of 8 MPa. Tensile properties were measured at room temperature and at 200°C. ETFE and PCTFE resin mixtures with extra-high molecular weight FEP were compression molded at 7–15 MPa. Their physical properties are given in Tables 6.38 and 6.39.

6.10.2 Transfer Molding of Fluoropolymers

Transfer molding is a popular process for manufacturing fluoropolymer parts. Generally, this family of plastics has a high melting point and melt viscosity, and low critical shear rate, which renders it suitable for the slower processing rates of transfer molding techniques. High quality parts such as lined valves, fittings, pump housings, and similar equipment can be produced by this technique. In this section, mold design, operation, and disassembly including processing conditions have been discussed for fluoroplastics.

6.10.2.1 Mold Design

As in other molding methods, these molds must be constructed from corrosion-resistant metals. Rusting and pitting can be avoided by plating the mold with nickel to a thickness of 10–50 µm.[63] The plate must be devoid of pinholes to enhance the durability of the nickel coating and produce high quality surface parts.

The diameter of the sprue bushing should be a minimum of 1.5 mm larger than the diameter of the runner and slightly greater than the opening of the nozzle. Sprue bushings are large in transfer molding and, unless the part is very small, they should have a diameter of 12 mm and a tapering angle of 3° or 4°.

To minimize pressure and heat losses, the runners should be round and as short as possible. Another preferred choice is trapezoid runners that are easy to machine and provide the same amount of resistance to flow as round runners. They should blend smoothly into the gates, without abrupt cross-sectional changes. The runner's length should be reduced and its diameter increased when the thickness of the molded part increases. A runner diameter of at least 6 mm is required for a 10 mm thick part. Thicker parts require runners that are 50%–100% larger in diameter than the thickness of the part. As in injection molding, pressure drop and material loss are de-

Table 6.37. Tensile Properties of Compression Molded* Alloys of PTFE and EHMW-FEP[62]

Variable	EHMW-FEP Content/PTFE Content, weight %						
	100/0	90/10	75/25	50/50	25/75	10/90	0/100
Sintering Temperature, °C	300	300	300	320	340–365	340–365	365
Room Temperature							
Tensile Strength, MPa	26.5	21	25	29	26	28	32
Elongation, %	330	310	370	500	520	520	650
At 200°C							
Tensile Strength, MPa	4.6	8.7	8.4	8.2	8.9	10.4	8.9
Elongation, %	340	340	500	450	500	680	480

* Compression molded at 8 MPa.

Table 6.38. Tensile Properties of Compression Molded* Alloys of ETFE and EHMW-FEP Resins[62]

Variable	EHMW–FEP Content/ETFE Content, weight %								
	100/0	99/1	90/10	75/25	50/50	25/75	10/90	1/99	0/100
Sintering (fabrication) Temperature, °C	310–380	300–350	300–340	300–330	300–320	300–320	300–320	280–330	280–340
Room Temperature									
Tensile Strength, Mpa	30	31	31.5	32	32.5	33	34	35	40
Elongation, %	300	300	280	260	200	150	100	100	100

* Compression molded at 8 MPa.

Table 6.39. Tensile Properties of Compression Molded* Alloys of PCTFE and EHMW-FEP Resins[62]

Variable	EHMW FEP Content/PCTFE Content, wt%								
	100/0	99/1	90/10	75/25	50/50	25/75	10/90	1/99	0/100
Sintering (fabrication) Temperature, °C	310-380	310-330	300-330	270-300	250-300	250-300	250-300	250-300	250-320
Room Temperature									
Tensile Strength, MPa	30	28	20	22	30	30.5	32	30	35
Elongation, %	350	300	40	100	250	180	200	150	150

* Compression molded at 8 MPa.

termined by the length of the runners. In multicavity molds, balanced or lateral runner layout can be selected. A balanced runner provides an equal flow path between the sprue and all cavities. This means that the resin that reaches every cavity undergoes the same pressure drop and residence time.

All corners and edges must be generously rounded (minimum radius 2 mm) to avoid stress concentration in the molded liner. Fitting liners that contain sharp corners may fail at these locations in chemical service after multiple temperature cycling. Unrounded liners may fail because of stress concentration that occurs by the hindrance of resin flow during the transfer operation and subsequent shrinkage during the cool-down.

Shearing of the molten plastic should be minimized to keep the stress concentration low. This is accomplished by designing the gate thickness equal to the wall thickness of the liner at the gate. Demolding becomes difficult when the gates are very small. Molten polymer may degrade mechanically due to abrupt changes of flow direction or cross-sectional changes in the gate areas. Diaphragm gates are preferred whenever possible, otherwise rectangular tab or fan-type gates that are well-flared in the mold cavity should be chosen.

In general, gates should be located at spots in the part that do not experience high impact or stress. Noncritical areas along the weld line are acceptable positions for the gates. The location of the gate should be such that minimal or no finishing is required and close to or at the thickest section of the part to reduce sink marks. Gate location should be at the center of a rotosymmetric part and, in all cases, consistent with the position of the vent. Figures 6.49 and 6.50 show two designs for gating transfer molds.

Improper venting of the mold can damage the part. Venting the mold prevents corrosion damage to the mold, allows complete filling of the mold, and the production of parts with high-strength weld lines. Adiabatic compression of the molten resin in the mold can raise the temperature significantly to about 800°C,[63] which would rapidly degrade any fluoroplastic. The main by-product of such degradation is hydrofluoric acid that will corrode nearly *any* metal.

Design of the vent (Fig. 6.51) is determined somewhat experimentally. The width of the opening and the taper angle must be chosen such that there is rapid freeze-off, minimal polymer escape, and burning is eliminated. The escape slot should be located farthest from the vent. This allows the slot to be used as an indication for the completion of the mold filling. A piece of metal (*slider*) can be put into the escape slot. At the final stage of filling, the melt pushes the slider out, signaling the end of the transfer operation.

A number of considerations should be taken into account for transfer molding of fluoropolymers. Table 6.40 gives a number of mold design considerations.

6.10.2.2 Operation of the Mold

The operations of mold and melt removal from the oven and melt transfer should be conducted as rapidly as possible to prevent premature cooling of the melt. Fluoroplastics have fairly high viscosity and require relatively long transfer time. To avoid premature cooling and freezing prior to the completion of transfer, mold temperature should be maintained at above the melting temperature of the polymer.

After the melt transfer has taken place and the mold has been filled, a hold-up time under pressure is required. This time allows shrinkage to take place while the resin is being cooled. The hold-up time allows stress relief in areas where shearing may have taken place. Cooling proceeds under pressure until the gate has been frozen, beyond which point no further pressure needs to be applied until demolding occurs. Figure 6.52 illustrates an example of a transfer molding cycle for a fluorinated ethylene propylene polymer.

6.10.2.3 Transfer Molding Process Variables

The important variables of transfer molding are the polymer type, melt temperature, pot hold time, transfer pressure, transfer rate, hold-up time in the filled mold, and the mold cooling. These variables are briefly reviewed in this section.

Selection of the fluoropolymer depends on the end use requirements, part design, and process conditions. Viscosity of the molten polymer has a great influence on the transfer rate into the cavity. Temperature changes can alter polymer viscosity as long as it has sufficient thermal stability in the given temperature range. Cleanliness of the melt can affect the quality of the part and thermal stability of the molten resin.

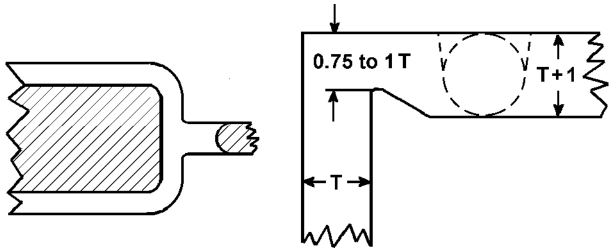


Figure 6.49 Example of gate a design for transfer molding.[63]

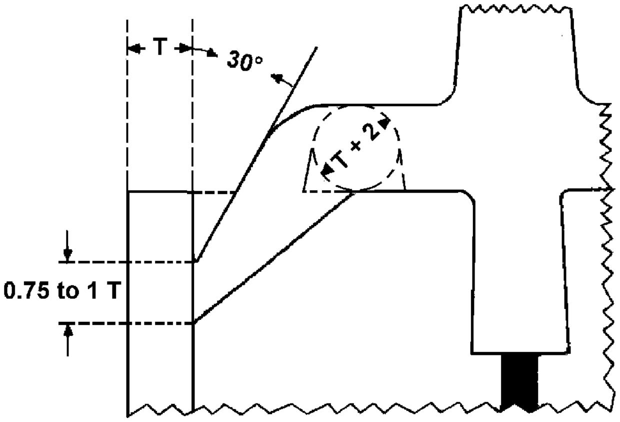


Figure 6.50 Example of a gate design for transfer molding.[63]

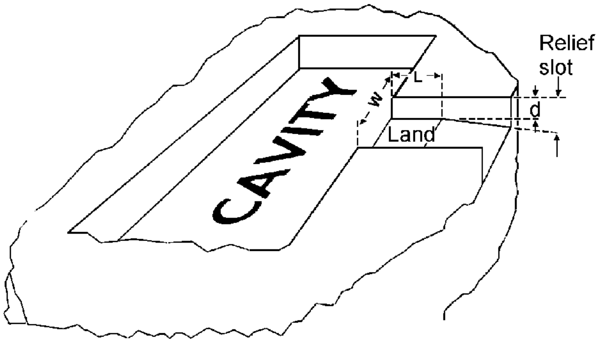


Figure 6.51 A typical vent arrangement for transfer molding.[63]

Table 6.40. Mold Design Considerations[63]

Design Factor	Consideration
Surface Finish	Finer than 32 rms finish. Surface finish should be monitored, e.g., pitted mandrels are hard to extract.
Geometry	Mandrels and pin cores should be straight. Thickness non-uniformity will result in a part that is not "true," subsequently leading to premature liner failure.
Casting Surfaces	A casting such as a fitting serves as a substrate for coating and must be smooth and free of oil and rust. Sandblasting is effective for surface preparation.
Pressure Rating	Depending on the fluoroplastic, a mold rating of 7–28 MPa at 370°C is sufficient for the highest melting point and melt viscosity fluoropolymer.
Tooling Lubricants	High temperature lubricants such as graphite pastes work well.
Mold Release Agent	Silicones and fluorocarbon release agents do not perform well. Frekote® 33 (a registered trademark of Frekote Co., USA) has a successful track record.
Heating Medium	Circulating hot air is superior to electrical or thermal fluid heating.

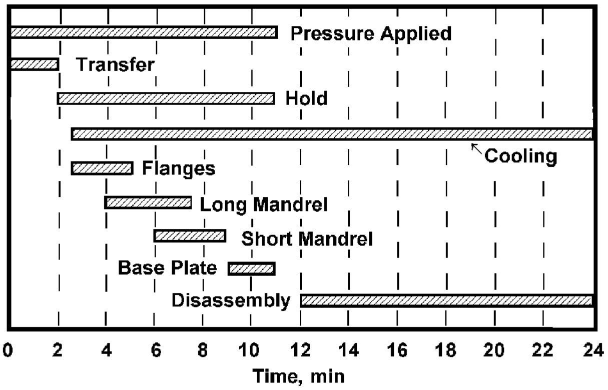


Figure 6.52 A typical transfer molding cycle for FEP.[63]

Table 6.41 shows temperature ranges of transfer molding of a few fluoropolymers. The choice of temperature is significant because a small increase can have a substantial effect on reducing melt viscosity. Temperature uniformity of the molten resin is a common requirement regardless of the type of resin or part design. Screw plastication is more effective than the melt pot method due to the static nature of the latter and poor thermal conductivity of fluoropolymers. Melt pots require significantly longer heat up time for the polymer to reach transfer temperature. There will always be a temperature gradient between the melt near the wall and the cooler material at the center of the pot.

Figure 6.53 shows actual data for melt-pot transfer molding of FEP into a liner for a 5 cm diameter T-fitting. Melt temperature at the center of the pot and the mold temperature were monitored using thermocouples. A time period of three hours was required to bring the melt pot and the mold to 340°C which was the selected process temperature. After the desired temperatures have been obtained, the next step is to transfer the melt under pressure into the heated mold cavity that will form the final shape.

After the molten polymer has been stored in the pot and reached the required temperature, it is transferred into the mold cavity under positive pressure. The pressure and rate of transfer are the significant variables of the process. Critical shear rates at which the molten fluoropolymers exhibit unsteady flow are fairly low when compared to other polymers (Table 6.42). Critical shear rate increases with temperature as seen in Figs. 6.54–6.56 for three commercial grades of FEP, PFA, and ETFE. Careful gate design and transfer rate is necessary to keep the flow below the critical shear rates.

Shear rates in channels such as gates are calculated by Eq. (6.7). In this equation, γ is the shear rate (sec^{-1}), q (cm^3/sec) is the volumetric flow rate, and D (cm) is the gate diameter. The calculated value of shear rate from this equation for a proposed gate design transfer rating can be compared to the critical shear rate of the polymer prior to mold construction. For a given gate design (fixed D), the polymer flow rate (transfer rate) can be manipulated to control the shear rate. Equation (6.7) can be rearranged [Eq. (6.8)] to determine the maximum flow rate (transfer rate) when the critical shear rate is known. Maximum flow rate (transfer rate) can be increased by enlarging the gate or increasing the temperature, which helps raise the critical shear rate (Figs. 6.54–6.56).

Eq. (6.7)
$$\gamma = \frac{32q}{\pi D^3}$$

Eq. (6.8)
$$q_{\max} = \frac{\gamma_{\text{crit}} \pi D^3}{32}$$

In transfer molding, pressure is used as the independent control variable because most presses are not equipped with speed controllers for the hydraulic piston. The general range of transfer pressures at which fluoropolymers approach critical shear rates is 15–25 MPa. Filling the mold in the "super shear" mode results in adverse effects on the properties of the molded part.

Pressures above 15 MPa help fill the mold before its components such as the mandrel and casings begin to cool. Above 25 MPa melt pressure, the mold part may crack at the gate. The equipment should allow control of transfer rate and transfer pressure. Once the filling is nearly complete (90%–95%), the transfer pressure should be lowered to half to two-thirds of its initial value to avoid stress concentration in the gate area. The pressure profile has to maximize hold pressure (Fig. 6.57) for packing without crack formation at the gate.

Cooling of the filled mold is accomplished by ambient or by fluid such as compressed air and should take place slowly at a controlled rate. Low thermal conductivity of fluoropolymers does not permit rapid cooling. The mold cooling should begin at positions farthest from the gate and proceed slowly. A frozen front forms that moves towards the gate during cooling. This approach allows addition of molten resin to the mold to compensate for the volumetric shrinkage, thus eliminating sink marks and shrinkage voids. Premature gate freezing or pressure release leads to void formation.

6.10.3 Examples of Transfer Molded Parts

Over the years, improvements have been made to broaden the types and sizes of parts that can be manufactured by transfer molding. Crane Resistoflex

Table 6.41. Transfer Molding Temperature of Fluoroplastics[63]

Fluoroplastic Resin	Molding Temperature, °C
FEP[1]	300–330
PFA[2]	340–380
ETFE[3]	300–320

[1] Teflon® FEP 160
[2] Teflon® PFA 350
[3] Tefzel® 280

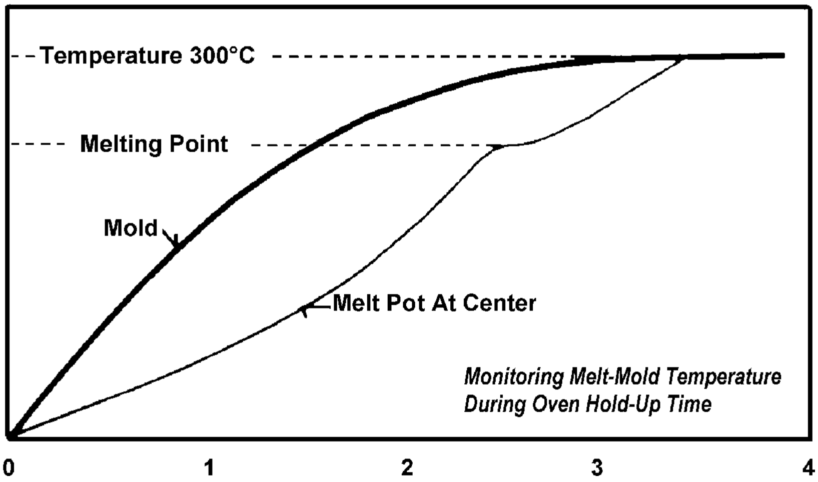


Figure 6.53 Temperature vs pot hold-up time for transfer molding FEP.[63]

Table 6.42. Critical Shear Rate of Fluoroplastics and Engineering Polymers[63]

Resin Type	Critical Shear Rate, sec^{-1}
Fluorinated Ethylene Propylene Polymer (FEP)	4–20
Pefluoroalkoxy (PFA)	10–50
Ethylene Tetrafluoroethylene Polymer (ETFE)	200–3,000
Polyacetal	5,000–10,000
Nylon 66	5,000–10,000

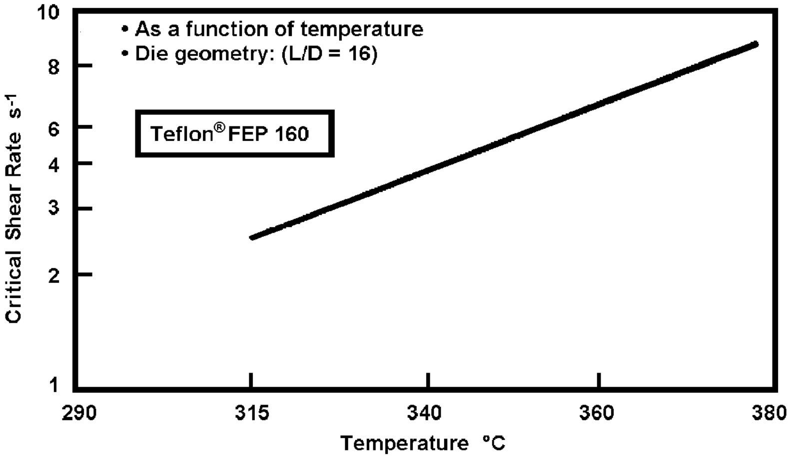


Figure 6.54 Critical shear rate of FEP vs temperature.[63]

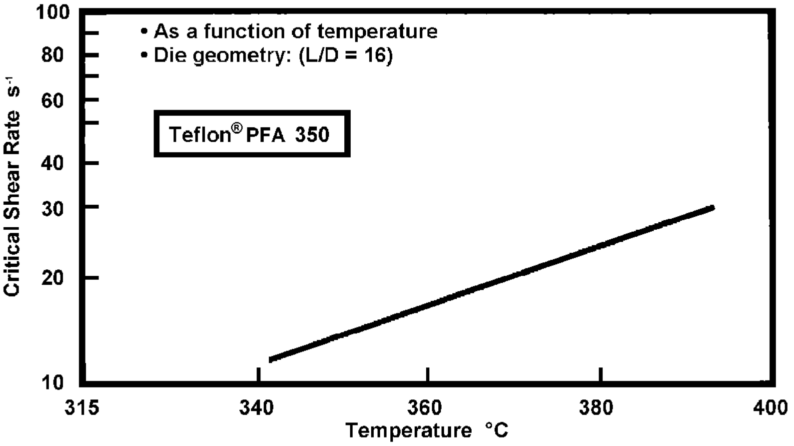


Figure 6.55 Critical shear rate of PFA vs temperature.[63]

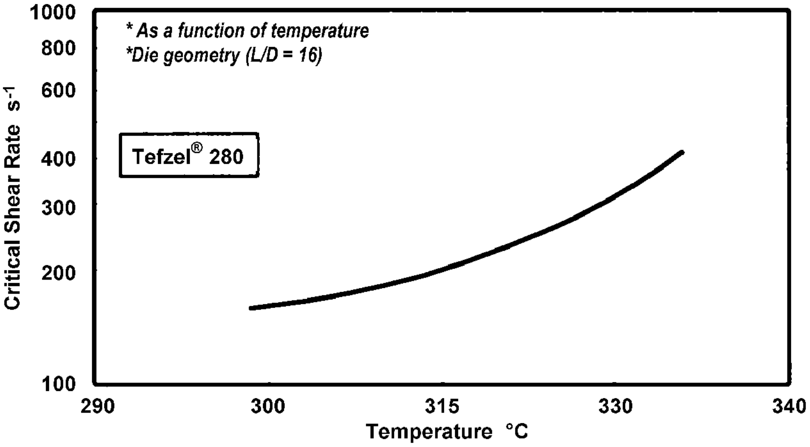


Figure 6.56 Critical shear rate of ETFE vs temperature.[63]

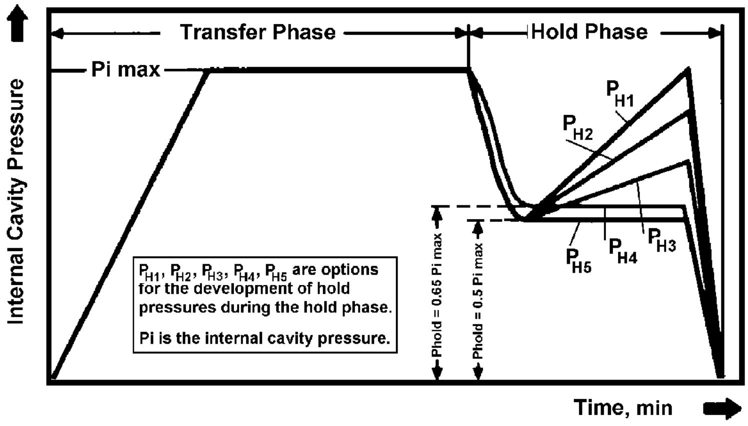


Figure 6.57 Mold cavity pressure vs time.[63]

Corporation[64][65] disclosed a process that allowed molding/lining of large T-fittings. They found that larger parts could not be made free from defects because the transfer rate could not be increased significantly by temperature increase. Critical shear rate would not increase sufficiently even when the fluoroplastic is heated beyond its degradation temperature. For example, FEP degrades appreciably at above 338°C. Consequently, as a result of slow transfer, the mold cools below a critical temperature during the transfer operation.

In the new process, the transfer operation took place inside a hot air oven rather than in ambient air. This way the temperature could be maintained at an optimum value within a narrow range, thus allowing the molten polymer to be transferred into the mold cavity at low pressure over an extended period of time. Low pressure allowed the core to be hollow and light, facilitating the cooling operation. Oven (transfer) temperature could be maintained below the degradation point, which kept the melt flow rate unchanged. Low pressure simplified the sealing of the piston and virtually eliminated flash. A higher pressure was applied during the cooling operation. For example, a 15-cm T-fitting was successfully molded from FEP, PFA, and other resins by this technique at less than 3.5 MPa transfer pressure; oven temperature, and transfer and cooling pressures are given in Table 6.43.

In another example,[66] a problem with poor physical properties of molded fluoroplastics was overcome. Transfer molded material was found to have low modulus of elasticity above 150°C and was prone to irreversible cold flow. The solution involved embedding a metal or plastic insert as a core material in the mold. The choice of the core material depended on the end use performance requirements. An engineering plastic core was found preferable; examples included polyetherether ketone (PEEK), polyphenylene sulfide (PPS), and polyether imide (PEI). Polytetrafluoroethylene bearers were placed in the mold to keep the core material away from the walls of the mold. No special cavity modifications were required. Any hot-melt fluoroplastic could be molded surrounding the insert; examples include PVDF, FEP, ETFE, PFA, ECTFE, and PCTFE.

6.10.4 Blow Molding Fluoropolymers

The best way for the reader to learn is to study actual examples of parts made by the blow molding of fluoropolymers. A majority of such parts have a multilayer construction to combine the properties of other plastics in a composite structure. The most common technique for producing multilayer sheet/film is coextrusion. The chemical resistance of fluoropolymers makes them attractive materials for inner layers of containers that come in contact with aggressive chemicals that can swell or degrade thermoplastics.

In one fabrication example,[67] a multilayer container was comprised of an inner layer of a fluoropolymer such as ETFE, an outer layer of a polyolefin like low-density polyethylene, and an intermediate layer that bonded the inner and outer layers. The tie layer consisted of a polyolefin modified by grafting unsaturated glycidyl compounds, including glycidyl methacrylate and glycidyl acrylate. The modified polyolefin may be a graft polymer prepared by mixing an olefinic polymer including polyethylene, polypropylene, or an ethylene vinyl acetate copolymer with the unsaturated glycidyl compound followed by irradiation of the mixture in the presence of a catalyst.

Table 6.43. Transfer Molding Temperature of Fluoroplastics and Polypropylene[64][65]

Resin Type	Oven Temperature, °C	Transfer Pressure, MPa	Cooling Pressure, MPa
Fluorinated Ethylene Propylene Polymer (FEP)	326–349	1.3–1.6	4.3–5.3
Pefluoroalkoxy (PFA)	326–349	1.3–1.6	4.3–5.3
Polyvinylidene Fluoride (PVDF)	221–249	1.3–1.6	4.3–5.3
Polypropylene	176–199	1.3–1.6	4.3–5.3

High-density polyethylene with a density of 0.95 and a melt index of 0.3 was used as the outer layer. The intermediate layer was a resin mixture of 45% by weight of graft polymer. It was obtained by grafting an ethylene-vinyl acetate copolymer with a density of 0.94 and a melt index of 1.8 with glycidyl methacrylate with 20% by weight of ethylene propylene terpolymer (70% ethylene, 15% propylene and 15% ethylidenenorborene) and 35% by weight of high-density polyethylene with a density of 0.955 and a melt index of 0.05. The inner layer was formed from an ETFE resin with a melting point of 270°C and melt viscosity of 10^4–10^5 poise at a temperature of 300°C to 330°C. A hollow container with a volumetric capacity of 500 ml and a weight of 45 g was prepared by multilayer coextrusion blow molding. The wall thickness ratio of outer/intermediate/inner layers was 7/1/2. Peel strength between the inner and intermediate layers ranged from 13.3 to 53.2 grams per centimeter width.

Another advantage of composite-wall plastic containers with a fluoropolymer inner layer is the inertness of these polymers that preserves the purity of the content of the container. A frequent application for the containers is storage of chemicals used in semiconductor manufacturing that require high purity. Glass containers introduce ions such as potassium, sodium, boron, phosphorous, and others into the chemicals in the container. A multiple-layered container (Fig. 6.58) was produced[68] by blow molding that provided an effective liquid and vapor barrier for the storage of high-purity corrosive chemicals. The surface in contact with the chemicals was a fluoropolymer, most of which contained less than 50 ppb of ionic contamination and less than 0.096 particles/l.

The three layers consisted of a fluoropolymer inner layer, a polyolefin outer layer, and an intermediate tie layer that bonded them. The tie layer consisted of a polymer containing a blend of polyethylene-vinyl acetate and a block copolymer of styrene-ethylene-butadiene-styrene (SEBS) or styrene-butadiene-styrene (SBS) at a weight ratio in the range of 10:90 to 90:10.

A container with a volume of about 2 liters was produced by coextrusion blow-molding according to the following procedure in a Bekum BM-401 blow-molding machine (produced by Bekum America Corp., Williamston, Michigan). The fluoropolymer inner layer was polyvinylidene fluoride and the outer layer was comprised of high-density polyethylene (HDPE). The tie layer was a blend of 50% by weight of a copolymer of ethylene and vinyl acetate (40%) and 50% copolymer of SEBS. Three of the five extruders, each at a length-to-diameter ratio of 20:1, produced the molten feed streams for the sheet die. Table 6.44 gives the temperature profiles and other characteristics of the extruders. It should be noted that only three extruders are required for a three-layer composite. Figure 6.59 exhibits the working mechanism of a four and six layer blow-molding head (die).

Air pressure of 0.6–0.9 MPa was used to blow-mold the three-layer parison. Weight control of the blow-molding machine was set at 035 which is parison programming variable specific to the blow-molding machine. The extrusion head (die) had an adjustable gap, which allowed altering the thickness of the parison to accommodate the variable thickness along the height of the container. For example, the parison has to be thicker at the bottom and in the neck area. The programming was achieved by varying the timing interval. The timing sequence was 3100-0800-0200-2800-0350 (program code) with the weight control set at 210 g. BM-401 is a fairly old blow-molding machine and only capable of few parison programming points. A modern blow-molding machine can go up to 100 points in changing the parison thickness.

The materials were extruded and the molten parison was captured in a shuttle mold. The parison was blown with dry filtered air at 0.27–0.55 MPa at a mold temperature of 15°C–38°C. After molding, the container was allowed to cool in ambient air for 20 to 60 seconds. It was removed from the mold and had an average weight of 186 g. Thickness of the layers was 0.12–0.30 mm for the inner layer, 0.37–1 mm for outer layer, and 0.12–0.25 mm for the tie layer.

Another invention[69] has described a method of producing a laminated composite for use as intravascular catheters such as angioplasty catheters (Fig. 6.60). In the first step, a parison was formed in a coextrusion of a multilayer sheet through a die. The parison was heated in a mold and drawn to several times its original length. Next, the parison was expanded radially to the desired dimension and strength. The exterior of the expander was coated

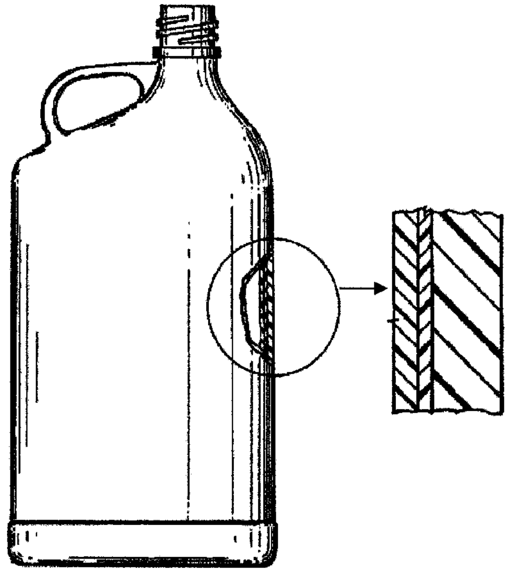


Figure 6.58 Shape of blow-molded container and the design of its wall.[68]

Table 6.44. Blow Molding Coextrusion Operating Conditions[68]

Characteristic	Extruder		
	1	2	3
Polymer Type	PVDF	HDPE	Tie Layer
Compression Ratio	1.849	1.01	1.04
Residence Time, min	1–4	1–4	1–4
Zone Temperatures, °C	165 188 221 221 221	154 165 168 174 174	193 204 204 — —
Extruder Diameter, mm	50	50	38
Screw Speed, rpm	35	20	35

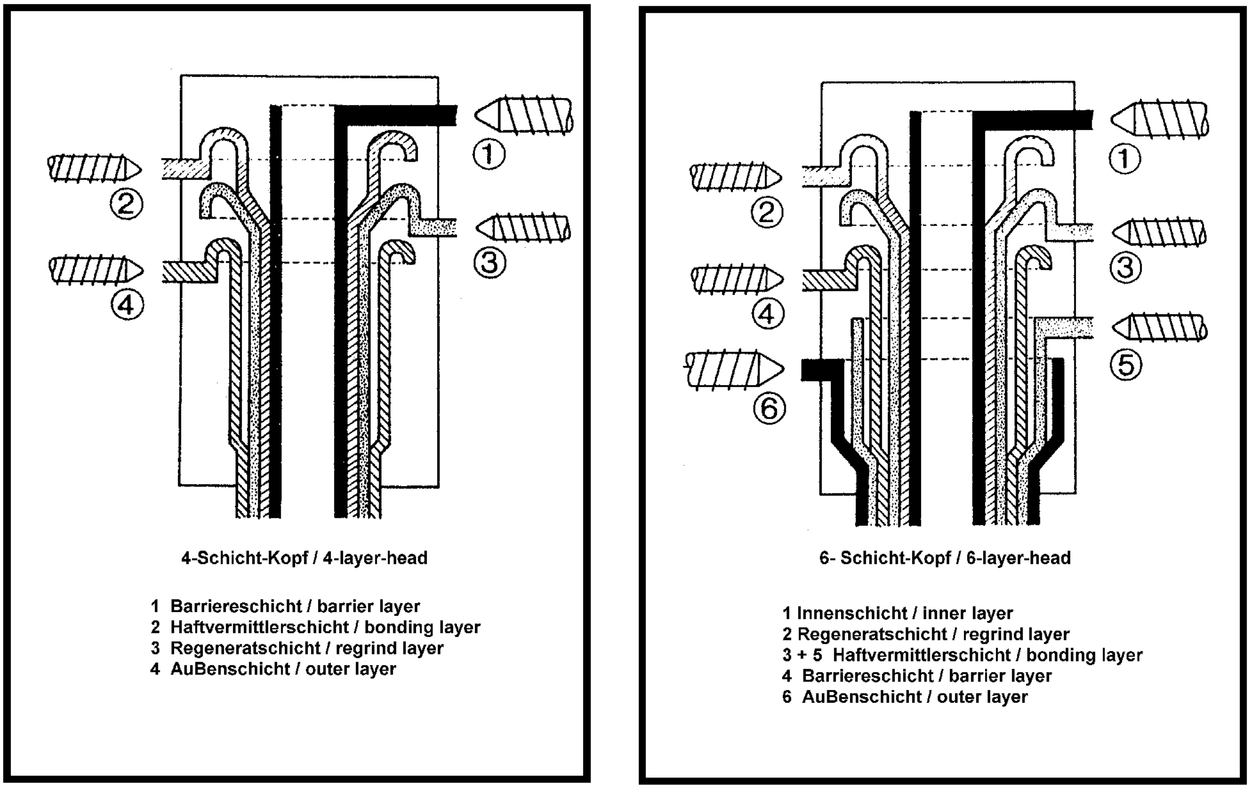


Figure 6.59 Blow-molding head for four- or six-layer parison coextrusion. *(Courtesy Bekum America Corp.)*

with hydrophilic material. Finally, the expander was bonded to the exterior of a tubular catheter. Fluoropolymers such as ETFE, ECTFE, PCTFE, PVDF, and PFA have been mentioned as intermediate layers that bond the outer layers (polyethylene terphthalate, PET), which were coextruded.

In another example,[70] a coolant conduit is described that consists of multiple polymer layers that render the composite structure resistant to hydrolysis and pressure with high burst strength. Motor vehicle engines are an application for a tubular form of this conduit (Fig. 6.61). In a two-layer construction, the inner layer was comprised of a fluoropolymer such as ETFE, FEP, or PVDF that has been functionalized for compatibility with the polyamide outer layer. Such a tube was formed by blow molding.

Coextrusion blow-molding technology was employed[71] to produce corrugated tubing, pipe, and hose for applications that require flexibility and close tolerances such as in the automotive industry. Composites of two or more layers formed the walls of these articles to take advantage of different materials. Tubing made by this technique has a high degree of flexibility, resistance to hydrolysis and bursting, and stability with respect to linear extension. For instance, in gasoline filler necks, it is important that the corrugated tubing have areas of great stretching stability and areas with reduced stretching stability, such as provided by this technology.

Monolayer hoses or pipes of two or more layers of polymers, which were compatible with each other or required an interim tie layer, were fabricated. A desirable two-layer composite consisted of an outer layer made from polyamide (e.g., linear aliphatic with 6–12 carbons). The choice of plastic for the inner layer was a fluoropolymer such as PVDF or ETFE. An interim layer of a polyolefin containing functional groups was sandwiched between the inner and outer layers. Figure 6.62 shows a depiction of a section of the tube wall in the blow mold after it has conformed to the corrugation geometry of the mold. Figure 6.63 shows a segment of the completed tubing. The thickness of individual layers varied from 0.05 mm to 3 mm.

More recently,[72] thin walled articles have been fabricated by blow-molding composites of liquid crystal polymer (LCP) and expanded porous polytetrafluoroethylene sheeting[73] material. Container application examples include food and pharmaceuticals, automotive gas tanks, bottles, and other vessels. Unlike most other thermoplastic polymers, thermotropic LCP forms high-viscosity melts that have thixotropic characteristics. Applying shear force to the melt substantially alters the melt viscosity of LCP and the orientation of its polymer domains. These attributes are useful to

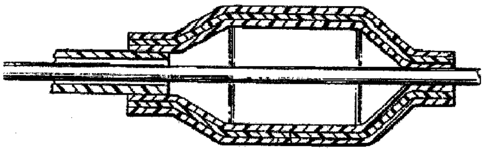


Figure 6.60 Schematic diagram of an angioplasty catheter.[69]

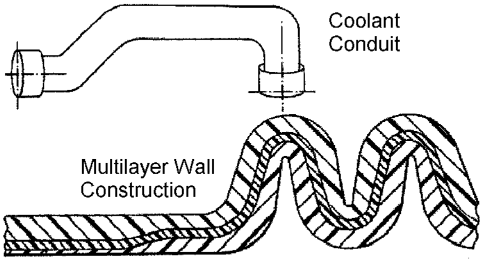


Figure 6.61 Coolant tube and design of a multilayer composite.[70]

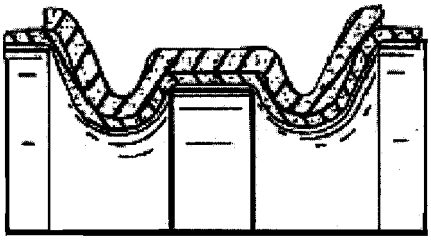


Figure 6.62 A depiction of blow-molded section of a tube wall.[71]

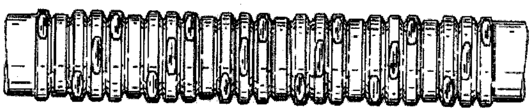


Figure 6.63 A section of a two-layer blow-molded tube.[71]

the production of articles with anisotropic properties. LCP melt behavior can be controlled, to a great extent, in planar articles such as sheet, film, and other flat shapes. The same properties render the LCP extremely difficult to form hollow and complex-shaped objects. This is the rationale for the formation of a composite of LCP and porous PTFE sheeting.

A thermotropic liquid crystal (Sumika Super E7000 supplied by Sumitomo Chemical Co.) was extrusion blow-molded to form a tube 20 cm long and 20 mm in diameter and a wall thickness of 1 mm. The liquid crystal polymer tube was wrapped spirally with two layers of expanded PTFE membrane (50 µm thick) to form a composite blow-molding parison. The membrane was wrapped sufficiently tightly to remain in place without the application of an adhesive. The parison was mounted in a traditional bottle-forming mold. The mold was heated to 320°C and air, heated to 380°C, was forced into the parison for blow molding. Afterwards, the mold was opened, cooled, and the bottle (22 cm long, 24 mm inside diameter and 0.7–0.8 mm wall thickness) was removed. Figure 6.64 shows a schematic of the molded part which, in addition to the inner layer of liquid crystal polymer and outer layer of porous PTFE, includes an intermediate layer that is a mixture of both PTFE and liquid crystal polymer.

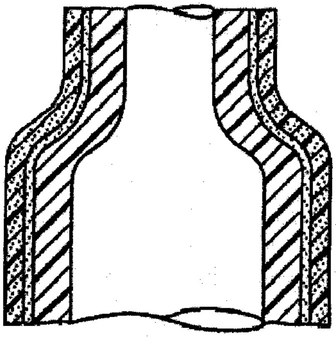


Figure 6.64 Schematic drawing of a blow-molded bottle of a LCP/porous-PTFE sheeting.[73]

6.11 Vacuum Bagging

There are a variety of methods for bonding and laminating, one of which is called "vacuum bagging." This is an old technique that originated during World War II. The majority of composite parts are made by vacuum bagging. The part being bonded is surrounded with an airtight membrane (vacuum bag) or diaphragm and utilizes the surrounding pressure to squeeze the vacuum bagged article, followed by curing in an autoclave (oven).[74]

The article, which is usually in the form of an impregnated fabric, is laid-up on a mold or a base plate (Figure 6.65 and 6.66) which defines the surface shape of the article. A release agent is applied to the mold surface to prevent adhesion of the part to the mold. A release film, such as a fluoropolymer typically a fluorinated ethylene propylene copolymer or a glass fabric coated with polytetrafluoroethylene is often the next layer. Other films such as nylon or polyester can be used where release is less demanding such as lower cure temperature resins.

A *bleeder* cloth, a nonstructural layer of material such as polyester felt, is used to allow the escape of excess gas and resin during cure. This material is removed after the curing process is completed and the excess resin taken with it. Next, a *barrier* film is

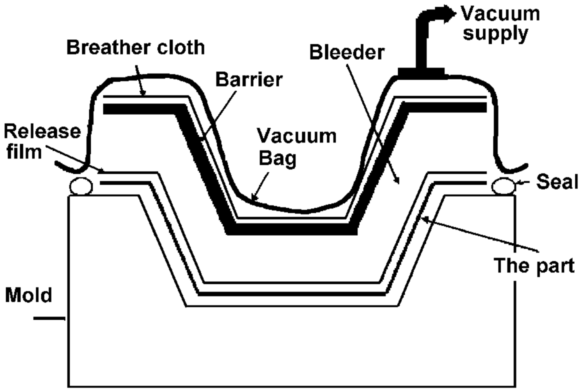


Figure 6.65 Diagram of a typical vacuum bagging lay-up.

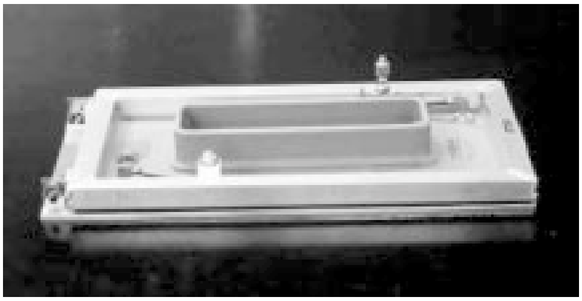


Figure 6.66 Vacuum bagging system.[75]

added to the lay up which prevents the excess resin absorbed into the bleeder from soaking into the breather. Finally, a *breather* cloth, a loosely woven or nonwoven material, that acts as a continuous vacuum path over a part caps the lay-up.

An airtight membrane (vacuum bag) is placed over the lay-up and sealed along the perimeter of the mold. Examples of vacuum bag materials and their properties are given in Table 6.45. A thick rubber based adhesive tape that is sticky on sides is used to form a seal between the vacuum bag and the tool surface. It has the ability to remain soft and pliable at temperatures in excess of 177ºC. A vacuum source is attached to the membrane and the air is removed, allowing the surrounding pressure to force the membrane tight against the article being bonded, similar to a vacuum-packaged item (Fig. 6.67).

Once the article is vacuum bagged (Fig. 6.67), it is allowed to cure for a specific amount of time. For articles comprising heat-activated (thermoset) or heat-formed (thermoplastic) resins and adhesives, the vacuum-bagged articles (Fig. 6.68) are cured in ovens or, when more pressure is required, in autoclaves and mechanical presses. These temperatures and pressures normally exceed 120°C and 0.34 MPa. Vacuum bagging produces exceptionally strong parts with little, if any, air entrapment. Forming to every contour of the part, vacuum bagging, in many cases, eliminates the need for expensive matched-die molds and presses while producing higher-quality parts.

A list of the steps taken in vacuum bagging is shown below:

- Prepare plies
- Stack plies in tool
- Add bleeder layer (dry material) to absorb excess resin & remove volatiles
- Apply vacuum bag & cure in autoclave (see Table 6.46 for a typical cycle)
- Oven post-cure for environmental durability
- Trim part
- Inspect
- Assemble

Table 6.45. Vacuum Bag Materials and Their Properties[74]

Property	Thermoplastic Elastomers				Semicrystalline Polymers	
	Polyolefin	Polyamide	Polyester	Urethane	Nylon 6	Nylon 66
Tensile Strength, MPa	7–28	15–50	7–48	28–75	41–165	90
Tensile Elongation at Break, %	200–800	300–700	200–600	400–1,000	300	150–300
Yield Strength, MPa	11	24	9–21	NA	52	45
Heat Distortion Temperature, °C	50	71–121	54–170	60–170	185	218

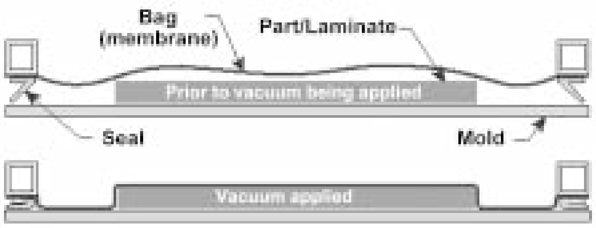


Figure 6.67 Vacuum bagging lay-up before and after applying vacuum to the bag.

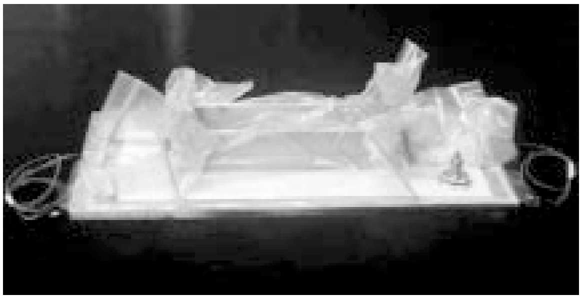


Figure 6.68 Vacuum-bagged part ready for cure in an oven.]75]

Table 6.46. Epoxy Oven (Autoclave) Cure Cycle[76]

Steps	Cure Cycle	Steps	Cure Cycle
1	Apply vacuum inside bag at 70–100 kPa	6	Release vacuum
2	Apply autoclave pressure at 585 (+35) kPa	7	Raise temperature to 177°C (+5°C) at 2°C–3°C/min
3	Heat slowly to 120°C (+5°C) at 2°C–3°C/min	8	Hold at temperature and pressure 120 (+10) min
4	Hold at temperature and pressure for 60–70 min	9	Cool slowly to below 40°C at 3°C/min
5	Raise pressure to 690 (+35) kPa	10	Release autoclave pressure

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7 Fabrication Techniques for Fluoropolymers

7.1 Introduction

Many fluoropolymers are melt-processible and can be molded into articles and stock shapes by extrusion, injection molding, transfer molding, and similar techniques. Polytetrafluoroethylene cannot be processed by melt-processing techniques due to its extremely high viscosity. PTFE granules are fabricated into "preforms" by compression molding techniques like ram extrusion, then sintering. Machining can be used to finish both preforms and stock shapes into parts.

It is sometimes necessary to bond the fluoropolymer parts to themselves or to other materials. Of course these polymers are known for their nonstick properties and must be rendered adherable. Machining and treatment for adhesion are two examples of finishing techniques routinely applied to fluoropolymer parts. This chapter describes a number of techniques commonly used to finish parts made from fluoropolymers.

7.2 Machining

All customary high-speed machining operations can be carried out as long as the cutting tools are very sharp. The closest analog for the free turning of fluoropolymers among metals is brass. Tool wear is similar to stainless machining. The low thermal conductivity of fluoropolymers such as PTFE causes heating of the tool and the charge material during turning. This can cause deformation of the polytetrafluoroethylene and excessive wear of the tools. PTFE parts can be machined to a depth of about 1.5 mm without the use of a coolant. It is necessary to use a coolant to achieve critical tolerances or to machine by automatic lathes. Machining technology has been developed for PTFE because the majority of parts made from this polymer are manufactured by machining. PTFE guidelines can be a good starting point for machining other fluoropolymers.

Dimensions of PTFE parts should be measured at a specified temperature due to the large dimensional change (1.3%) that takes place between 0°C and 100°C.[1]

All standard machining operations, including turning, tapping, facing, boring, drilling, threading, reaming, grinding, etc., can be performed on polytetrafluoroethylene and other fluoropolymers. Special machinery is not required for any of these operations. Speed selection, and tool shape and use, are important considerations in successful machining.

Other than poor thermal conductivity, fluoropolymers have much higher coefficients of linear thermal expansion than metals. This means that any type of heat buildup will cause significant expansion of the part, resulting in overcuts or undercuts, thus deviating from the desired part design.

PTFE stock shapes may require extensive machining to produce complex shapes. Coolants should be applied to remove heat if the surface speed of the tool exceeds 150 m/min. At higher speeds, low feeds are helpful in reducing heat generation. Surface speeds between 60 and 150 m/min are satisfactory for fine-finish turning. At these speeds, feed should be run between 0.05 and 0.25 mm per revolution. At higher speeds than 150 m/min, feed must be dropped to a lower value.[2]

Choice of tools is important to the control of heat buildup. Standard tools can be used but best results are obtained with specially shaped tools. A single point tool can be designed according to the following information: the top-rake should have a positive angle of 0°–15° with a 0°–15° side-rake and side-angle; the front or end rake should have an angle of 0.5°–10°. Boring tools require angles on the higher end of these ranges.

A dull tool also affects tolerances achieved during machining. The tool that is not sharp pulls the stock out of alignment thereby causing overcutting and excessive resin removal. An improperly edged tool tends to compress, which results in shallow cuts. A very sharp tool is desirable, particularly for turning filled parts. Carbide and Stelite® tipped tools reduce tool-sharpening frequency.

Other considerations include material support, especially when turning long thin stocks due to the flexibility of PTFE. Another issue is the characteristics of machined resin, which tends to be continuous and curly. It should be removed to prevent blockage of coolant flow or pushing the work away from the tool.

Polytetrafluoroethylene parts can be finished to tolerances in the range of -12 µm to +25 µm by machining. Finishing to low tolerances is often not required for PTFE parts because they can be press-fitted at a lower cost. Resilience of this plastic allows its conformation to the working dimensions. It is usually essential to relieve stress in the stock.

The annealing procedure for PTFE entails heating the stock shape 10°C above its service temperature (always below 327°C, melting point of PTFE). It should be held at temperature at the rate of 25 min/cm of thickness. Stresses are relieved during this operation. At the end of the hold time, the part should be cooled slowly to room temperature. After rough cutting the part to about 300–500 µm, re-annealing will help remove stresses induced by the tool, before the final cut is made.

Lapping and grinding compounds could be used for finishing the surface of PTFE. These powders can become embedded in the surface of the part and may not be easily removed. This is true of any contaminants from machinery that is not dedicated to polytetrafluoroethylene finishing.

Micromachining of PTFE has been reported by means of radiation.[3] High-energy radiation was used to abrade away the polymer. In this technique, a work piece was prepared by applying masking that contains the pattern. Ultraviolet light, with an extremely short wavelength (160 nm), was then applied to the PTFE surface.

7.2.1 Sawing and Shearing

Fluoropolymers, including polytetrafluoroethylene parts of any size, can be sawed. Coarse saw blades are preferable to fine-toothed blades that can become blocked with resin. Longer saw blades perform better than short blades such as a hacksaw blades. A band saw operated at moderate speeds is ideal because the long blade can remove the heat.

Shearing of rods and sheets of PTFE can be done as long as the work and the blade are firmly supported to prevent angular cuts. The limit for shearing sheets is a thickness of 10 mm and for cutting rods is a diameter of 20 mm.

7.2.2 Drilling (Tapping and Threading)

Drilling can be performed on fluoropolymer parts using normal high-speed drills. For PTFE, a speed of 1,000 rpm for up to 6 mm diameter and 600 rpm for up to 13 mm diameter holes are recommended.[1] To improve the accuracy of drilling, heat should be removed. This can be accomplished by reducing friction by taking a sharply angled *back-off* to the cutting edge and to the polished flutes. Another consideration is the relaxation of the polymer. To increase accuracy of the holes, a coarse hole should be drilled followed by a finishing cut after allowing the part to relax for 24 hours at room temperature.

7.2.3 Skiving

A popular method for producing fluoroplastic (especially PTFE) tapes is by skiving a cylindrical molding of the resin. Skiving is similar to the peeling of an apple where a sharp blade is used at a low angle to the surface. A comparable industrial operation is production of wood veneer. This operation removes layers of PTFE by applying a sharp blade to the surface of the cylinder. A grooved mandrel is pressed into the center hole of the billet and the assembly mounted on a lathe. A cutting tool mounted on a rigid cross-slide is advanced towards the work at a constant speed to peel off the continuous tape with a constant thickness. The cutting tool must have an extremely sharp blade that has been finished on a fine stone and honed or stropped to prevent formation of “tram lines” on the skived film.

A typical skiving tool can be seen in Fig. 7.1. For relatively thin tapes (50–250 µm) it should be set on the center line of the stock, but for higher thickness tape the blade should be set above the center line of the molding. Sheets up to 400 µm thickness and 30 cm width can be skived on a 20 cm wide lathe.

The blade should be fabricated from high-quality tool steel or tungsten and regularly sharpened. Skiving speed should be low and the chuck speed should be in the range of 20–30 rpm.

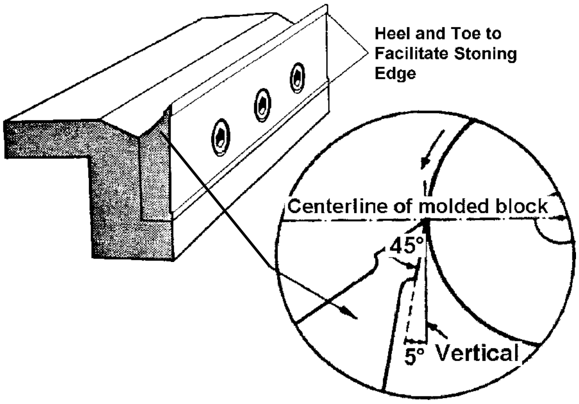


Figure 7.1 Cutting tool for machining tape from a molded block.[1]

7.3 Adhesive Bonding Methods

One of the attributes of fluoropolymers is the nonstick property of their surface, which is useful for innumerable applications. This characteristic prevents bonding of these plastics to themselves and many other materials. Many applications require bonding of fluoropolymer parts to themselves or other substrates. There are two types of solutions to the bonding problem of fluoropolymers: with and without an adhesive; the former is described in this section.

There are two types of adhesives by which fluoropolymers bond: contact adhesives and bonding adhesives. The distinction between these two adhesives is that contact adhesives can be applied without modification of the surface of the plastic, while bonding adhesives require surface modification.

7.3.1 Contact Adhesives

Contact or pressure-sensitive adhesives are suitable for applications where large surface areas are to be adhered together, such as lining process equipment. Examples include hoppers, chutes, and conveyor belts lined with PTFE sheet. Tapes of polymer can be reinforced with glass cloth by using pressure-sensitive adhesives. These adhesives can be applied to the PTFE surface after thorough cleaning and removal of all contaminants without surface modification.

Bond strength is relatively low due to the surface energy of polytetrafluoroethylene. The range of bond strength is 0.1–1.8 kg/cm depending on the type of adhesive. The adhesive can be applied in the form of a fluid by working it on the surface to achieve an even thickness. A more convenient alternative is two-sided tapes to which the pressure-sensitive adhesive has already been applied. All bubbles should be removed to lessen the chance of delamination and peeling.

7.3.2 Bonding Adhesives

It is necessary to modify the surface of fluoropolymers to obtain stronger adhesive bonds. Modification or surface treatment alters the structure of the polymer at the surface enabling formation of true adhesive bonds. Mechanical abrasion imparts little improvement and chemical etching is required. Chemical resistance of perhalogenated polymers such as PTFE, PFA, FEP, and PCTFE mandates the use of highly potent agents. Alkali metals, particularly sodium, can carry out the surface modification. Another method is plasma treatment in which the plastic surface is struck by energized atomic fragments. Other techniques include flame treatment and corona discharge methods. The surface of partially fluorinated fluoropolymers such as polyvinyl fluoride and polyvinylidene can be modified with strong acids and bases to render them adherable. These techniques have not attained commercial importance. The readers may readily find research articles about the subject in journals that specialize in the areas of adhesion and surface modification such as: *Journal of Adhesion, Journal of Adhesion Science and Technology, International Journal of Adhesion and Adhesives, Surface Science, Surface and Coatings Technology,* and *Surface Engineering.*

Sodium is the most economical choice, but it must be handled with utmost care. There are two ways to prepare solutions of sodium. It can be dissolved in anhydrous liquid ammonia or made into a complex with naphthalene followed by dissolution in an ether such as tetrahydrofuran or dimethyl glycol ether. Special precautions must be taken while working with sodium etching solutions. Fluoropolymers surface-treated by sodium etching should be stored in a cold, dark atmosphere free from oxygen and moisture. The useful shelf life of etched polymer stored under these conditions at <5°C is three to four months.

Once the fluoropolymer sheet, film, etc., has been etched, it is an adherable surface. The choice of adhesive depends on the required service conditions and, to some extent, the substrate. Some of the considerations in the selection of adhesive include chemical resistance, flexibility, and temperature resistance.

7.3.3 Sodium Etching

The original method for surface treatment of PTFE for adhesive bonding is etching in a sodium solution in anhydrous liquid ammonia.[4][5] The reagent is prepared by simply dissolving metallic sodium in liquid ammonia to obtain a 0.5%–1% by weight concentration. The solution has a dark blue color and should be stirred thoroughly before use. The surface of the fluoropolymer should be cleaned carefully with an organic solvent such as acetone to remove oils or grease and other contaminants that can cause poor treatment and weak bonding. Moisture must be kept from the solution by storing it under positive pressure in protective packaging.

The fluoropolymer needs to be in the solution for a brief duration ranging from 2 to 10 seconds.[1] Ammonia rapidly volatilizes after the article is removed from the bath. Sodium can be removed by dipping the treated article into ethyl alcohol. Too long an immersion time actually weakens the adhesive bond. The optimum time depends on the freshness of the etching solution. The treated fluoropolymer has a shiny dark brown color that grows into a dull brown after exposure to air. Analysis of the baths shows the presence of fluoride and/or chloride ions suggesting defluorination and/or dechlorination of the surface during treatment (Table 7.1).

Different methods have been devised to test the bondability of the treated plastic. The specimen can be joined in different ways: butt joint, disk joint, and lap shear. An adhesive layer or film is applied to the treated surface, which is then placed against the substrate and heated in a press or oven. The substrate could be a duplicate of the plastic itself. Table 7.1 gives the bond values of fluoropolymers before and after etching, obtained by the lap shear test method. Bond strengths of the treated surfaces of PTFE, PVF, and ECTFE are larger than that of the untreated surfaces by an order of magnitude or more.

Etching has a profound effect on the surface chemistry of the fluoropolymers. Electron spectroscopy for chemical analysis (ESCA) also known as x-ray photoelectron spectroscopy (XPS) is a technique that has been used to study the chemical composition of surfaces. ESCA does not detect hydrogen, and elemental compositions exclude this element. Results of surface chemical composition of fluoropolymers have been summarized in Table 7.1. The consistent changes in surface composition of fluoropolymers because of treatment are a reduction in fluorine and/or chlorine content, and an increase in carbon and oxygen content. The treated PTFE surface is virtually comprised of carbon and oxygen and a small amount of fluorine.

The change in the surface of the treated fluoropolymers is also reflected in the contact angle. For example, water contact angle of FEP and PTFE decreases from 109° to 52° (advancing) upon sodium/ammonia treatment.[7][8] Heating the treated fluoropolymer for a lengthy period can reverse the change in the surface. Water contact angle of treated PTFE increases back to 101° after 96 hours exposure to a temperature of 200°C.

Table 7.2 shows the effect of sodium etching on several fluoropolymers by Tetra-Etch® on the surface composition and lap shear bond strength. In general, the data for various fluoropolymers indicate an increase in the adhesive bond strength with increasing fluorine and chlorine content. Kinetics of treatment is more favorable to perfluorinated PTFE than PVF that contains one fluorine per monomer unit according to the data in Table 7.2.

Another solution consists of a bath that is a mixture of 1:1 molar ratio sodium in naphthalene dissolved in tetrahydrofuran.[10] For example, 23 g of sodium is mixed with 128 g of naphthalene flakes (sometimes called sodium naphthalenide) then dissolved in one liter of tetrahydrofuran. The reaction begins slowly and accelerates with time accompanied by a color change of the solution from inky blue to dark brown and finally black. It takes about two hours to prepare the solution.

Commercial solutions of etchant do not contain ammonia or tetrahydrofuran for safety and health

Table 7.1. Effect of Sodium Etching on the Surface Compostiiton and Adhesion Bond Strength of Fluoropolymers[6]

Polymer	Treatment	Surface Chemical Analysis (%) by ESCA*[1]							Bond Strength, Mpa*[2]
		F/C Ratio	Cl/C Ratio	O/C Ratio	Cl	C	F	O	
PTFE	None	1.60	—	-	—	38.4	61.6	—	2.1
PTFE	Tetra-Etch®*[3] (1 min)	0.011	—	0.20	—	82.2	0.9	16.9	21.3
PTFE	N/1 min*[4]	0.005	—	0.14	—	87.2	0.4	12.4	21.4
PVF	None	0.42	—	-	—	70.4	29.6	—	1.8
PVF	Tetra-Etch®*[3] (30 min)	0.21	—	0.026	—	80.7	17.2	2.1	20.8
ECTFE	None	0.64	0.27	—	14.1	52.5	33.4	—	1.2
ECTFE	Tetra-Etch®*[3] (1 min)	0.16	0.05	0.12	3.8	74.9	12.2	9.1	10.0

*[1] Electron Spectroscopy for Chemical Analysis. *[2] Lap shear test (see Fig. 7.2). *[3] Supplied by WL Gore Corporation.
*[4] Treatment with a 1 mole soulution of sodium naphthalenide in tetrahydrofuran at room temperature.

Table 7.2. Kinetics of Sodium Etching on Surface Compostition and Adhesion Bond Strength of Fluoropolymers[9]

Polymer/ Treatment	Surface Chemical Analysis (%) by ESCA*[1]							Bond Strength, N*[2]
	F/C Ratio	Cl/C Ratio	O/C Ratio	Cl	C	F	O	
PVF								
None	0.41	-	0.011	-	70.4	28.8	0.8	360
10 sec	0.37	-	0.012	-	72.4	26.7	0.9	800
1 min	0.37	-	0.021	-	75.4	23.0	1.6	2,080
60 min	0.13	-	0.015	-	87.3	11.4	1.3	3,020
PVDF								
None	0.93	-	0.014	-	51.4	47.9	0.7	1,580
1 min	0.17	-	0.12	-	77.4	12.9	9.7	2,450
60 min	0.11	-	0.14	-	79.5	9.2	11.3	2,940
ECTFE								
None	0.61	0.27	-	14.3	53.2	32.5	-	240
1 min	0.24	0.05	0.095	3.7	72.5	17.7	6.9	3,300
PTFE								
None	1.6	-	-	-	38.4	61.6	-	420
10 sec	0.01	-	0.13	-	87.6	0.8	11.6	4,280
1 min	0.01	-	0.20	-	82.2	0.9	16.9	4,260

*[1] Electron Spectroscopy for Chemical Analysis. *[2] Bond strength in Newton (N) using lap shear test (see Fig. 7.2). An epoxide adhesive was used for PVF, PTFE, and ECTFE, a cyanoacrylate adhesive for PVDF.

reasons. For example, Tetra-Etch® contains 25% by weight of sodium-naphthalene complex and 75% of ethylene glycol dimethyl ether. Fluoro Etch® (offered by Acton Technologies, Inc., Pittston, PA) contains about 30% sodium-naphthalene complex and 70% of an ethylene glycol solvent. Acton Technologies has reported successful use of both ethylene glycol dimethyl ether and diethylene glycol dimethyl ether as solvents.[11]

Using a commercial dispersion of sodium in naphthalene can reduce preparation time. The shelf life of the bath is sixty days provided that it is stored in a closed container and isolated from air. The polymer is immersed in the solution for 1 to 5 minutes followed by rinsing in alcohol or acetone. Bond strength using epoxy adhesives ranges from 7 to 14 MPa in tensile mode. This broad range of adhesive bond strength is obtained in the butt tensile, disk tensile, and lap shear test configurations seen in Fig. 7.2.

Research has shown that the defluorination depth of the polymer surface extends about 300 nm (Fig. 7.3) as a result of sodium naphthalenide treatment.[13] The report shows that exposure to x-ray decreased the defluorination depth to 30–150 Å. The structure of the defluorinated layer is highly porous. The suggested adhesion mechanism is the mechanical interlocking of adhesive with this porous structure. Bond failure nearly always occurs by stripping the etched layer as opposed to cohesive failure of the adhesive.

Etching solutions can be purchased from a number of sources. They include Fluoro Etch® by Acton Corp. and Tetra-Etch® by W. L. Gore & Associates. Some companies, such as Acton Corp., provide surface treatment service. Operational safety and waste disposal are two issues concerning parties that deal with etching solutions.

7.3.4 Plasma Treatment

Plasma (glow discharge) is sometimes referred to as the fourth state of the matter. It is produced by exciting a gas with electrical energy (Fig. 7.4). It is a collection of charged particles containing positive and negative ions. Other types of fragments, such as free radicals, atoms, and molecules, may also be present. Plasma is electrically conductive and is influenced by a magnetic field. Plasma is intensely reactive which is precisely the reason that it can modify surfaces of plastics.[15] Plasma can be used to treat parts to make their surfaces harder, rougher, more wettable, less wettable, and easier to adhere to. Plasma treatment can be carried out on a variety of plastic parts and even powder additives like pigments and fillers.

The plasma used for treating material surfaces is called cold plasma, which means its temperature is about room temperature. Cold plasma is created by introducing the desired gas into a vacuum chamber (Fig. 7.5), followed by radio frequency (13.56 MHz) or microwave (2450 MHz) excitation of the gas. The energy dissociates the gas into electrons, ions, free radicals, and metastable products. Practically any gas may be used for plasma treatment but oxygen is the most common. The electrons and free radicals created in the plasma collide with the polymer surface and rupture covalent bonds thus creating free radicals on the surface of the polymer. The free radicals in the plasma may recombine with the surface's free radicals to generate a more stable functional group. After a predetermined time or temperature is reached, the radio frequency is turned off. The gas particles recombine rapidly and the plasma is extinguished.

Table 7.3 contains data that compares the results of plasma treatment and sodium etching for four fluoropolymers. Peel strengths of untreated and treated samples were measured by bonding them to T-peel specimens using the flexibilized epoxy adhesive Scotch-Weld® 3553 (available from 3M Corp.). The laminates were cured for several hours at 70°C and peel-tested at 12.5 cm/min pull rate. Polytetrafluoroethylene does not accept plasma treatment as well as PFA and FEP, as indicated by its relatively low peel strength. Sodium etching is the only effective method of modifying the surface of PTFE.

A study of adhesion improvement of ETFE by plasma treatment using oxygen, ammonia, and oxygen + SF_6 gases has been reported.[17] Joints were made using commercial epoxy adhesives by a double lap shear configuration (Fig. 7.6). Bond strength of the plasma-treated ETFE significantly exceeded bond strength of sodium-etched polymer specimen (Table 7.4). A range of values were obtained for bond strengths with different adhesives.

Plasma treatment is a dry process that does not utilize solvents and generates little waste compared to sodium etching. It is a more expensive process due

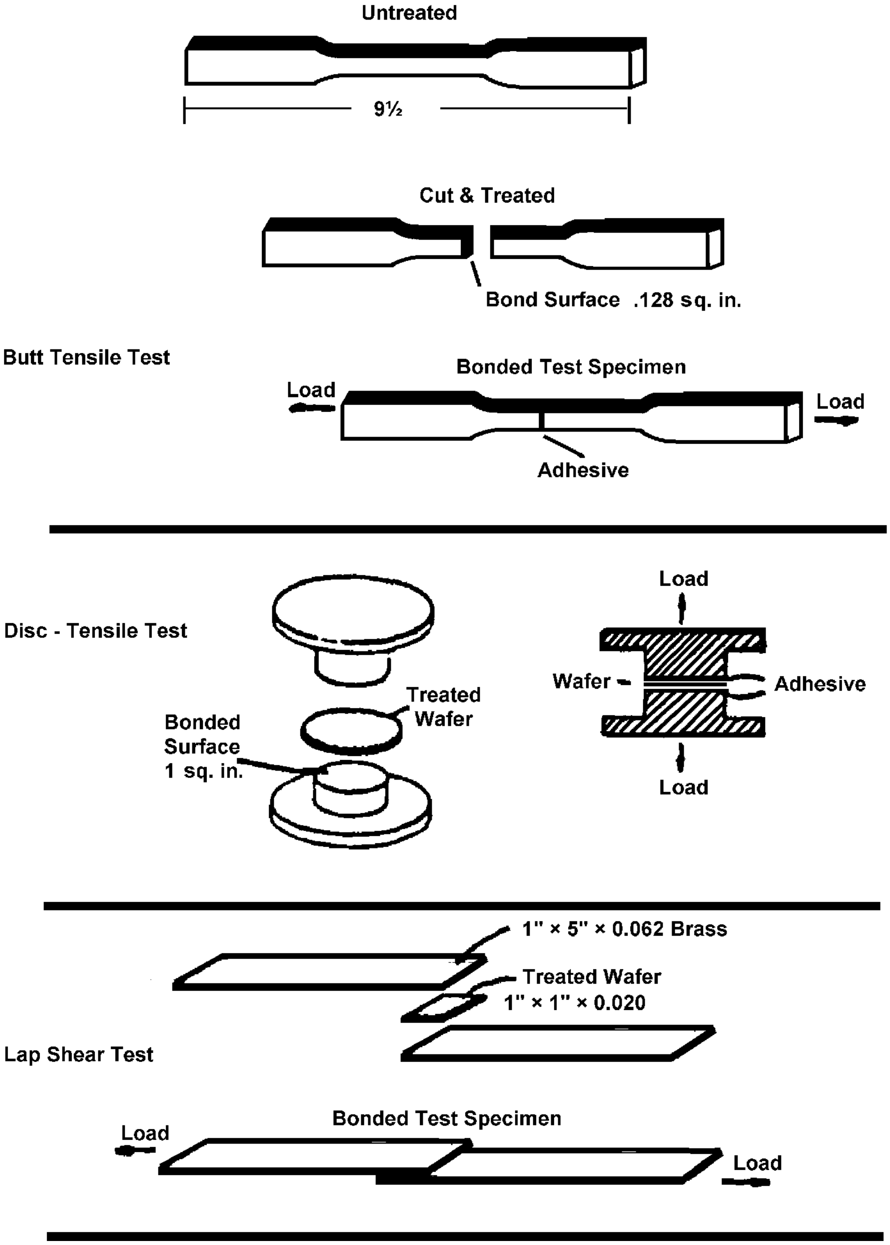


Figure 7.2 Test specimens for determination of bondability of treated PTFE.[10]

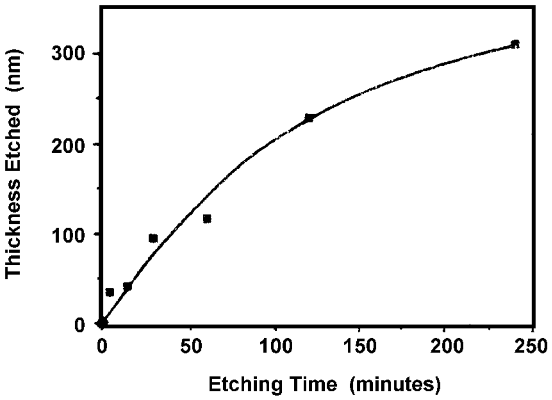


Figure 7.3 Apparent defluorination depth as a function of Na/naphthalene treatment time.[12]

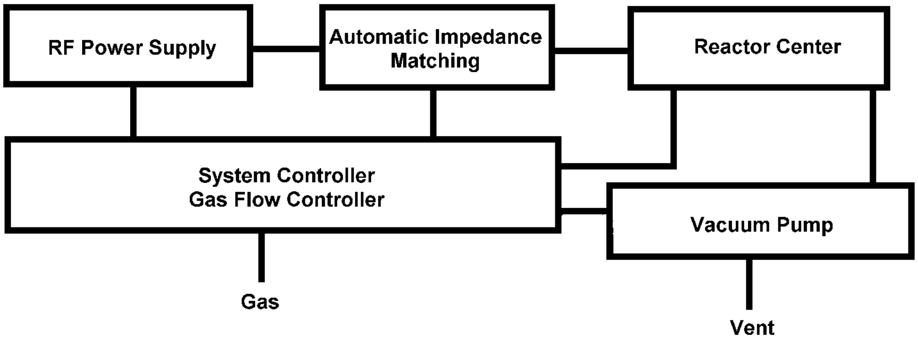


Figure 7.4 Schematic diagram of a plasma system.[14]

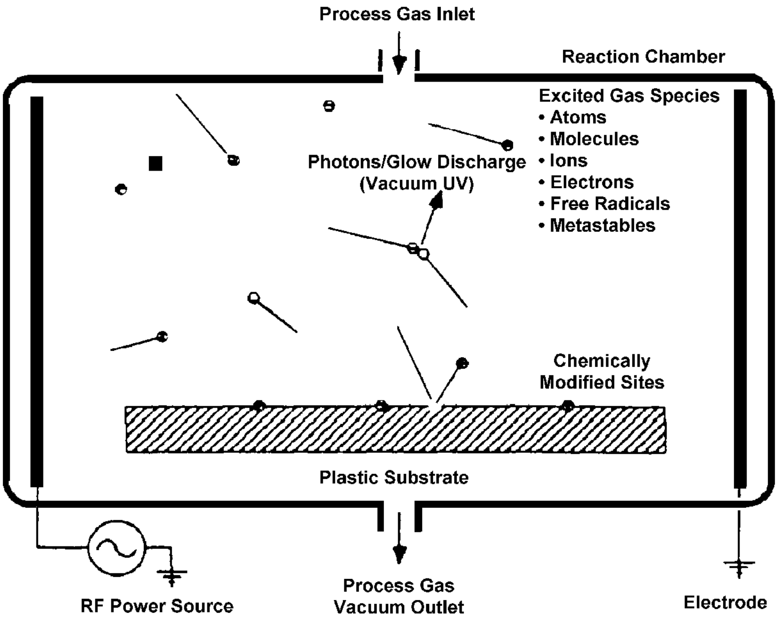


Figure 7.5 Schematic of the surface modification of plastic in a gas plasma reactor.[16]

Table 7.3. Peel Strength of Adhesive Bonded Fluoropolymers*[1]

Treatment	Material			
	PTFE	FEP	ETFE	PFA
Untreated	*[3]	0.1	*[3]	0.04
Sodium Etched*[2]	5	8.2	—	6.4
Plasma Treated	2.2	10.4	15.8	8.3

*[1] Source of data: Gasonics/IPC Applications Notes, Gasonics International, San Jose, California.

*[2] Tetra-Etch® by WL Gore & Associates, Inc. *[3] Too low to measure.

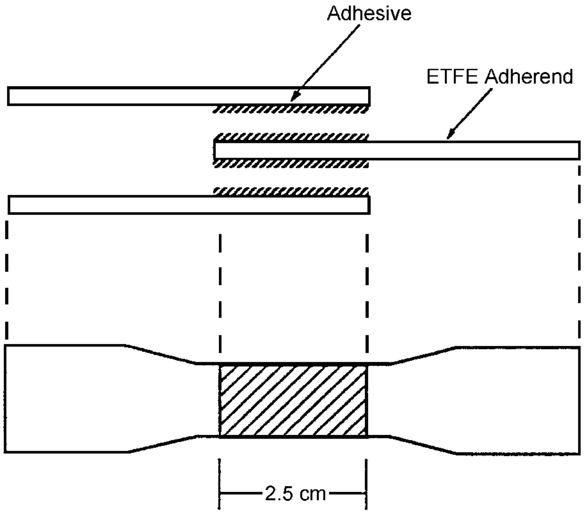


Figure 7.6 Schematic of the double lap shear test specimen.

Table 7.4. Bond Strength of Plasma-Treated ETFE Using a Double Lap Shear Test and Epoxy Adhesives[17]

Treatment Type	Bond Strength, MPa
None	0.07
Tetra-Etch®[1]	0.78
Plasma (O_2+ SF_6)	1.49–2.31
Plasma (O_2)	1.47–1.83
Plasma (NH_3)	1.40–1.72

[1] Tetra-Etch® by WL Gore & Associates, Inc.

to equipment requirements and vacuum operation. It also does not impart a sufficiently strong adhesive bond to polytetrafluoroethylene, the most common perfluoropolymer. In the 1990s, progress was made in the plasma treatment technology for surface modification of PTFE.[18]–[20] Nevertheless, the bond strength of plasma-treated PTFE is, at best, 60% of that obtained by sodium etching.

An alternative plasma treatment technique is the *glow discharge* method that can be done at atmospheric pressure. To generate the glow discharge, a pair of insulation-coated electrodes is placed at a predetermined distance apart inside a chamber connected to a gas inlet tube. The object being treated is moved between the electrodes, one of which is connected to a power source while the other electrode is grounded. For example, several fluoropolymer films were treated by glow discharge in helium atmosphere.[21] Strips of the treated and untreated films were bonded to 0.2 mm thick aluminum foils using a urethane adhesive cured at 100°C for 15 min. The treatment conditions and bond strengths of the samples are given in Table 7.5.

7.3.5 Flame Treatment

Flame treatment is a commercial process to render polyolefins and polyethylene terephthalate adherable. The polymer article (e.g., film) is passed over an oxidizing flame formed by of an oxygen-rich (relative to stoichiometry) mixture of hydrocarbon gas. Variables affecting the extent of oxidation include the flame characteristics (e.g., excess oxygen) and the speed of the article movement. Gas flame contains excited fragments and species such as atomic oxygen (O), NO, OH, and others that can abstract hydrogen from the surface of the polymer that is replaced by oxygenated functional groups (mostly $-C=O$ and $-OH$). This method is not effective in the adhesion treatment of perfluoropolymers.

The data in Table 7.6 reveal a large increase in the bond strength of PVF and ECTFE after flame treatment. The fluorine-to-carbon ratio (F/C) of PVF remained unchanged but the oxygen-to-carbon (O/C) ratio increased significantly. In the case of PTFE, the F/C ratio actually increased which could explain the drop in the bond strength as a result of flame treatment. The flame probably removed contamination that had previously masked (covered) some of the F atoms on the surface.

7.3.6 Corona Discharge (Hybrid Plasma) Treatment

Corona discharge takes place at atmospheric pressure in contrast to low-temperature (cold) plasma that requires vacuum. The corona is a stream of charged particles such as electrons and ions that is accelerated by an electric field. It is generated when a space gap filled with air or other gases is subjected to a sufficiently high voltage to set up a chain reaction of high-velocity particle collisions with neutral molecules, resulting in the generation of more ions. Corona discharge has been applied to treat the surface of plastics to render them adherable (Fig. 7.7). In this method, the plastic article is exposed to a corona discharge produced by high-frequency high-voltage alternating current.

Table 7.5. Effect of Atmospheric Glow Discharge Treatment in He on Bond Strength[21]

Fluoroplastic	Untreated, g/cm	Treated, g/cm
PFA	0	600
FEP	0	640
ETFE	0	430
PVDF	100	830

Treatment conditions: gas flow rate = 5 1/min, discharge frequency = 5 kHz.
Treatment time = 60 sec.

Table 7.6. Effect of Flame Treatment on the Surface Composition and Adhesion Bond Strength of Fluoropolymers[9]

Polymer/ Treatment	Surface Chemical Analysis (%) by ESCA*1							Bond Strength, N*2
	F/C Ratio	Cl/C Ratio	O/C Ratio	Cl	C	F	O	
PVF								
No	0.41	—	0.011	—	70.4	28.8	0.8	360
Yes	0.41	—	0.065	—	67.6	28.0	4.4	3,240
ECTFE								
No	0.61	0.27	—	14.3	53.2	32.5	—	240
Yes	0.25	0.12	0.087	8.0	68.8	17.2	6.0	2,980
PTFE								
No	1.60	—	—	—	38.4	61.6	—	420
Yes	1.94	—	—	—	34.0	66.0	—	80

*1 Electron Spectroscopy for Chemical Analysis. *2 Bond strength in Newton (N) using lap shear test (see Fig. 7.2) using an epoxide adhesive.

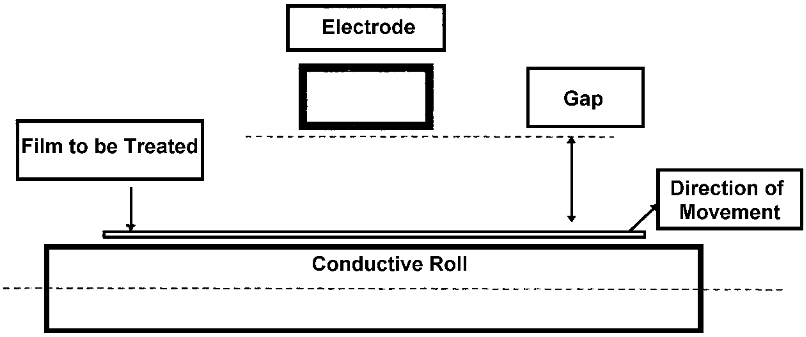


Figure 7.7 Conceptual schematic diagram of a film corona treatment system.

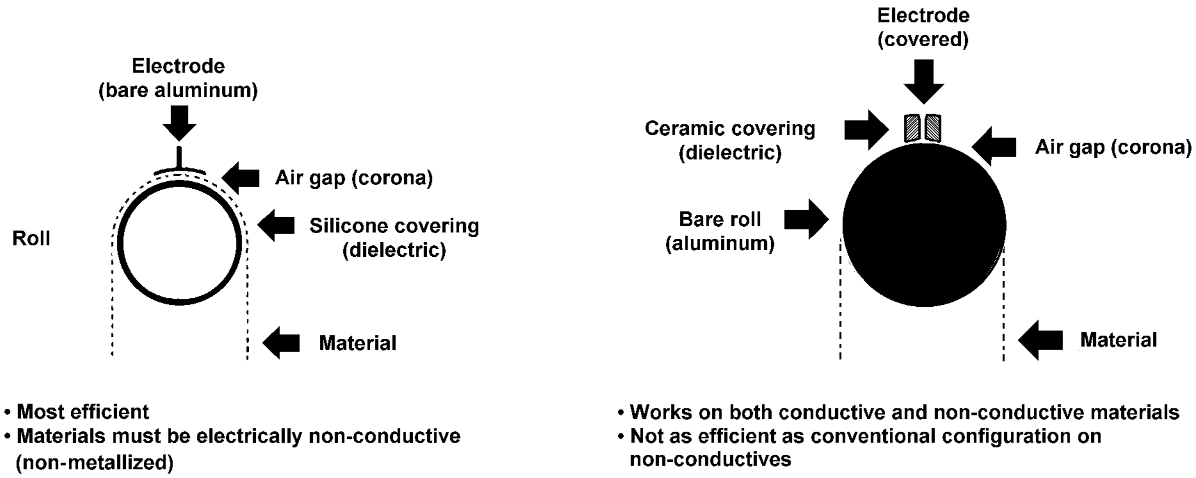
There are three types of treating configurations (Fig. 7.8) and they all consist of the same parts including an electrode, an electrical insulator or dielectric, and a return path or ground. The differences among the three configurations are in the location of the electrode. In a conventional system (Fig. 7.8a), the web passes over a roll that is covered with insulating material such as a silicone rubber. A metal electrode is suspended above the roll so that an air gap of 1.5–2.5 mm exists between the electrode and the insulated roll. High voltage operates across the air gap, ionizing it and forming a corona discharge curtain between the electrode and the material (e.g., film) that is being treated. The conventional configuration can be used only with nonconductive material. The second configuration is called *bare roll* (Fig. 7.8b) in which the electrode is covered with a dielectric (usually ceramic) and the roll is made of anodized aluminum. In the third configuration, called *double dielectric,* the roll and the electrodes are covered with dielectric material.

The main parameters for controlling the treatment process include the voltage, width of the air gap, film/web speed, and the width of the electrodes. Most machines allow treatment of one side of the web (Fig. 7.9) and require two passes for two-sided treatment. There are machines that are equipped with two sets of electrodes for one pass, two-sided treatment.

There are several ways to test the level of treatment. One common method involves using solutions made from a mixture of two chemicals that produce liquids (Dyne) with surface tension in the range of 30–70 dynes/cm. The test consists of placing droplets of the various dyne liquids on the treated surface and observing the spreading of the drops in two seconds. Successive liquids with different surface tensions allow narrowing of the surface tension range of the web. This method is subjective but it provides a rapid means of assessment of the treatment level. There are also pens that operate similarly to Dyne liquids. A more quantitative approach is the measurement of contact angle, which decreases with increase in treatment level.[7] A perfect wetting liquid forms a contact angle of zero on the solid surface.

Corona discharge treatments of FEP and PTFE films in air have been reported[23] to improve adherability of these films as indicated by higher values of peel strength. The bond was inconsistent and fairly weak. Later, corona treatment of FEP was reported[24] under an atmosphere of gases other than air (Fig. 7.10). Typically, process conditions included a voltage in the range of 10,000–30,000 V, pulsing peak voltage of 100,000 to 500,000 cycles per second, and less than 5% by volume of a suitable gas in nitrogen. A suitable gas had to have a vapor pressure of 0.25 mm of mercury at 60°C. Examples included glycidyl methacrylate, tetrahydrofuran, carbon tetrachloride, vinyl butyl ether, and methyl vinyl ketone.

For example, McBride and Wolinski[24] corona-treated FEP film (0.25 mm thick) under the atmosphere (0.5% by volume) of various chemicals. A voltage was applied in the range of 10,000–30,000 with pulsating peak voltages up to 100,000 volts while the film moved at a speed of 1.5 meters per minute. The treated film was stuck to a strip of cold-



(a) (b)

Figure 7.8 Configurations of corona treatment equipment.[22] (*a*) Conventional configuration. (*b*) Bare-roll configuration.

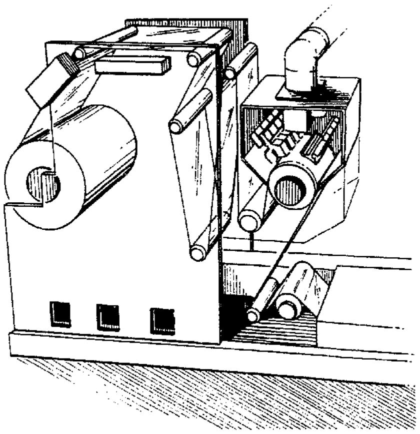


Figure 7.9 A typical single-side corona treatment machine.

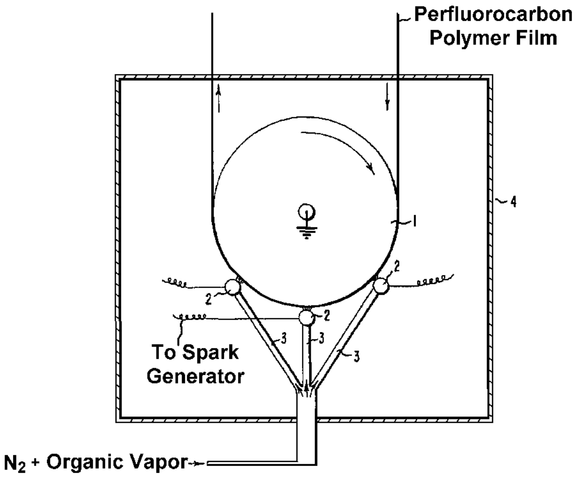


Figure 7.10 Schematic diagram of a corona treater under an organic vapor.[24] (*1*) Metal roll, (*2*) stationary hollow tube, (*3*) distributor duct, (*4*) enclosed chamber.

rolled steel using an epoxy containing 1% amine hardener. Bond strength was then measured at a peel angle of 90°C in a Suter tester, which is essentially an extensiometer equipped with jaws that can be separated at a controlled speed. Table 7.7 shows the bond strength for various chemical atmospheres; film treated without a vapor phase chemical developed a weak bond.

Kreuz and Zytkus[25] reported the corona treatment of FEP under an atmosphere of acetone (<5% to 40% by volume in nitrogen) which had the advantage over the previous atmospheric compounds of producing a film that did not block in roll form. Treated FEP could be printed and marked with inks, was heat-sealable, and adhered well to metals. Adhesion of FEP film (25 μm thick) to metal was accomplished by first laminating it to a thin polyimide film (13 µm thick) using a nip roll at 250°C–270°C at a pressure of 270 kPa. The treated FEP surface was then laminated to a 13 µm thick (Fig. 7.11) aluminum foil in a nip roll at a speed of 6–9 m/min. In some cases, the laminate was post-heated to test the effect of heat on the bond strength and the locus of bond failure (Table 7.8).

The importance of the role of acetone in the corona treatment atmosphere is shown by the data in Table 7.9. In this case, an FEP film at a thickness of 13 µm was treated in an atmosphere of acetone (3.1% by volume) and nitrogen. The treated film was heat-sealed to a 25 µm thick polyimide (PI) film, both corona-treated and untreated, at different temperatures. Untreated polyimide produced a weaker bond while FEP treated in air (versus acetone/N_2) yielded almost no bond strength.

7.4 Welding and Joining

The bonding techniques involving adhesives are normally suitable for applications where the fluoropolymer does not carry large loads such as those experienced by chemical processing equipment. The load could consist of temperature, chemical corrosion, and force. Welding or adhesiveless joining is a method by which complex parts are manufactured without sacrificing the load-bearing capability of the part. There is a variety of welding techniques for thermoplastic polymers that allow formation of strong joints, even approaching the strength of the parent material itself. This method allows economical fabrication of complex parts by joining individual components. Table 7.10 shows the common methods for welding different fluoropolymers.

Table 7.7. Bond Strength of Corona-Treated FEP under the Atmoshpere of Different Chemicals[24]

Chemical Atmosphere	Bond Strength, g/cm
None	39.7-119
N-vinyl-3pyrolidone	3,571
Acrylonitrile	2,500
p-Chlorostyrene	1,190
Toluene-2,4-diisocyanate	1,952
Vinyl acetate	1,913
Xylene	1,389
Hexane	1,349
Carbon tetrachloride	1,587
Tetraisopropyl titanate	1,428

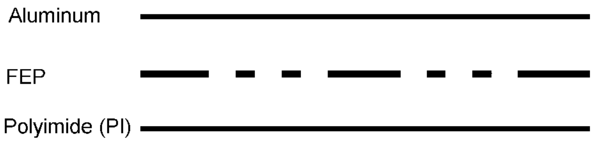


Figure 7.11 FEP laminated to aluminum foil and polyimide.

Table 7.8. Bond Strength of Corona-Treated FEP under the Atmosphere of Acetone[25]

Lamination Temperature, °C	Post Heat Treatment	Bond Strength, g/cm	Failure Interface
230	Yes	137	FEP-Al
230	No	161	FEP-Al
235	No	167	FEP-Al
241	No	127	FEP-Al
240	Yes	182	FEP-Al and PI-FEP
272	Yes	244	PI-FEP
272	No	226	PI-FEP

Table 7.9. Effect of Corona Treatment and Heat-Sealing Variables on Bond Strength of FEP[26]

FEP Corona Treatment Atmosphere	FEP Film Speed, m/min	Bond Strength, g/cm at heat seal temperature of 315°C		Bond Strength, g/cm at heat seal temperature of 350°C	
		Treated PI	Untreated PI	Treated PI	Untreated PI
Air	15.1	13.5	-	15.5	-
Air	24.2	16.3	-	13.9	-
Acetone	15.1	208	110	416	253
Acetone	24.2	196	50	287	138

Table 7.10. Common Methods for Welding Fluoropolymers

Fluoropolymer	Welding Technique			
	Hot Gas	Ultrasonic	Hot Plate	Vibration
PTFE	Under some conditions	No	Under some conditions	No
FEP	Yes	Under some conditions	Yes	Under some conditions
PFA	Yes	Under some conditions	Yes	Under some conditions
ETFE	Yes	Under some conditions	Yes	Under some conditions
ECTFE	Yes	Under some conditions	Yes	Under some conditions
PVDF	Yes	Under some conditions	Yes	Under some conditions

The strength of a weld joint is determined by a comparison of the tensile or yield strengths of the plastic part at the joint to those of the bulk of the part. The *weld factor (WF)* is defined by Eqs. 7.1 or 7.2 as the ratio of tensile strength (T) or yield strength (Y) of the welded specimen (w) to the tensile strength of the parent material (p). The weld factor is defined for the weakest polymer if two different polymers are welded together. The closer the weld factor is to unity, the better the weld quality.

Eq. (7.1) $$WF = \frac{T_w}{T_p}$$

Eq. (7.2) $$WF = \frac{Y_w}{Y_p}$$

It is possible to obtain a good bond between fluoropolymers themselves, without the use of adhesives, by application of heat and pressure. Pressure can help drive the molten polymer into the pores of the substrate. Bond strength is dependent on the mechanical interlocking that is achieved by the adhesion or cohesion mechanism, improving with increased surface roughness of the substrate.

Joining refers to mechanical methods of fastening parts to each other. Joining techniques usually do not require adhesives and can be accomplished by designs similar to those applied to attach metals. This topic is covered in great detail in Ref. 27.

7.4.1 Welding Techniques

All welding methods are not applicable to all fluoropolymers. In general, the applicability of the welding method to a fluoropolymer is related to its rheology. High rheology, e.g., melt viscosity, makes welding difficult and reduces the number of applicable methods. The least number of methods are applicable to PTFE, while the majority of techniques can weld PVDF. Some of the more common methods include heated tool (hot plate), hot gas, ultrasonic, vibration, spin, and infrared welding techniques. Various welding methods and examples of their applications to fluoropolymers are described in this section.

7.4.2 Welding PTFE

Examples of parts made by welding technology include glass cloth-backed polytetrafluoroethylene sheets, multi-ply circuit boards, and coated aluminum or copper sheets. Achieving this type of bonding is more complex with polytetrafluoroethylene than melt-processible polymers. PTFE does not flow after melting due to its extremely high viscosity.

It is possible to achieve adhesiveless bonding using standard PTFE in special applications where the polymer can be heated to a temperature well above its melting point. It can then be forced under pressure into the substrate surface. These polymers are not suitable for applications where the geometry of the joining objects must be preserved, contact surfaces are smooth, or the objects being bonded are too large. In such cases, a different type of polytetrafluoroethylene is required.

Polytetrafluoroethylene for these applications is known as *modified*, which refers to the presence of a small amount of a second perfluorinated monomer, known as a modifier, in its structure. The modifier molecule always contains a pendent group.[28]

How does it work? The modification allows lowering the molecular weight of the polymer which, in turn, reduces its melt viscosity. Lower melt viscosity increases the mobility of the polytetrafluoroethylene chains. This facilitates diffusion and entanglement of polymer chains at the bonding interface. The pendent group of the modifier disrupts the crystals of PTFE, thus preventing excessive crystallization. Too high crystallinity results in poor mechanical properties such as poor tensile and flex properties. An optimally modified PTFE has good mechanical properties in addition to weldability.

Welding can be achieved using PTFE made by dispersion or suspension polymerization. Most applications involve welding of parts made from granular resins (suspension polymer). Dispersion polymerized PTFE is also used for applications such as wire coating. A thin (50–100 µm) tape of the “modified” polytetrafluoroethylene is wrapped around the conductor followed by sintering. The layers of the tape adhere to each other and form a solid insulation, due to its good interlayer adhesion, around the conductor at the completion of the sintering cycle.

The quality of a welded area is defined by the strength of the bond. One of the ways to measure bond strength is to cut a microtensile bar specimen in such a way that the weld line would fall near its center (Fig. 7.12). Tensile strength and elongation can be determined by extensiometry.

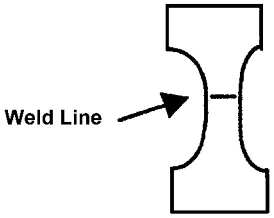


Figure 7.12 Schematic diagram of a microtensile bar for weld strength measurement.

Three variables are significant in welding a given modified PTFE part: welding temperature, pressure, and time. Optimal combinations of these three parameters must be found for successful welding of parts. The temperature should be well above the melting point (320°C–330°C), typically in the range of 360°C–380°C. Little pressure is required to weld the parts after reaching the gel state; less than 350 kPa and often less than 35 kPa pressure. Normally, it is not possible to trade higher welding pressure for lower temperature and vice versa. Time, the third variable of the process, is dependent on the size and shape of the part. The actual weld time, defined as time at the final temperature, is of the order of 1–2 minutes. It often takes a great deal longer to heat the part to the welding temperature. High heating rates do not accelerate the process due to the low thermal conductivity of PTFE. Heating rates similar to those of sintering cycles of preforms can be used.

The mating surfaces should be smooth and uniform and free from any contamination. Unsintered preforms and sintered parts of modified polytetrafluoroethylene can be welded. Sintering and welding can be combined. Parts can often be stacked up in the sintering oven without additional pressure. A weld factor of one can be routinely obtained in the combined process. A higher pressure is required for welding sintered parts partly to counteract the residual stresses, which tend to move the parts upon release. It is important to cool the welded parts slowly to minimize stresses stored in the part. Figure 7.13 illustrates a device for hot-tool welding films and sheets.

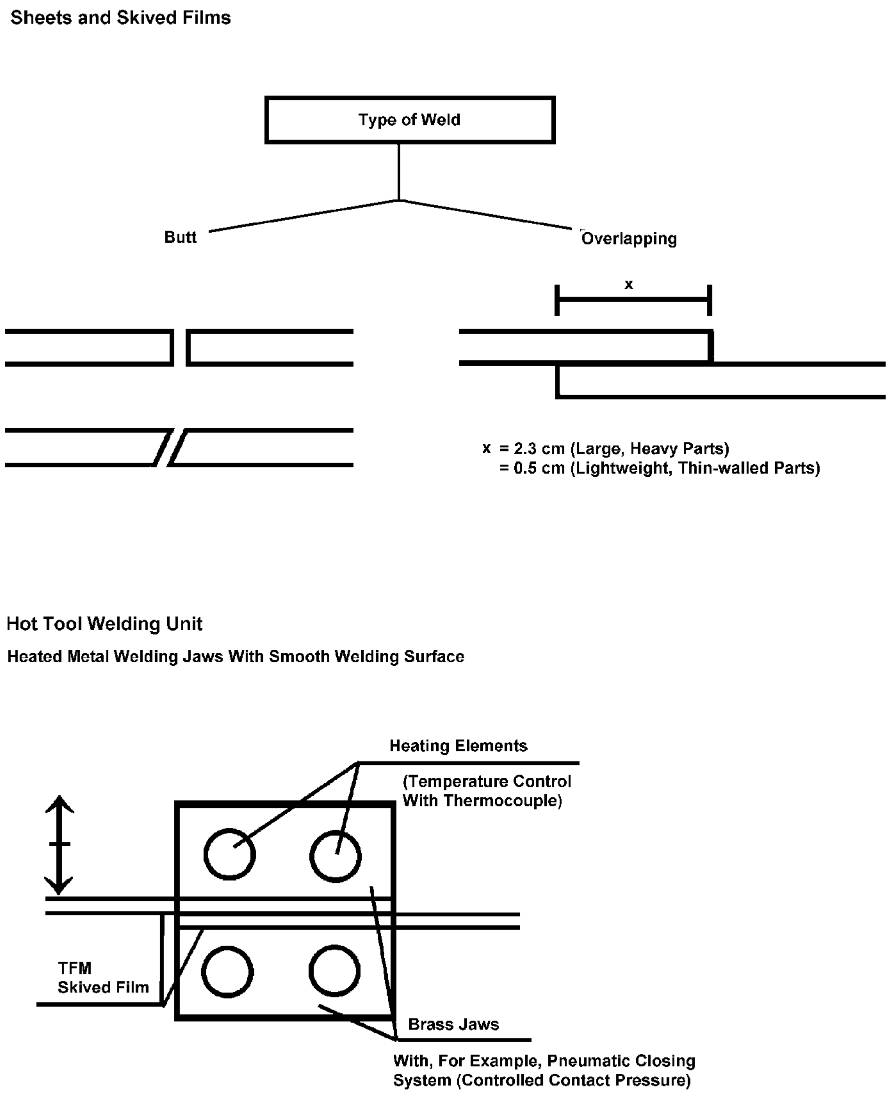


Figure 7.13 Welding sheets and skived films.[29]

Figure 7.14 shows a comparison of the stress-strain curves of a conventional and a modified PTFE for the original and welded material. The weld line in conventional PTFE when welded to itself, at best, fails at very low strains. In the case of a modified resin welded to itself, the weld factor attains value of 0.80–0.85. The weld factors for welding of conventional to modified PTFE have been reported in the range of 0.66–0.87.[31]

Another method used to weld the liner of large tanks is hot gas welding using a PFA (melt-processible) rod. Sheets of skived polytetrafluoroethylene are joined together by welding to lined chemical storage tanks. PTFE is heated at the seam by hot air until it is in a gel state. Simultaneously, a PFA rod is molten and used to fill the seam.

PTFE (and other fluoropolymers) tubes and lined pipes are welded by the butt fusion technique (Fig. 7.15). A uniform bead is required for the formation of a strong butt weld. The two ends of the plastic tubing are cut back to obtain square ends. The pipe ends are faced together by a device such as the one shown in Fig. 7.16 which allows the application of a measured axial force to the tubes. A heated plate or a clam shell heater can be used to heat the ends of the tubes. An important step is to thoroughly clean and wipe the ends of the tubes with acetone or another solvent.

Melt-processible fluoropolymers can be directly welded while PTFE requires an “adhesive” ring. PFA film (13–50 µm thick) is the most effective adhesive material for welding PTFE. A PFA ring is inserted on each end of the tube and the ends are brought into contact be means of the welding device (Fig. 7.16). Next, a cylindrical heater that has been heated to 410°C–425°C is inserted over the tube ends and held in position for 4–5 min while a force of 8–12 kg is applied to the tube ends. After removal of the heater at the end of the cycle, the application of force on the tube ends is continued until the weld has cooled down.[34]

7.4.3 Welding FEP

FEP can be welded by the hot gas method using extruded virgin rods of FEP with diameters in the range of 2.4 to 4.8 mm. Hot air should be supplied by a source such as a electrical heat gun that produces an air temperature of about 425°C at a distance of 0.5 cm from the tip of the gun. Gas pressure should be regulated to about 140 kPa. All surfaces, including welding rods and adjacent plastic about 2–3 cm beyond the joint, should be cleaned with a solvent immediately prior to welding. The edges of the FEP sheets should be beveled according to the angles in Table 7.11. The joints must be kept in alignment by clamping during welding.

To begin welding FEP, the hot gas is heated to 345°C to preheat the starting edges of the joint material and the end of the rod until they become tacky (shiny appearance). The welding tip should be held 6 mm from the intersection of the weld joint and the FEP rod. The end of the rod is trimmed at a 45° angle. It must be held at a 90° angle to the joint and moved up and down slightly in the heat until it sticks to the base FEP (Fig. 7.17). Continuous welding is achieved by moving the hot air torch uniformly between the sheet and the rod, also known as the *pendulum* technique. The rod is then positioned at a 45° angle to the base material while applying a downward pressure, around 1–2 kg. The rod is soft and stretching should be avoided. The recommended movement rate of the rod is 1–5 cm/min. Welding conditions may be adjusted according to the skill and proficiency of the operator.

FEP parts can be joined by the spin welding technique. Joints can be designed to allow the rotation of one part relative to the other at a fast rate. Heat generated during the rotation melts the FEP at the joint and allows the formation of a weld. FEP requires minimal speed (3,000 rpm) for spin welding. In one example, a joint with better than 60% of the tensile strength of base FEP was obtained.[36]

7.4.4 Welding PFA

PFA tubes and pipe liners can be butt-welded in a similar procedure to that used for PTFE (Sec. 7.4.2). PFA does not require adhesive to form a bond. PFA is easily welded by a heated platen technique in which the liner ends contact the heated plate until a bead is formed. A heater plate temperature of 399°C, a contact time of 15–30 secs, and a soak time of 90–105 secs are required for liners with a diameter of 2.5–5.0 cm.[37] *Soak time* is the time period allowed after the bead has been formed. No pressure is applied

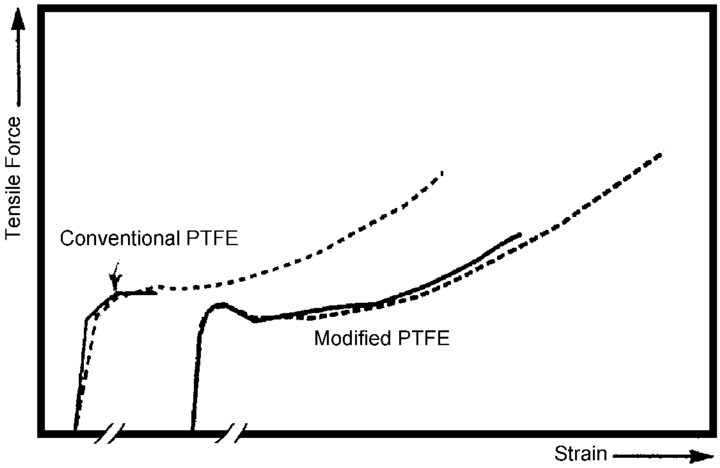
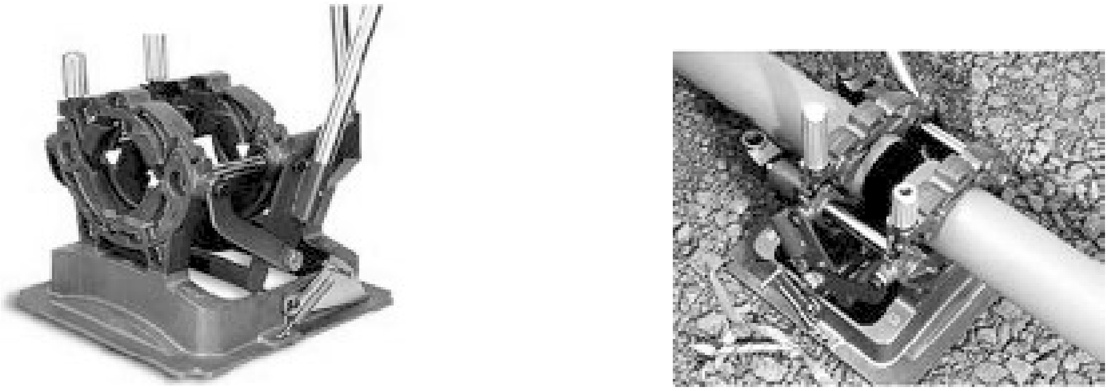


Figure 7.14 Tensile stress-strain graph of welded specimens and original material.[30]

Figure 7.15 Example of a butt weld.[32]

Table 7.11. Beveling Angle for Different Joint Types[35]

Joint	Beveling Angle,°
Butt Joints	60
Corners	60
Fillets	45
Laps	Not Required



(a) (b)

Figure 7.16 (*a*) Welding device for (*b*) butt fusion welding of pipes.[33]

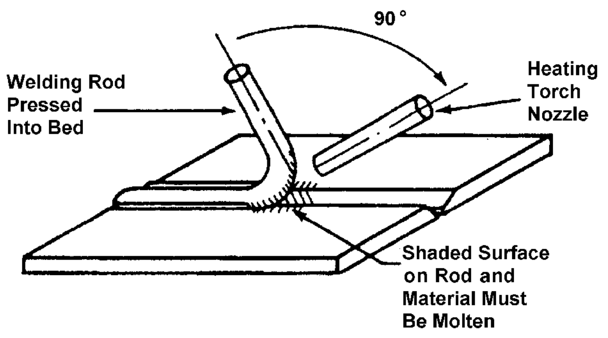


Figure 7.17 Schematic diagram of welding FEP sheets with a rod.[35]

during the contact and soak periods. The plate is carefully removed at the end of the soak time. The liner ends are rapidly brought in contact using a welding device (see Fig. 7.16) without applying pressure.

Amorphous plastics, such as acrylics, are transparent to infrared rays. Some semicrystalline polymers, such as PFA, have surprisingly high levels of infrared transmission. PFA can be welded by infrared under certain circumstances. For example, a transparent tube of PFA was welded to a black sheet of PFA that absorbed the infrared light generated by a Nd:YAG laser (1,064 nm).[38] A tube composed of natural PFA (6.4 mm outer diameter and 3.2 mm inner diameter) was pressed into a 6.4 mm diameter hole in an aluminum sheet. The aluminum sheet was used to shield the black PFA sheet from stray radiation. The IR light was defocused to a diameter of 6.4 mm and aimed at the end of the tube in the aluminum. A laser power of 30 W with a tube length of 50 mm produced a strong weld in a few seconds.

Procedures have been developed in which PFA has been welded to sintered PTFE.[39][40] An example was a ring consisting of PFA and PTFE sections (Fig. 7.18). This procedure was comprised of placing the sintered PTFE segment in an appropriately designed mold and charging PFA pellets in the space directly in contact with the PTFE part. A weight was placed on top of the ram to apply a slight pressure (35 kPa) to the PFA. The assembly was then placed in an oven at 340°C for 120 min. At the end of this period, the assembly was removed from the oven and placed in a press. The weight was removed and a pressure of 965 kPa was gradually applied to the PFA over a period of 25 seconds to compress the molten PFA. The pressure was held until the assembly had cooled to room temperature. This fusion weld was so strong that, when the welded part was placed under tensile load, failure occurred in one of the resins and not at the weld. The length of oven dwell times depends on the size of the part. Pressure, however, must be maintained at low levels to achieve a high-quality weld.

7.4.5 Welding PVDF

Polyvinylidene fluoride can be welded by all standard welding techniques. Detailed instructions on welding conditions can be obtained by referring to Ref. 41.

Items produced from all non-reinforced grades of PVDF can be easily assembled using standard welding methods such as hot air welding with welding rod, polyfusion (butt or socket welding), heat-sealing, ultrasonic, vibration, friction, dielectric heating (high frequency), or solvent bonding.

In rod welding, the parts to be welded are profiled (beveled or double beveled). After deflashing and cleaning, they are clamped in place. During the rod welding operation, the parts must be preheated at the same time as the rod is melted by continually moving the hot air jet in a reciprocating movement from the part to the end of the rod. The air is heated to 350°C (temperature taken at 5 mm from the end of the nozzle) in the hot air gun which should have a flow of 50 liters/min. The melted rod is inserted into the preheated bevel (from opaque white, the rod becomes transparent) maintaining a continuous vertical pressure of 20–40 kPa.

Welding is carried out in successive passes in order to completely fill the bevel. In order to equalize as much as possible the stress which will occur

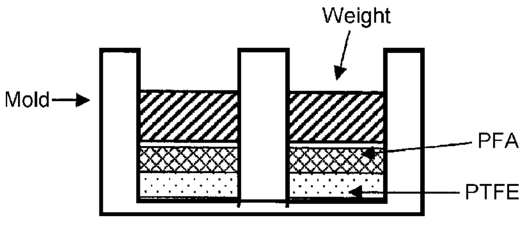


Figure 7.18 Welding of PFA and PTFE.[39][40]

during cooling, it is recommended whenever possible to weld in a double bevel, ensuring that the rod is added alternatively on each of the two sides of the bevel until the gap is completely filled.

With extrusion welding, the support is prepared (beveled or preferably double beveled) and preheated using a hot air gun to reach a surface temperature of 250°C–260°C. The molten extrusion (maximum length— 20 cm) is pressed into the bevel using stainless steel or PTFE coated tools.

The weld factor, which is generally defined as the relation between the strength of the weld and the strength outside the welded zones, determined by tensile stress tests, will give values between 0.7 and 0.8 for rod welding and between 0.8 to 0.9 for extrusion welding.[42]

In the extrusion welding technique, the mating parts are heated by pressing onto a metal heater which is held at 250°C–270°C and which has been surface-treated (usually with PTFE) to minimize adhesion. For butt welding, the heater is a flat plate; for spigot and socket welding, there are male and female surfaces. The ideal pressure on the hot surface is 50–60 kPa, and the time should be sufficient for the fusion of the material to a depth of 4–5 mm at the contact surface. The heating unit is removed and contact is made under a pressure of ideally 0.06 to 0.08 bar, ensuring that the formed bead of the melt is not too large. Welding factors obtained by this method are generally between 0.9 and 1.[42]

PVDF parts are easily welded using spin welding. Welding data for 25 mm diameter, 1.9 mm thick pipes are as follows:

Heating period

- rotation speed: 600 rpm
- pressure: 200 g
- duration: 3 min
- transition time: 1 to 2 s

Welding period

- pressure: 20 kg
- duration: 15 to 20 min

Rotation speed can be increased, in which case the heating period should be reduced. A practical check is that it changes from opaque to transparent when it melts. Welding factors thus obtained are between 0.7 and 0.8.[42]

In spin welding, the weld initiation time (WIT), consists of stage I and stage II and decreases with axial pressure. The WIT is found to be 1.5 sec at 2.0 MPa, 0.75 sec at 4.3 MPa, and less than 0.25 sec at 6.8 MPa. All of these effects may be attributed to the increased temperature rise, hence melting rates, that occur at higher pressures.

A distinct increase in weld penetration results from an increase in axial pressure. The rotational speed yields a similar behavior as the weld penetration increases steadily with increasing rotational speed. The effects of normal force and rotation speed are also highly nonlinear.

For a longer test duration, axial pressure and rotational movement are maintained for a longer period of time. This allows more melting and, thus, greater weld penetration for increased test duration. This increase in weld penetration with increasing test duration appears to be quite linear in most cases. The final weld penetration increases with increasing rotational speed and increasing axial pressure.

The axial pressure is shown to have a greater effect on the WIT, while the rotational speed only affects the WIT moderately. At 3000 rpm, the WIT is reduced from 1.5 to 0.25 sec when the axial pressure is increased from 2.0 to 6.8 MPa. At 4.3 MPa, the WIT is only reduced from 1.0 to 0.7 sec when the rotational speed is increased from 2000 to 3500 rpm.

For each axial pressure condition, as the rotational speed is increased, the weld strength reaches a maximum value before diminishing. At low axial pressure, the bonding of the samples does not occur at low rotation speeds for 3.4 sec weld duration, and high-strength welds can only be achieved at high rotation speed. In this case, there is a peak in the strength data. At high axial pressures, good welds could be formed at rotation speeds down to 2000 rpm (this is the lowest rotation speed utilized in experiments), and at each normal force a peak is observed, the magnitude of which appears to decrease with further increase in axial pressure. This may be related to the formation of very high chain orientation primarily aligned in the weld plane in the hoop direction.[43]

Ultrasonic welding can be used to weld parts made from all grades of PVDF including copolymers or alloys, reinforced or not. The standard procedure for crystalline polymer welding by ultrasonic techniques can be applied for all elements made from PVDF.[42]

Based on the principle of dielectric loss, induction welding is particularly suitable for high-loss thermoplastics such as PVC. However, by adapting certain measures, PVDF films from 10 to 50 µm can be welded.[42]

A new infrared welding machine has been developed,[44] offering a range of advantages over existing butt fusion welding equipment. These include: contact-free heating, reducing the risk of contamination on the joining face; joining distance control of the fusion process, resulting in high reproducibility and high weld quality; and the absence of the equalization process, significantly improving the bead geometry and weld strength.

Experiments have shown that a range of welding parameters can be used to reach the maximum weld quality, with melt depth and joining distance being the determining parameters. The melt depth is fixed by the energy going into the joint, and this is a function of the nature of the heater, temperature, exposure time, geometry of the welding assembly, and the polymer to be melted.

The mechanical testing conducted on high-quality infrared welds has shown that the welding factors achieved for PVDF when tested at -40°C were greater than 0.9.

PVDF parts can be welded using a PVDF powder base bonding agent, dissolved in a polar solvent such as dimethylformamide. This technique, which at first sight appears easy to apply, nevertheless has certain disadvantages.

- The characteristics of the solvent used:
    - high boiling point (>150°C), low vapor pressure, difficult to eliminate
    - presents health hazards
    - poor dissolving power, hence dry matter is limited (25% w/w)
- The difficulty of ensuring control and measuring the complete elimination of the solvent which, when present, can considerably diminish the strength of the weld.[42]

PVDF pipe liners and tubes can be butt-welded in a similar procedure to the one used for PFA (Sec. 7.4.4). A heater plate temperature of 218°C, a contact time of 10–15 seconds, and a soak time of 75 seconds are required for liners with a diameter of 2.5–10.0 cm.[37]

7.4.6 Welding ETFE

ETFE parts can be efficiently joined by spin welding.[45] The matching surfaces are rotated at high speed relative to each other by keeping one surface fixed and rotating the other surface. The surfaces are brought into contact resulting in the generation of frictional heat that melts the interface. The weld is allowed to solidify under pressure after the motion is stopped.

The ultrasonic welding of ETFE can be achieved[45] with a weld factor of 0.8. The success of this technique is dependent on joint design and welding parameters such as the contact time and pressure. Typical welding conditions include a contact pressure of 170 kPa and a cycle time of 2 secs.

7.5 Heat Bonding

Melt-processible fluoropolymer films can be heat-bonded to high-temperature substrates such as metals and glass cloth. The molten polymers have a significantly lower surface tension than the substrates, thus meeting the criterion for wetting the substrate surface. In a typical operation, the surfaces of the fluoropolymer film and the substrate are heated above the melting point of the polymer and the two are brought into contact. Mechanical interlocking and the intermolecular forces are the sources of the formation of the adhesion bond.

The surface of the substrate should be thoroughly cleaned for good bonding. Roughening the substrate surface by sand blasting or chemical etching enhances the bond by increasing the contact surface between the polymer and the substrate. Laminates can be produced in a platen press or on a continuous laminating machine. FEP and ETFE bonding require a minimum temperature of 270°C.

7.5.1 Sheet Liners

An example of heat bonding is fluoropolymer sheets for lining metallic and non-metallic surfaces that require chemical protection such as vessels, reactors, and joints. Fluoropolymers are difficult to bond to other materials due to their non-stick properties. Even when their surfaces are modified for adhesion bonding, the strength of the bond may be insufficient for many applications. To overcome this problem, fluoropolymer sheets are *fabric-backed* by heat-bonding to a substrate such as woven glass fabric which can then be bonded to the surface to be protected using an adhesive. The seams between adjacent sheets are welded using rods of the same polymer as the sheet.

Typically a sheet of fluoropolymer that could be less than 1 mm up to 5 mm in thickness is bonded to a fabric with thickness of about 0.5 mm. Fabric-backing of sheets can be done in batch or continuous processes. The economical method of fabrication is a lamination technique using hot nip rolls where the glass and fluoropolymer sheets are heated while pressed together. The process for lamination of sheet to fabric is generally thermal, requiring the fluoropolymer to exceed its melting point so that adequate bonding to the glass fabric would take place.

Fabric-backed sheets of almost all fluoropolymers, whether perfluorinated or partially fluorinated, can be purchased for lining equipment. Several companies offer these product including Electrochemical Engineering and Manufacturing,[46] SYMALIT AG,[47] and Allied Supreme Corp.[48]

7.6 Thermoforming

Fluoropolymers such as PVDF, FEP, PFA, and modified polytetrafluoroethylene can be thermoformed[35] by vacuum forming, pressure forming, and matched-die forming (Fig. 7.19). In all methods, a sheet of the fluoropolymer is heated until it reaches its gel point. It requires more “soak” (heat up) time than conventionally thermoformed plastics due to its low thermal conductivity. Vacuum forming uses the pulling force generated by vacuum to force conformation of the molten fluoropolymer sheet to the contours of a mold. In pressure forming, hot pressurized air is used to generate the conformation force. In the matched-die technique, mechanical force is generated by the male half of the mold, which drives the fluoropolymer gel into conformation with the contours of the female half of the mold.

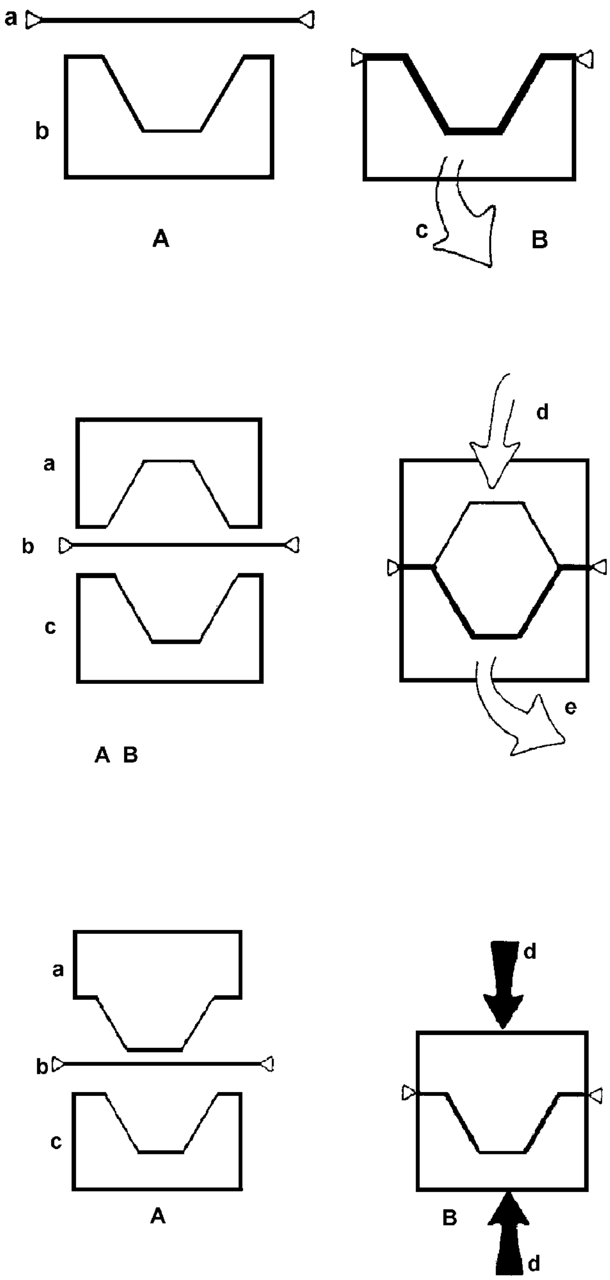
7.7 Other Processes

Fluoropolymer parts can be processed by other common techniques such as encapsulation, hot stamping, and ink printing.

Encapsulation of metal parts can be easily achieved with fluoropolymers. Parts, such as butterfly valves, are used in applications where extreme mechanical integrity and rigidity, combined with chemical resistance, are required.

Hot stamping is conducted using a stamp heated well above the melting temperature of the polymer (> 360°C for PTFE). Application of pressure to the hot stamp for a period of time will imprint the desired pattern. Temperature, pressure, and time should be determined by trial and error.

Inks having a fluorocarbon base can be used to print stripe patterns on wire for identification. In practice a wheel coated with the desired color runs along the wire prior to the sintering step of the manufacturing process. For more than one stripe, additional wheels are needed. The ink is sintered at the same time as the insulation. PTFE and FEP dispersion have been used as the base to produce ink. Inorganic pigment that is stable under the sintering conditions of polytetrafluoroethylene must be used.



Vacuum Forming.

A: Preheated sheet prior to forming.
B: Formed sheet into female mold.
  a – Preheated, clamped sheet.
  b – Female mold with vacuum holes.
  c – Vacuum.

Pressure Forming.

A: Preheated sheet prior to forming.
B: Formed sheet into female mold.
  a – Pressure box.
  b – Preheated, clamped sheet.
  c – Female mold with vacuum/vent holes.
  d – Applied air pressure.
  e – Venting or vacuum.

Matched Die Forming.

A: Preheated sheet prior to forming.
B: Sheet formed by simultaneous motion of two mold halves.
  a – Male mold half.
  b – Preheated, clamped sheet.
  c – Female mold half.
  d – Applied force.

Figure 7.19 Schematic configuration of different thermoforming methods.[49]

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8 Design and Construction of Linings and Vessels

8.1 Introduction

This chapter deals with the actual fabrication of linings for vessels, piping, valves, hose, expansion joints, and internals. It also deals with the shop and field assembly of these components.

8.2 Lining of Vessels

The lining options for vessels have been described in Ch. 4 and reproduced here to aid our discussion. The selection of lining technology depends on several factors such as chemical resistance, material availability, vessel size, heat transfer consideration, shop versus field application, and cost (Tables 8.1 and 8.2). Details of construction of these five technologies are produced below.

Table 8.1. Comparison of Lining Technologies for Vessels

Technology	Materials (sizes in milli-inches)*[1]		Fabrication	Design	Size limit, ft*[2]	NDT	Repair
Adhesively bonded	PVDF (60, 90, 118) ECTFE (60,90)	Synthetic and glass-backed	Contact or thermosetting adhesive Weld rod and Cap strip welds Shop or field	Pressure ok Full vacuum up to 120°F (49°C) Max Temp 275°F (135°C)	None	Visual spark	Possible. Testing recommended
	ETFE (60, 90) PTFE (80, 120) FEP (60, 90) PFA (60, 90, 110) MFA (60, 90)	Glass backed					
Rotolining	ETFE PVDF ECTFE (All up to 250) (normal thickness: 186)		Rotationally molded No seams No primer Shop only	Pressure OK Limited vacuum ability	Max size 8 × 22	Visual spark	By hot patching Testing recommended
Spray and Baked –Dispersion	FEP (10), PFA (10–40 and up to 80 when reinforced or filled) PVDF (20–40 and up to 90 when reinforced with carbon cloth)		Primer and multicoat conventional spray equip Each coat baked Shop only	Pressure OK Vacuum OK	12 × 12 × 37	Visual spark	By hot patching Testing recommended
–Electrostatic spray	ETFE (up to 50), FEP (10), PFA (25-40) ECTFE (35–90), PVDF (35–40)		Primer and multicoat Each coat baked Shop only				

*[1] To convert from milli-inches to mm, multiply by 0.0254. Note: thickness is for fluoropolymers only. For glass backing add 35 milli-inches and for synthetic add 15 milli-inches.

*[2] To convert from ft to m, multiply by 0.3048.

(Cont'd.)

Table 8.1. ***(Cont'd.)*** **Comparison of Lining Technologies for Vessels**

Technology	Materials (sizes in milli-inches)*[1]	Fabrication	Design	Size limit, ft*[2]	NDT	Repair
Loose lining	FEP PFA Modified PTFE (All 60, 90, 125, 187)	Liner fabricated outside the housing and slipped inside. Liner fabricated by hand and machine welding. Shop only	No vacuum. Pressure OK	Determined by body flange (12) and section height (12)	Visual spark	Difficult
Dual Laminate (Fluoropolymer lined FRP)	Same as Adhesively Bonded	Fabricate liner first on a mandrel (hand and machine welding) and build FRP laminate over the liner. User carbon cloth for spark testing Shop and Field	Pressure OK (RTP-1 Dual lam or Section X) Vacuum OK for FRP/fluoropoly mer bond. Design FRP for vacuum	~ 33 dia max	Visual spark AE	Possible. Testing recommended

*[1] To convert from milli-inches to mm, multiply by 0.0254. Note: thickness is for fluoropolymers only. For glass backing add 35 milli-inches and for synthetic add 15 milli-inches.

*[2] To convert from ft to m, multiply by 0.3048.

Table 8.2. Fluoropolymers Used for Dual Laminate Structures

Fluoropolymer (milli-inches*)	Backing	ASTM
PVDF (60,90,118)	Synthetic, glass or carbon-fiber backed	D3222 (Homopolymer only)
ECTFE (60,90)		D3275
ETFE (60, 90)	Glass backed	D3159
PTFE (80, 120)		D4894, D4895, D3293, D3294
FEP (60, 90)		D3368
PFA (90, 110)		D3307
MFA (60, 90)		D3307

* Thickness is for fluoropolymers only. For glass backing add 35 milli-inches and for synthetic (polyester) add 15 milli-inches. To convert from milli-inches to mm, multiply by 0.0254.

8.2.1 Adhesively Bonded Linings for Vessels

The principle of adhesive bonding is that of "wall papering" the inside of the vessel with the fluoropolymer sheets. The surface is blasted to white metal blast per SSPC SP 5. Depending on the application, either an epoxy adhesive or a contact adhesive based on neoprene is applied to the metal surface and the fabric backing of the sheets. For neoprene adhesive, a primer based on the same resin is also applied. The sheets are thermoformed where necessary to fit the contour of the vessel, particularly on the heads. For epoxy adhesive, vacuum bagging is also applied and maintained until the adhesive is cured. This is particularly important for the heads where either pie shapes or straight sections are laid out. Sheets are laid out in such a fashion that the adjoining sheets are in close contact with each other. A root pass is applied by hot gas welding using a 6.3 mm thickness of the same material. A spark test is conducted to ensure continuity, followed by making the root pass smooth and overlaying it with a cap strip by hot gas welding. A final spark test is conducted. A hydrostatic test is done only for the purpose of checking the sealing of the flanges. As far as possible, pneumatic testing should be avoided. Figures 8.1 through 8.5 illustrate the fabrication of bonded sheet lining.

The following are critical success factors:

- *Material selection.* The choice of the right fluoropolymer and thickness is based on application parameters such as the process chemical, temperature, and permeation concerns.
- *Choice of adhesive.* Use neoprene adhesive for applications where vibration, bumps, etc., are encountered such as over-the-road trailers. For higher temperatures epoxy is preferred. Neoprene-based adhesive should be allowed to dry to touch before the sheets are applied over it. Neoprene adhesive is used for application temperature not exceeding 107°C while epoxy adhesive is used for up to 121°C. It is important to note that adhesive can become a weak link in an otherwise strong chain.
- *Fabrication of the vessel for lining.* Make sure that sharp edges are avoided. Where this is not possible, round the edges to at least a radius of curvature of 6.3 mm.
- *Surface preparation.* White metal blast is essential. Surface profile replicas or a comparator is highly desirable.
- *Application of sheets by thermoforming and vacuum bagging.* It is important to make close contact between the sheets and the metal surface when epoxy adhesive is used. All trapped air must be removed. The vacuum bag is maintained until the epoxy is hardened. Details of vacuum bagging are found in the chapter on fabrication (Ch. 6).
- *Nozzles.* Nozzles are fabricated form the same sheet materials and inserted over an adhesive. For nozzles less than 76 mm, extruded inserts without the fabric backing are used.
- *Welding.* The welding procedure needs to be qualified following the guidelines in ASTM C1147.
  - Use of clean, dry air is essential. (Hot air is usually acceptable although nitrogen is required for ECTFE.)
  - Control of welding speed.
  - Application of right amount of pressure on the weld rod or cap strip.
  - Temperature setting of the gun.
- *Quality of welds (per American Welding Society G1.10M).* This document defines cracks, voids, solid inclusions, lack of fusion, and shape defects as the main categories with various subcategories. For each defect there are three evaluation groups: I, II, III with Group I being the most demanding.
- *Spark test of root pass.* Voltage is typically 10,000.
- *Hydrostatic test.*

Figure 8.6 shows the supply chain for bonded linings.

8.2.2 Rotolining

The principle of rotolining or rotational lining is straightforward. A steel vessel or pipe serves as the mold in which the powder of the fluoropolymer is placed. The choice of fluoropolymers is limited to PFA, ECTFE, ETFE, and PVDF. The amount of the fluoropolymer is a function of the thickness of the lining required. The flanges are closed and the vessel is placed in an oven in a way that it can be rotated around (usually) two axis. The powder is thus melted and a fairly uniform seamless lining is obtained. The flange faces are machined to achieve a flat, sealable

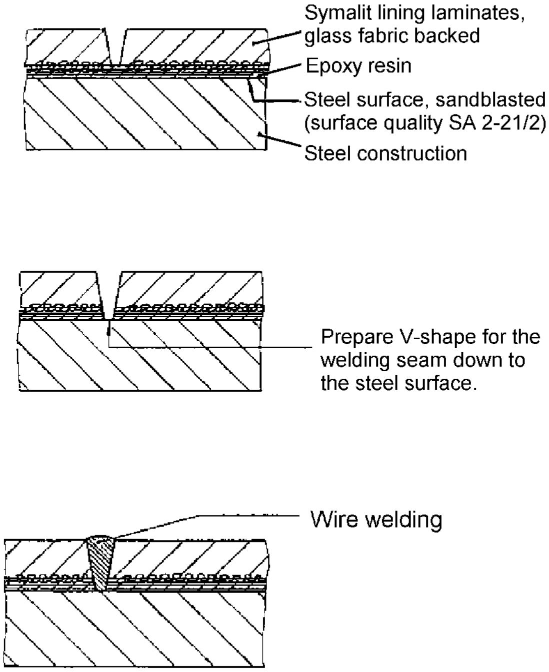

Figure 8.1 Schematic of a bonded lining system for metallic substrates. *(Courtesy Symalit Co.)*

Figure 8.2 Adhesively bonded lining: *(top)* thermoforming of sheets, and *(middle and bottom)* finished lined head. *(Courtesy Electrochemical Engineering and Manufacturing Company.)*

Figure 8.3 Preparation of the lining for root pass. *(Courtesy Electrochemical Engineering and Manufacturing Company.)*

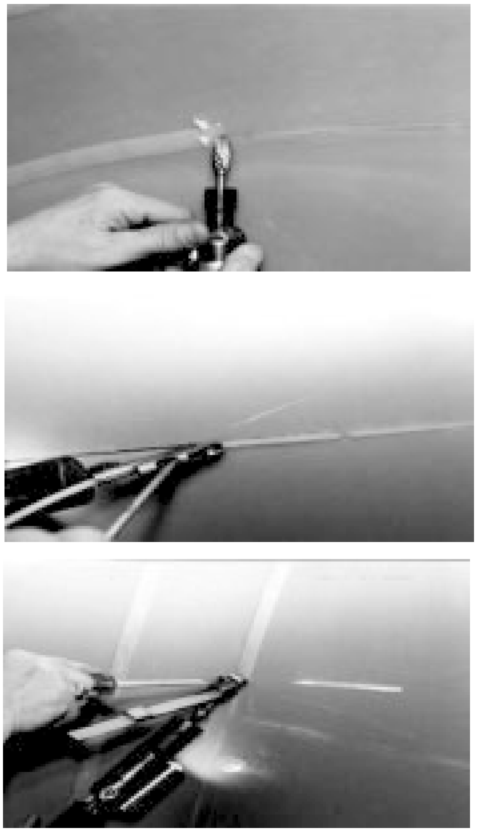

Figure 8.4 Welding of adhesively bonded lining. Root pass welding and cap strip welding. *(Courtesy Electrochemical Engineering and Manufacturing Company.)*

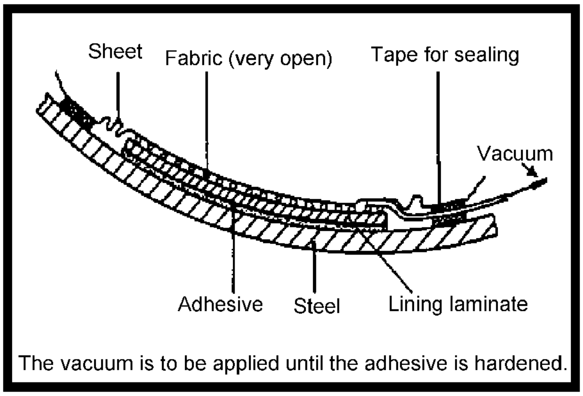

Figure 8.5 Schematic of vacuum bagging. *(Courtesy Electrochemical Engineering and Manufacturing Company.)*

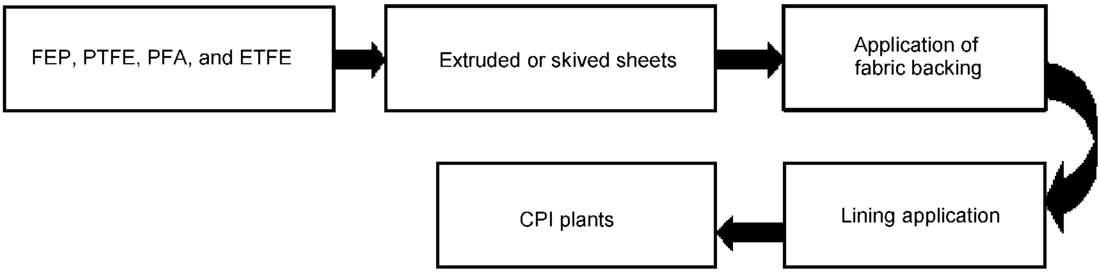

Figure 8.6 Supply chain and job sequence for bonded lining.

surface. Unlike rotational molding where the part is removed from the mold, in rotolining, the polymer is retained in the mold as an adhered lining. Figures 8.7 through 8.9 illustrate the process of rotolining as well as the complexity of parts that can be rotolined. The supply chain is depicted in Fig. 8.10.

The following are critical success factors:

- *Selection of material: PVDF, ECTFE, ETFE, and PFA.* Choice of material will depend on chemical and temperature resistance required.
- *Thickness of the lining.* Although the lining thickness can be theoretically unlimited, the practical thickness for fluoropolymer lining is around 4.5 mm. The lower limit of rotolining is typically 90 milli-inches.* The choice of thickness will depend on the permeation resistance required and the cost.
- *Surface preparation.* White metal blast per SSPC SP 5.
- *Rotolining process.* Time and temperature in the oven to achieve a uniform thickness without beginning degradation.
- *Inspection.* Visual, spark testing, and thickness measurement where accessible.
- *Hydrotesting.*

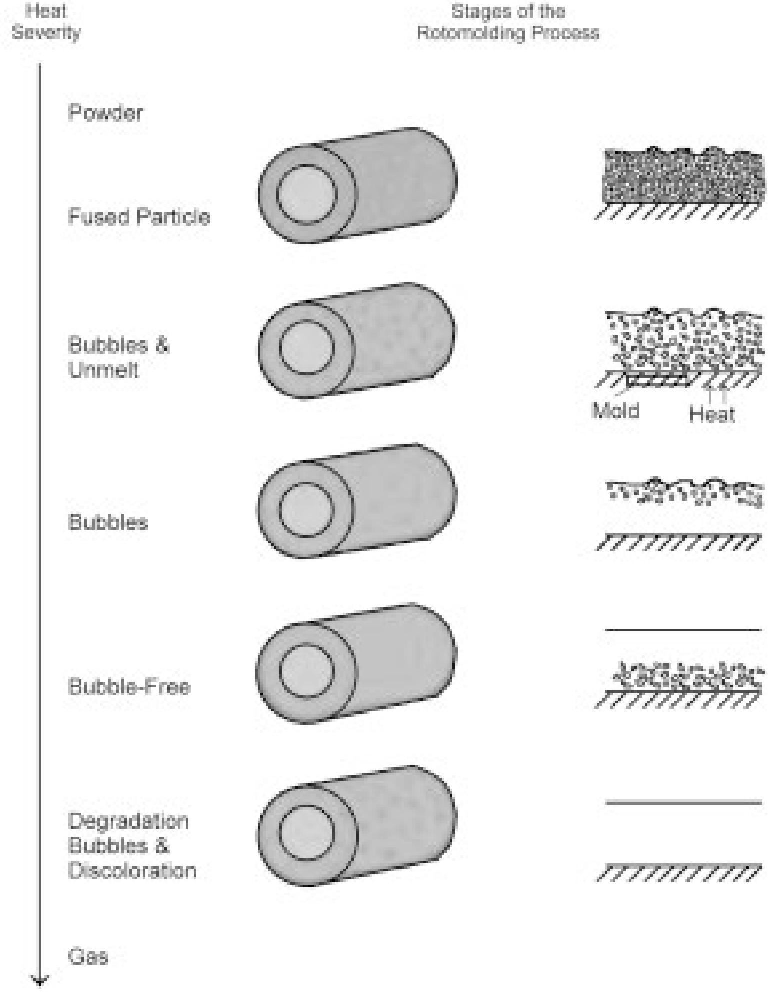

Figure 8.7 Stages of rotolining. *(Courtesy DuPont Company.)*

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* To convert milli-inches, multiply by 0.0254.

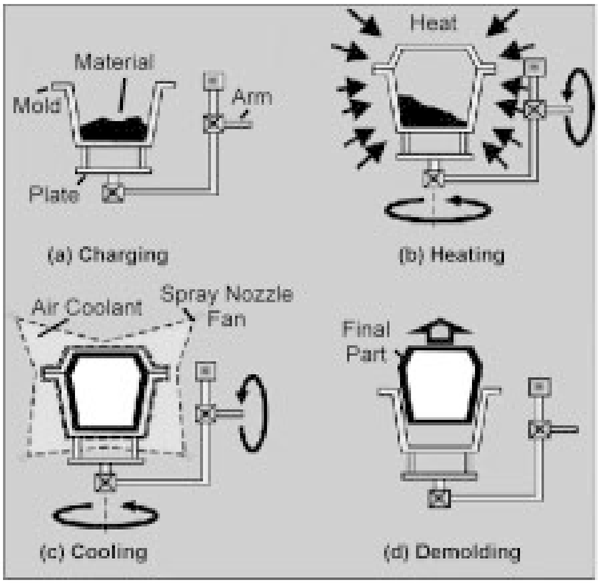


Figure 8.8 Schematic of rotolining equipment showing the four principal stages of rotational molding. *(Courtesy RMB Products, Fountain, CO.)*

Figure 8.9 *(Top left)* Component showing the complexity of a rotolined part*. (Bottom left)* Complex pipe ring lined with ETFE Tefzel®*. (Right)* Multisection column made of rotolined sections. *(Photographs courtesy RMB Products.)*

Figure 8.10 Supply chain and job sequence for rotolining.

8.2.3 Spray and Baked Coatings

There are two distinct ways of coating a metal surface with a fluoropolymer coating.

- Powder coating
- Liquid dispersion coating

The supply chain for this process can be seen in Fig. 8.11. Electrostatic spray coating or powder coating is a way of applying a dry paint to a surface. Most people have used liquid paints with a brush, a spray can, or even with their fingers. Powder coatings are dry; there are no liquid solvents. The dry powder is applied to an item (substrate), then the powder is turned to liquid, usually by melting. The dry powder in its molten state can then flow out to cover the substrate, coalesce, and crosslink. The end result is a painted surface.

Some parts might need to have a coating thickness less than what other lining processes can provide. These might include valves, tubes, pipes, and impellers. These parts may still need to be protected by a fluoropolymer coating. One of the best references is published by the Powder Coating Institute[1] although other sources are also available.[2]

Powder coatings are available in FEP, PFA, MFA, ECTFE, ETFE, and PVDF. Typically, a multicoat application is required to achieve a required thickness. The powder size ranges from 1–3.54 milli-inches (25 to 90 microns).

Powder coating has advantages over liquid coatings, but it also has limits. Most of the advantages are environmental and economic. Powder coatings generally contain no volatile organic content (VOC), so there are no atmospheric emissions. This reduces the cost of permits and environmental compliances. Spray booth air can be filtered and returned to the room reducing cooling and heating costs. *Overspray*, the powder that missed the part being coated, is usually considered non-hazardous waste, at the worst, solid hazardous waste, which reduces disposal costs. The overspray can sometimes be collected and reused, reducing material costs. Ovens do not need to remove solvents, thus requiring less air turnover, which reduces energy costs.

A characteristic of electrostatic coating with both charging processes is that the charged powder will wrap around the back of the substrate, especially as the powder builds up on the front of the part being coated. This is usually referred to as *electrostatic wrap*. This can be both an advantage or a disadvantage.

Powder coatings have trouble penetrating deep depressions. The electric field lines do not penetrate into these tight areas and the charged powder can not penetrate and deposit there. This is observed in almost all ninety-degree corners and is commonly referred to as a *Faraday Cage effect*. While this effect can not be eliminated entirely, it is minimized by using triboelectric equipment.

As powder is applied to the substrate, a limit is reached where additional powder starts to repel itself because of the buildup of like charge on the surface. This occurs even though the part is grounded because neutralization of that charge takes time and

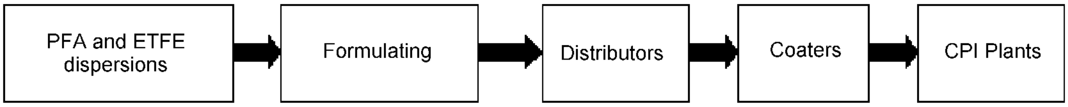


Figure 8.11 Supply chain and job sequence for spray and baked coatings.

the powders themselves are not usually conductive. Also, some remaining charge is desired to help hold the powder onto the part being coated. Care must be taken when moving a freshly powder-coated part because the powder can fall off. The film thickness limit for powder coatings, per coat applied electrostatically, is dependent on the powder coating material, part geometry, and voltage on the powder. It is typically 2–4 milli-inches (50–100 microns) of dry film thickness.

For chemical process applications, high film buildup is often desired. Powder coating requires many coats and bakes, and gets more difficult for thicker coatings because the fluoropolymer insulates the grounded part from ground. There is a way to apply thick powder films by a process called *hot flocking,* described below.

8.2.3.1 Powder Coating Processes

While there are several ways to apply powders, two are most commonly used for CPI applications. They are called *electrostatic spray application* and *hot flocking*.

Electrostatic Spray Method. Electrostatic spray can be used to apply thin or thick films. A thin film might be as low as 1 milli-inch (25 microns). Thick films might be applied as high as 0.1 inch (2.5 mm), though typically thick films are 40–60 milli-inches (1000–1500 microns). The equipment used is depicted in Fig. 8.12. A large number of manufacturers make this type of equipment.[4][5] The process starts with fluidization of the powder. This is commonly done in a hopper or a vibratory feeder.

A hopper, shown in Fig. 8.13, is usually a cylinder with a porous bottom or fluidizing plate. Compressed clean dry air passes through the plate and into the powder. The air flows uniformly through the fluidizing plate and mixes with the powder, increasing its volume. The fluidization serves two purposes. One is to get the powder to flow easily allowing it to move from the hopper to the spray gun. The second is to break up any loosely agglomerated powder particles. This powder exhibits very little resistance to movement. It is a dry fluid. The fluidized bed looks like the powder is boiling. In some cases, especially with finer powders, the bed is stirred or vibrated to aid in fluidizing uniformity.

An alternate approach to fluidization is with a device called a vibratory box feeder. This device fluidizes the powder directly in the box that commonly contains it during shipping. It fluidizes the powder near the pick-up tube using compressed air while the box is vibrating. Good fluidization is required to get consistent coating application.

The powder is transported through the supply tubing to the spray gun. If the powder is passed through the gun without further interaction, it would just be sprayed into the air as a cloud. There would be no physical reason for the powder to deposit on the substrate to be coated. To make this attraction happen, a charge must be applied to the powder. This is done by two methods called *corona charging* and *tribocharging*.

A high voltage power supply is attached to the spray gun in a corona charging system. These power supplies provide an adjustable voltage (typically 0–100,000 volts) or controlled current. When the high voltage is applied to a charging electrode in the gun, a strong electric field is created between the charging electrode and grounded attractor electrode shown in Fig. 8.14. This strong electric field ionizes the air creating what is called a *corona*. Normally, 30 kV will ionize clean dry air, but it can occur at lower voltages especially when particles are present, as in powder coating. Ions are created and electrons are emitted. The electrons interact with oxygen in the air to form negative ions. (Nitrogen molecules in air can produce positive ions.) The oxygen negative ions hit the powder particles and transfer the electrons to those particles, giving them a negative charge.

Once the powder particles are charged, they are blown out of the gun towards the substrate to be coated. If the substrate is grounded, the powder particles will be attracted along lines of electric force to the substrate, as shown in Fig. 8.15.

Tribocharging is the process of electricity generation when two different materials rub against each other. Some materials easily give up or accept electrons from other materials under friction. The triboelectric series lists materials that give up electrons in order from easiest to hardest. For many materials, the dielectric constant determines the position of that material in the triboelectric series. The further apart the two materials are that rub against each other, the more charge is transferred.

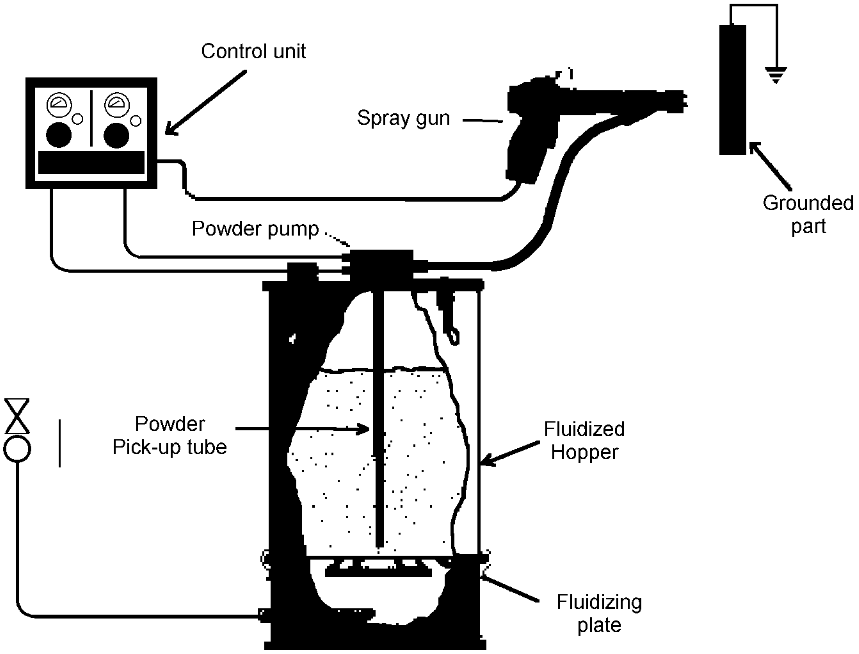


Figure 8.12 Powder coating application equipment.[3]

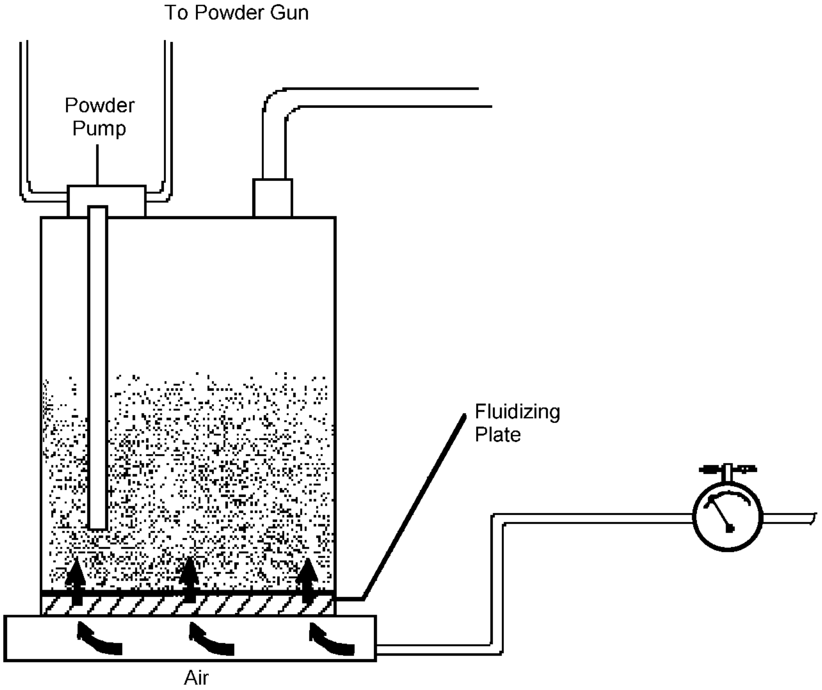


Figure 8.13 Fluidized hopper.[3]

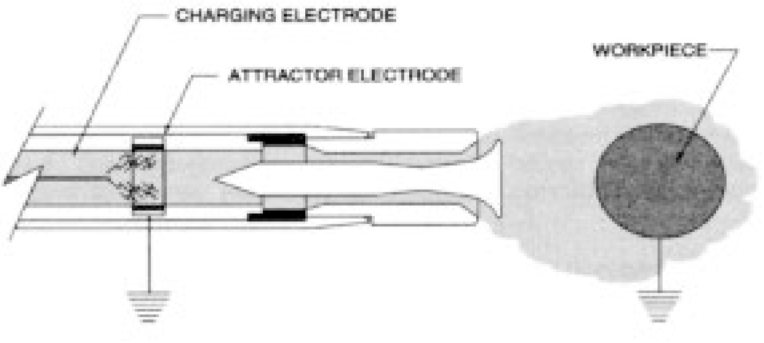


Figure 8.14 Corona charging in spray gun.[3]

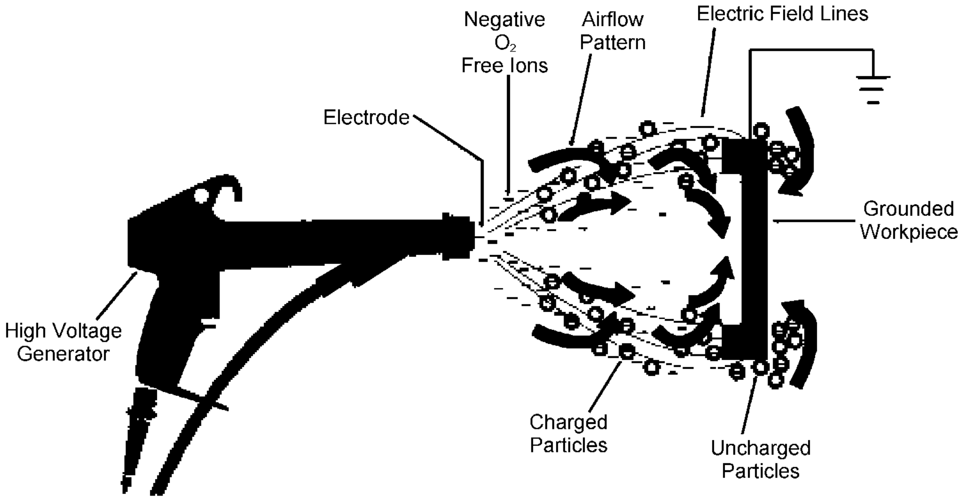


Figure 8.15 Powder from a corona charging spray gun is attracted to ground.[3]

To take advantage of this process for powder coating, a spray gun can be constructed without a high-voltage power supply. For most coating materials, the ideal material for gun construction would be PTFE since it is positioned at one extreme of the triboelectric series. However, for fluorpolymers, a gun constucted of nylon is best. Nylon is the engineering plastic that is furthest away from PTFE in the triboelectric series, so it provides the best charging of a fluoropolymer powder. The interior of the powder gun is constructed of nylon such that there is maximum contact between the powder coating and the gun. Grounding of the gun is important because the powder flows continuously over the same nylon surfaces, removing electrons. Those electrons must be replaced from ground for the gun to continuously tribocharge the powder and to avoid the buildup of dangerously large voltages.

Hot flocking. Powder coating is one of the best ways to coat a large impeller or a mixing blade with a layer of thick fluoropolymer. Usually, the process starts with a cold electrostatic powder coating step that applies a thin film. The part (impeller in this example) is baked above the melt point of the powder for a sufficiently long time to get a smooth continuous coating. The part is quickly removed from the oven and the powder is applied to the part while it is above the melt point of the powder. As the powder contacts the hot part, it melts. More powder can be applied until the melting stops. This is easily visible because the molten coating is usually quite glossy. When the melting stops, the part is put back in the oven to melt and flow out the last coat. It can be pulled out of the oven and hot flocked again and again until the desired film buildup is achieved. For PFA, a common material for CPI applications, one can apply up to 7.9–15.7 milli-inches (0.2–0.4 mm) per coat, mostly dependent on the mass of the part being coated.

Figure 8.16 shows the thermal history of a 0.25 inch (6.25 mm) thick steel panel being coated with PFA. The panel has a thermocouple attached so the temperature can be monitored even while it is in the oven. The first "tooth" shows the temperature after the panel has been primed and powder-coated with about 2 milli-inches (50 microns) of PFA. The melt point of PFA is about 305°C–310°C and even a 0.25 inch (6.25 mm) steel panel cools quickly. One must be ready to powder-coat immediately after the panel is pulled out of the oven. About 7.9–15.7 milli-inches (0.2–0.4 mm) of additional powder was applied on top of the first coat. The part was put back into the oven and rebaked. It can then be flocked again and again. The final bake time is usually extended to allow the coating to completely flow out, usually at a lower temperature, to minimize thermal degradation.

While the same powders can be used for hot flocking, usually a larger particle size is used. This is partly due to the fact that most people turn off the electrostatic high-voltage supply. Larger particles have more momentum to carry them to the part.

Commercial products. There are many grades of powder-coatings provided by the companies that make fluoropolymers. Any melt-processible fluoropolymer theoretically can be made into a powder coating. Some coating companies buy granular fluoropolymers and grind them to a particle size suitable for powder coating.

Powder coatings for electrostatic application usually average about 1.4–3.5 milli-inches (35–90 microns) in diameter. Finer particle-size coatings are available, but fluidization is more difficult and less consistent, leading to a more difficult-to-control coating process. The finer grades are generally designed for thinner smooth coatings usually not required in CPI applications. Larger particle sizes, especially those over 3.9 milli-inches (100 microns), have less surface area per unit weight, so they do not hold electrostatic charges well enough for coating.

Particle morphology or shape affects the ease of fluidization, the ability to hold charge, and how the particles pack onto the surface being coated. Shape varies greatly and is affected by the manufacturing process. The micrographs in Fig. 8.17 show the same pure molecular weight PFA prepared three different ways. Differences in the ways different PFA powders apply may be attributed, in part, to particle morphology.

Fluoropolymer powder coatings are not always neat fluoropolymers. There could be additives such as fillers, pigments, and stabilizers blended with the fluoropolymers. Most of these products are just dry blends. The different powders are put into a dry-powder blender and blended to uniformity. However, since the dry blends are mixtures of discrete particles of different materials, each particle has a different ability to fluidize and take up electrostatic charge. In fact, some particles may not charge at all. This manifests itself as a separation of materials during application. Dry-blended pigments often do not deposit on the part being coated in the same concentration as they started; there is no driving force except momentum to attract it to the substrate. Some companies make powder coatings that encapsulate the pigments within the fluoropolymer particles through special processing.[6]–[8] These materials, therefore, have distinct advantages over the dry-blended powder coating analogs.

There are many commercial materials. Many are made by companies for internal use only and are not sold except as applied. They are advertised and somewhat known in the industry, but physical data on the powders are not generally available. The best known of these materials are included in Tables 8.3–8.7 based on the base fluoropolymers.

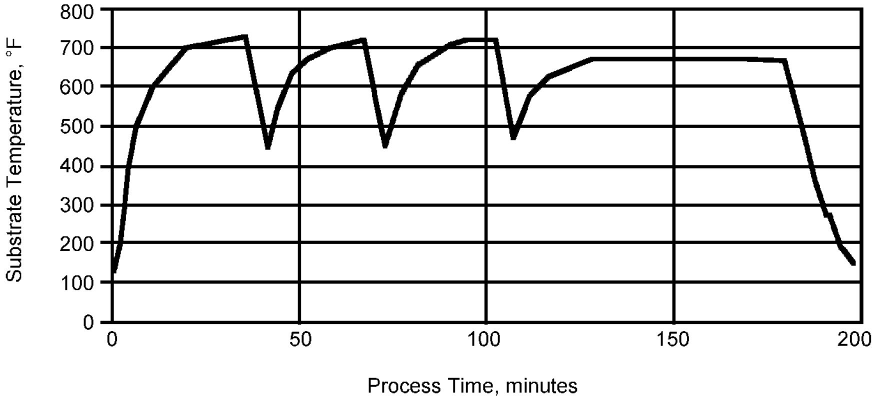


Figure 8.16 Hot flocking of PFA. *(Courtesy DuPont Company.)*

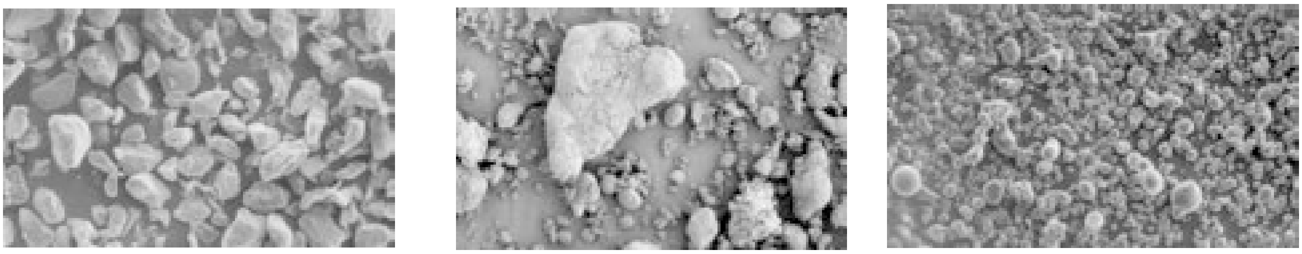


Figure 8.17 Powder coatings made by different processes. *(Courtesy DuPont Company.)*

Table 8.3. ECTFE Powder Coating Materials

Manufacturer:Code number	Melting Point (°C)	Melt Index (g/10 min)	Comment
Solvay Solexis: 6014	220	12	Topcoat
Solvay Solexis: 5504	240	12	Primer
Solvay Solexis: 6614		12	Primer
Solvay Solexis: 8014		12	Topcoat, improved stress crack resistance
Solvay Solexis: 5004		12	
Solvay Solexis: 5005		12	
Edlon: SC-2001			Filled, internal use only

Table 8.4. PVDF Powder Coating Materials

Manufacturer: Code number	Melting Point (°C)	Melt Index (g/10 min) or Melt Viscosity (kpsi)	Comment
Solvay Solexis: Hylar 301F	155–160	22–33 at 232°C at 100 s	—
Edlon: SC-3001	178		Filled
Whitford: Dykor 830	—	—	Chemical resistant Abrasion resistant Non-stick

Table 8.5. PFA and MFA Powder Coating Materials

Manufacturer and Code Number	Bulk Density	Average Particle Size (μ)	Melting Point (°C)	Melt Index (g/10 min)	Comment
DuPont:					
532–5010	640–680	29–41	302–310	14	Clear, FDA
532–5011	620–830	15–26	302–310	14	Fine
532–5012	540–800	25–41	302–310		High build tan, wear resistant
532–5310	640–850	29–41	302–310	4.1–8.9	Clear
532–7410	550–870	29–41	302–310	2.0	
532–5450	750–930	31–93	302–310		High build, heat stabilized
532–7000	560–860	26–41	302–310		Sparkling
532–7100	560–860	29–41	302–310		White
532–13054	750–930	55–95	302–310		Ruby red, high build permeation resistant
MDF:					
MP–10	850–1110	14–30	302–310		Clear
MP–102	890–1150	10–20	302–310		Clear
MP–103	>45	14–38	302–310		Clear
MP–300			302–310		Fluorinated
MP–302			302–310		Fluorinated
MP–310			302–310		Fluorinated
MP–10	850–1110	14–30	302–310		Clear
MP–102	890–1150	10–20	302–310		Clear
MP–103	>45	14–38	302–310		Clear
MP–300			302–310		Fluorinated
MP–302			302–310		Fluorinated
MP–310			302–310		Fluorinated
MP–311			302–310		Fluorinated
MP–312			302–310		Fluorinated
MP–501			302–310		Filled, corrosion and abrasion Resistant
MP–502			302–310		Filled, corrosion and abrasion resistant

(Cont'd.)

Table 8.5. ***(Cont'd.)*** **PFA and MFA Powder Coating Materials**

Manufacturer and Code Number	Bulk Density	Average Particle Size (µ)	Melting Point (°C)	Melt Index (g/10 min)	Comment
MDF: *(Cont'd.)*					
MP–504			302–310		Filled, corrosion and abrasion resistant
MP–505			302–310		White
MP–522	>70	10–25	302–310		Permeation resistant
MP–600	820–1000	11–21	302–310		Electroconductive
MP–610			302–310		Electroconductive
MP–614			302–310		Electroconductive
MP–620	810–1100	11–25	302–310		Thermally conductive
MP–621	810–1150	11–25	302–310		Thermally conductive
MP–622	790–1130	11–25	302–310		Thermally conductive
MP–630			302–310		White electroconductive
Daikin:					
AC–5500	450–650	20–70	303–313	1–7	Top-coat for corrosion-resistant lining
AC–5511		20–70			
AC–5539	450–650	20–70	303–313	1–7	Undercoat and top-coat for corrosion-resistant lining
AC–5600	450–650	20–70	303–313	1–7	Top-coat for corrosion-resistant lining and anti-stick coating
AC–5820		20–90			
Solvay Solexis:					
MFA–6010			285	10–17	MFA
PFA–7010			310	10–17	PFA
Whitford:					
Dykor 810					
Edlon:					
SC–7005					Filled, internal use only

Table 8.6. ETFE Powder Coating Materials

Manufacturer and Code Number	Average Particle Size μ	Melting Point (°C)	Melt Index (g/10 min)	Comment
Asahi Glass:				
Z – 8820X	20	260		
Z – 885A	50	260		
TL – 081				
ZL – 520N		260		Carbon Fiber Filled 20%
ZL – 521N		260		Carbon Fiber Filled 5%
ZH-885B		260		“Special” Filler
DuPont:				
532-6004	42–67			Primer, Green
532-6006				Primer, Blue
532-6010	34–74			Topcoat, Clear
532-6014	36–74			Intermediate Coat, Green
532-6018	36–74			Filled
532-6110	80			Clear Intermediate, High Build
532-6200	20–30			White
532-6210	80			High Build
532-6114	80			High Build Green
532-6118	80			Sparkling Beige
532-6200	20–30			Clear Topcoat
532-6210	20–30			Clear Topcoat
532-6006				Blue Primer
Daikin:				
EC-6500		260		
EC-6510		260		
EC-6515		260		
EC-6520		260		
EC-6800		260		
EC-6810		260		
EPW-1605GN		260		
EPW-1609BK		260		
EPW-1606BL		260		

Table 8.7. FEP Powder Coating Materials

Manufacturer and Code number	Bulk Density (g/l)	Average Particle Size (μ)	Melting Point (°C)	Melt Index (g/10 min)	Comments
DuPont:					
532-8000	—	4–30	228		Low melting
532-8110	—	26–47	264	6.6	
Daikin:					
NC-1500	450–650	20–90	265–275	0.8–1.5	Top-coat for corrosion-resistant lining and anti-stick coating
NC-1511	—	—	—	—	
NC-1539	450–650	20–90	265–275	0.8–1.5	Undercoat and top-coat for corrosion-resistant lining
NCX-1	—	—	—	—	

8.2.3.2 Liquid Dispersion Coatings

Liquid dispersion coatings are mostly water-based suspensions of fluoropolymers. Multiple-pass coating is needed to achieve the required thicknesses. Proprietary formulations involving additions of pigments and other processing aids make this option subject to a great deal of testing. Metallic mesh reinforcement is also incorporated in the coating system to enhance and retain adhesion.

Although FEP is available as a liquid dispersion, the commonly used material in liquid dispersion coatings are PFA and PVDF. Both materials are used in various ways such as filled or unfilled. Typical fillers for PFA are mica flakes. PVDF can be reinforced with fiberglass cloth or carbon fabric for additional permeation protection. Typical thicknesses achieved are up to 80 milli-inches (2 mm). PFA coatings are used with wire mesh reinforcment for additional protection from delamination.

The following are critical success factors:

- *Design of equipment for coating.* Vessels need access for spraying.
- *Selection of material and powder versus dispersion.*
- *Selection of pigmented or unpigmented topcoat.* Needed for FDA approved products.
- *Temperature control.* Adequate and precise temperature control in the oven is needed for proper baking of the lining.

8.2.4 Loose Lining

Loose linings are not bonded to the substrate like others. However, they are anchored at the flanges to retain them in place. Linings are first fabricated outside the vessel using a heated tool or flow fusion welding for the axial welds. Hot-gas hand welding for the circumferential welds is typically used. The nozzles are attached by cutting holes in the cylinder and welded using the flow fusion technique; thus, the liner is ready to be inserted into the vessel. Once inserted, the nozzles and body flanges are flared over the flange faces. Figures 8.18–8.22 illustrate the technique of loose lining. The supply chain for loose lining is shown in Fig. 8.23.

The following are critical success factors:

- *Choice of material.* Weldable (modified PTFE, FEP, ETFE, and PFA).

- *Welding.* High quality of machine and hand welds verified by spark tests. Welds to be qualified per DVS (German Welding Society) standards.
- *Venting.* Vent holes are needed to handle permeation.
- *Flanges.* Flaring of flanges and gasketing underneath the flared flanges.
- *Suitability.*
  - Not suitable for vacuum and agitated vessels.
  - Most suitable for columns.
- *Testing.* Hydrostatic test and spark test.

8.2.5 Dual Laminate

The principle of dual laminate construction is to line an FRP vessel or column with a fluoropolymer lining. However, the sequence of construction is to first make the liner out of fabric-backed sheets the same as in the adhesively bonded construction. The FRP structure is then laminated on the liner to provide the structural strength. This technology incorporates a distinct and separate technology of FRP fabrication. Use of part of the American Society of Mechanical Engineers (ASME) RTP-1 code which deals with dual laminate construction is essential. Figure 8.24 shows the supply chain for dual laminate fabrication.

Figure 8.25 shows an operator working on laminate fabrication. Figures 8.26 and 8.27 illustrate the fabrication technique and examples of dual laminate structures. The job sequence is as follows:

- Lining for the heads are thermoformed after pieces are welded. Carbon cloth is first laid using the resin. FRP is then laminated by contact molding (hand lay-up). The edge of the liner is left uncovered for subsequent welding.
- Nozzles and manways are fabricated and flanges are flared. FRP is laminated over the nozzles. An edge is left uncovered for subsequent welding.
- The cylindrical section of the vessel is fabricated using fusion welding followed by carbon cloth and FRP laminating.

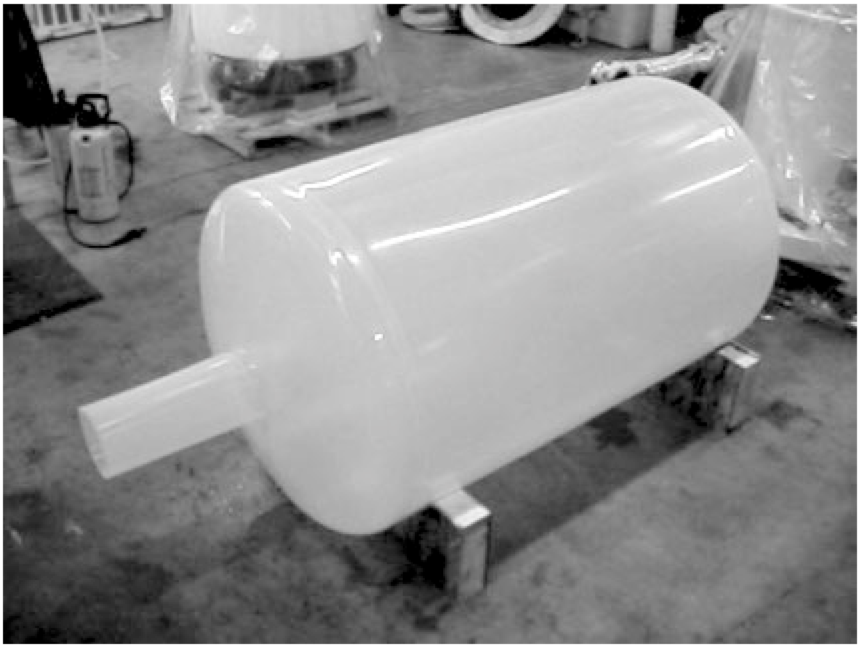


Figure 8.18 Loose lining for insertion in the steel housing. *(Courtesy Edlon Company.)*

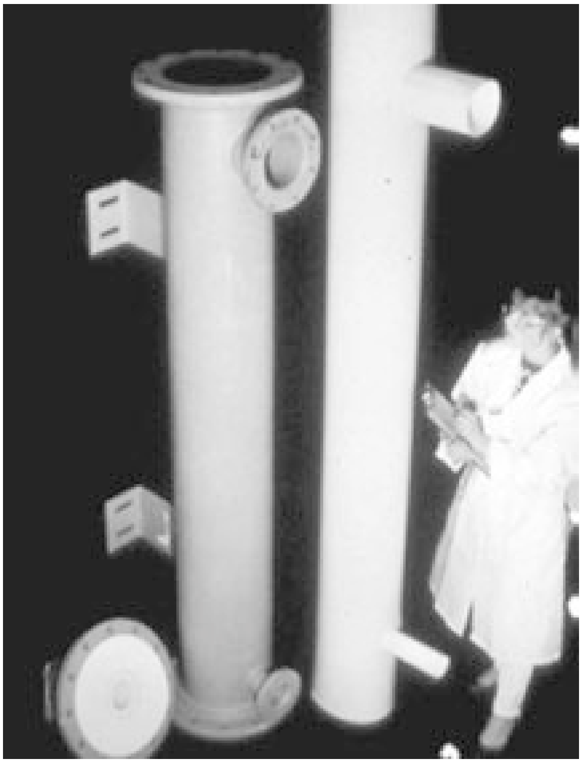


Figure 8.19 Loose lining ready for insertion. *(Courtesy Edlon Company.)*

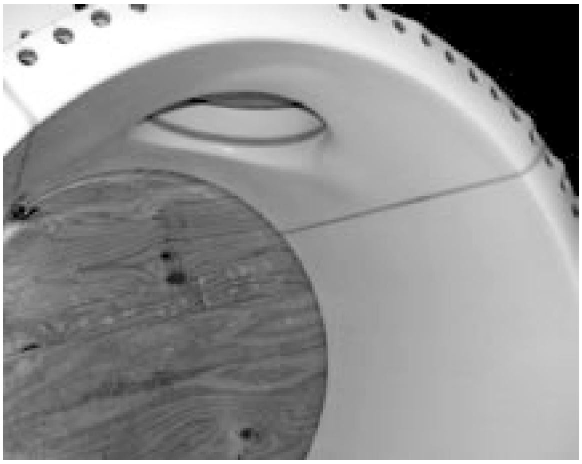


Figure 8.20 Loose lining ready for shipping. *(Courtesy Edlon Company.)*

Figure 8.21 Loose-lined modified PTFE column. *(Courtesy Edlon Company.)*

Figure 8.22 Machine butt welding of fluoropolymer prior to dual laminate construction. *(Courtesy CPF Dualam, Montreal, Canada.)*

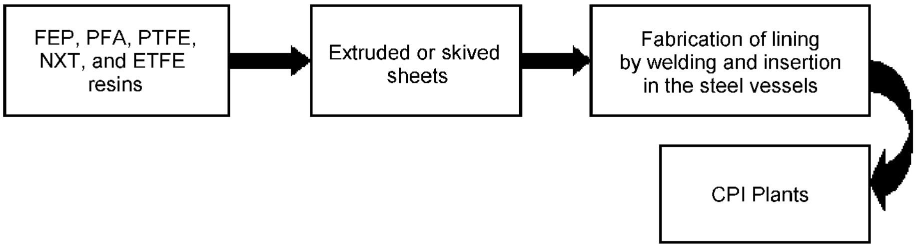


Figure 8.23 Supply chain and job sequence for loose lining.

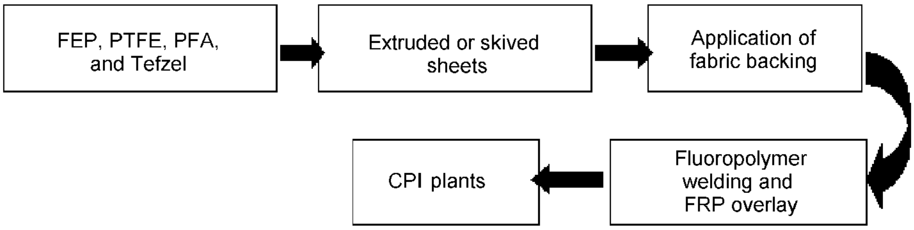


Figure 8.24 Supply chain and job sequence for dual laminate construction.

Figure 8.25 Dual laminate flange fabrication. *(Courtesy CPF Dualam.)*

Figure 8.26 Hot-gas welding of fabric-backed fluoropolymer sheets prior to laminating. *(Courtesy CPF Dualam.)*

Figure 8.27 Dual laminate scrubber column with ETFE Tefzel®. *(Courtesy RL Industries and DuPont Company.)*

- All parts are assembled by hot gas (hand) welding and a final FRP overlay over the welds.
- Spark testing.
- Hydrotest and acoustic emission test if needed.

The following are critical success factors:

- Choice a fabricator which has ASME RTP-1 accreditation.
- Choice of fluoropolymer and thickness.
- Design of FRP structure.
- Qualified weld procedures .
- Welding quality per American Welding Society (AWS) G1.10M.
- FRP fabrication and quality per ASME RTP-1.

8.3 Lining of Pipes and Fittings

Although any size piping can be lined with fluoropolymers, typically sizes up to 12" (30 cm) are available "off-the-shelf." Piping above 12" is specially made. Lined piping is governed by ASTM F1545.

Lined piping systems consist of straight pipe lengths, fittings such as elbows, tees and crosses, and concentric and eccentric reducers and spacers. All components are flanged and, as such, involve a great deal of care in bolting and tightening to complete a pipe installation.

Lined piping and components can be made by one of the following processes:

- Fabricate a liner, insert it in the steel piping and flare the ends over the flange. PTFE and PVDF account for most pipe below 12" in diameter. For pipe sizes above 14" (35 cm), the pipe is lined as a loose lining using FEP, PFA, or modified PTFE
- Rotoline the pipe with ETFE, PFA, ECTFE or PVDF. This technique is particularly useful for complex piping arrangement where it is necessary to keep the number of flanges to a minimum.

Processing of PTFE is a special case since it has to be processed using the powder metallurgy technique of compaction and sintering. This is done in the following sequence:

- Liner is made by either the ram extrusion process or the isostatic molding process.
- In the case of isostatic molding, the liner is inserted in the metallic piping by stretching it, after which the protruding lengths are flared over the flanges.
- In the case of ram extrusion molding, the liner is inserted in the oversized piping and the pipe is "reverse swaged," i.e., mechanically pressed onto the liner. The extended liner is flared over the flange face.
- Liners for fittings are made by isostatic molding and the metallic housing is inserted over the liner. Afterward, the metallic component pieces are welded to complete the fabrication. A fitting can also be used as a housing in which the lining is made isostatically.

PVDF, ETFE, and PFA liners are made by simple extrusion and inserted in the metallic housing, similar to PTFE.

Figures 8.28 through 8.31 illustrate various types of lined piping and fitting.

8.4 Lined Valves

The most commonly used valves in the chemical processing industries (CPI) are available with fluoropolymer lining. These are:

- Plug valve
- Ball valve
- Butterfly valve
- Diaphragm valve
- Clamp valve

Fluoropolymers serve two principal functions: as lining for the body and the plug, ball, etc., and as part of the valve stem packing system. PTFE accounts for a large part of the use, although ETFE and ECTFE

Figure 8.28 PTFE line pipe. *(Courtesy Crane Resistoflex.)*

Figure 8.29 Rotolined elbows. *(Courtesy RMB Products.)*

Figure 8.30 Lined piping, hoses, and expansion joints. *(Courtesy Crane Resistoflex.)*

Figure 8.31 Large diameter lined elbow and tee. *(Courtesy RMB Products.)*

are also used as linings. Unfilled and filled PTFE are almost exclusively used as packing. Lined valves used in the CPI are of flanged ends. For a review of the design and applications of these valves, see *Perry's Chemical Engineers' Handbook.*[8]

8.4.1 Plug Valves

Plug valves are available as lined or unlined. In lined plug valves (Fig. 8.32), the body of the valve is lined with FEP or, more often, with PFA. The plug is also lined or encapsulated with the same material or made of solid PTFE. In an unlined plug valve, there is still a solid PTFE sleeve around the metallic plug which provides sealing as well as smooth operation of the valve. Valves are available in sizes up to 12" (30 cm) and in steel classes of 150 and 300.

Liners are injection molded, or transfer molded in the case of PFA and FEP. In both cases, a locked liner is achieved.

8.4.2 Ball Valves

The same options available in plug valves are also available in ball valves except that the size is limited to 6" (15 cm) (see Fig. 8.33).

8.4.3 Butterfly Valves

The principal features of a lined butterfly valve (Fig. 8.34) are a PFA liner over an elastomeric seal ring fitted behind the body liner, and a transfer molded PFA liner over the disk. These valves are available in sizes up to 12" (30 cm), and larger sizes, up to 24" (60 cm), are available as special order.

8.4.4 Diaphragm Valves

Diaphragm valves (Fig. 8.35) consist of a straight PFA tube with a weir on which a PTFE diaphragm with a rubber backing is clamped down to control or stop the flow. These valves are available in sizes up to 8" (20 cm).

8.4.5 Clamp Valves

A PTFE clamp valve (Fig. 8.36) with full-flow, straight-through packless valve, is capable of bubble-tight shutoff and fine throttling. These features, coupled with minimum maintenance and corrosion resistance, makes the PTFE clamp valve an economical valve available for demanding chemical processing installations.

The clamp valve consists of a flexible PTFE tube and a clamp. It is somewhat similar to a pinch valve, but, unlike a pinch valve, the tubing is not kinked, creased, or pinched.

PTFE clamp valves are available in sizes 1" (2.5 cm) through 8" (20 cm) in various configurations and with a number of optional accessories.

Because all wetted surfaces are PTFE, the clamp valves offer unsurpassed chemical resistance at temperatures up to 400°F (205°C) for 6" (15 cm) and 8" (20 cm) valves.

8.5 Lined Hoses

Fluoropolymer lined hoses (Fig. 8.37) are used for chemical transfer during the loading and unloading process and, as such, see interrupted service. They are constructed out of a fluoropolymer tube which is either smooth bore or convoluted bore. The tube is topped off with a metallic overbraiding. Such a composite tube is connected to either screwed or flanged ends. Flanged ends are more commonly used in CPI than the screwed ones. Manufacturing, installation, and operation of hoses is one of the more complex operations since several players are involved, as the diagram in Fig. 8.38 shows.

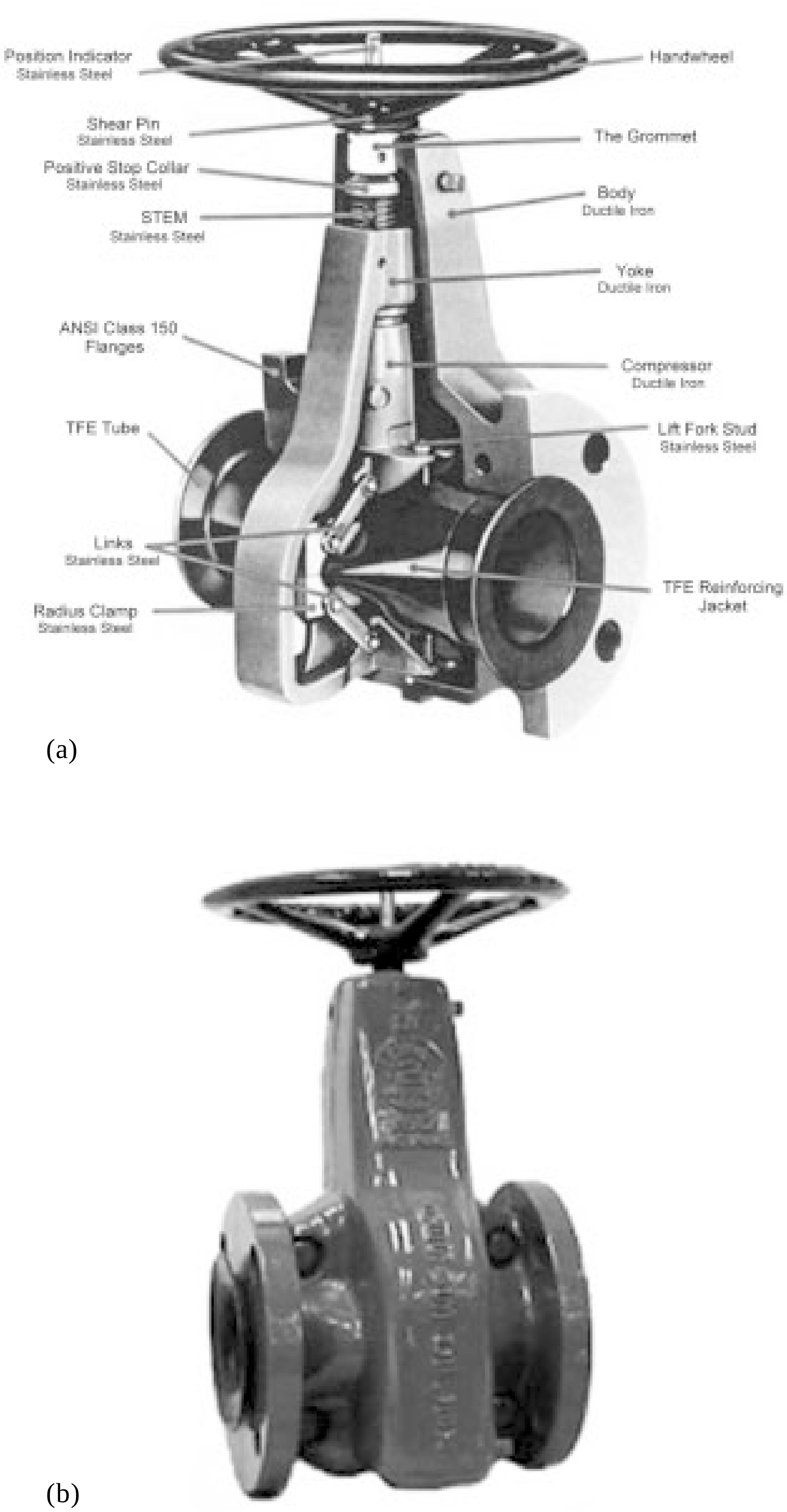
PTFE is by far the material of choice, however, ETFE is also sometimes used. Carbon-filled PTFE is often used where static discharge is desired. Although hoses are available in sizes up to 8" (20 cm), the most common size is 1" (2.5 cm) with 2" (5 cm) occasionally encountered. Smooth bore hoses are used where residual liquid is a safety or environmental concern. However, smooth bore lacks the flexibility that a convoluted bore provides. Although metal overbraiding is commonly used, elastomeric ones are also encountered.

Figure 8.32 Plug valve. *(Courtesy Xomox Corp.)*

Figure 8.33 Ball valve. *(Courtesy Xomox Corp.)*

Figure 8.34 Butterfly valve. *(Courtesy Xomox Corp.)*

Figure 8.35 Diaphragm valve. *(Courtesy Liquid Systems, South Wales, UK.)*



(a)

(b)

Figure 8.36 Clamp valve. *[Courtesy (a) Crane Resistoflex Co., and (b) Xomox Co.]*

Figure 8.37 A steel-braided lined hose. *(Courtesy Crane Resistoflex Corp.)*

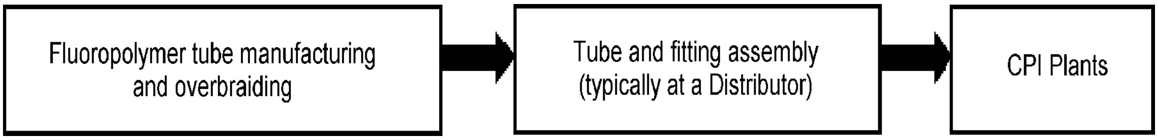


Figure 8.38 Supply chain for lined hoses.

8.6 Lined Expansion Joints

Expansion joints provide a flexible connection between components such as piping, pumps, and vessels to counter expansion, contraction, bending, torsion, and other operational forces such as vibration (Fig. 8.39). PTFE is the material of choice. Unlike hoses, an expansion joint is used either with a cover, usually elastomeric, or merely with rib supports between the convolutions. Expansion joints are available in two or three convolutes. The choice depends on the requirements of the installation.

PTFE convolutes are manufactured by either tape wrapping or the isostatic molding process.

8.7 Lining or Coating of Internals

Typical vessel internals are agitators, baffles, and dip tubes. Agitators and dip tubes are covered by fluoropolymer by either coating as explained in “Spray and Baked Coatings,” (Sec. 8.2.3) or by fluoropolymer sheets, typically shrink-wrapped PTFE. Baffles are covered with the lining or coating system used for the vessel. (Figs. 8.40–8.42)

8.8 Design and Fabrication of Vessels for Lining

In addition to fabrication of the vessels per codes such as ASME (American Society of Mechanical Engineers) Section V or API, there are additional requirements for lining. These have to do with the shape and quality of welds and edges. Figure 8.4 shows the requirement of weld quality. The guiding principle is that the lining should be applied over a smooth surface and over a high radius of curvature. Figure 8.43 and Table 8.8 show the design guidelines for vessels for lining.

8.9 Shop Versus Field Fabrication

There are special considerations for field fabrication. Field fabrication is needed for large diameter tanks, or where the removal of a vessel from a plant to line/reline is impractical.

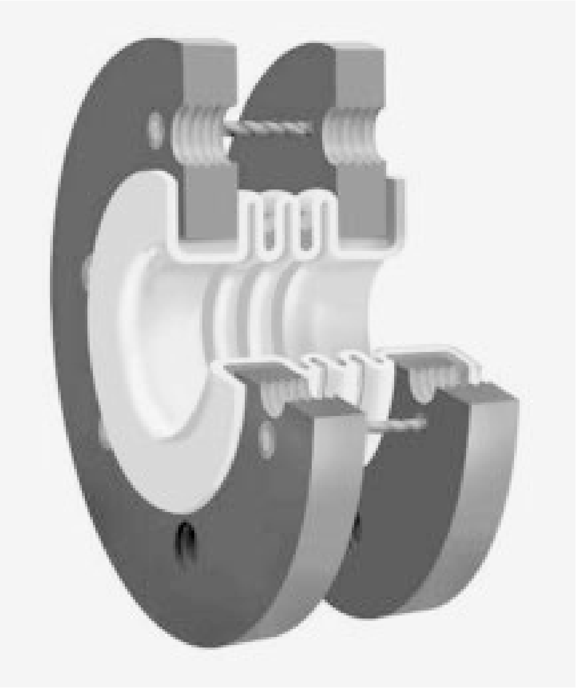


Figure 8.39 Cutaway of a typical expansion joint. *(Courtesy Edlon Company.)*

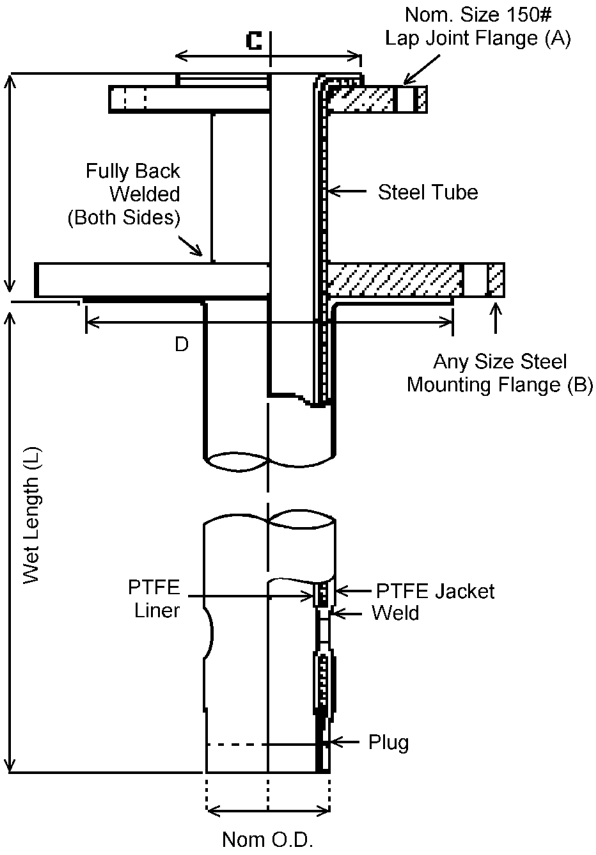


Figure 8.40 Schematic of a dip tube. *(Courtesy Edlon Company.)*

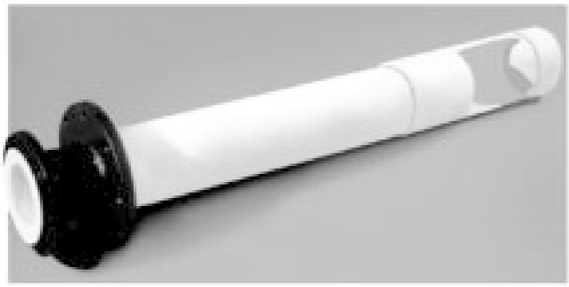
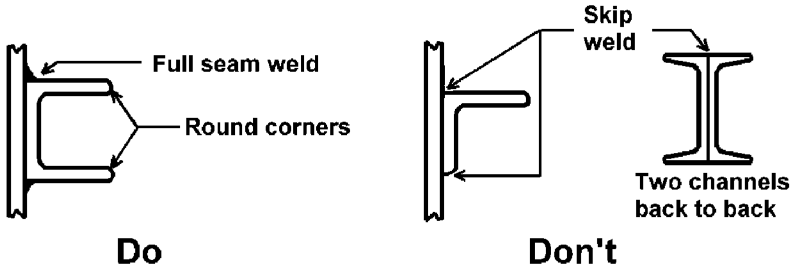
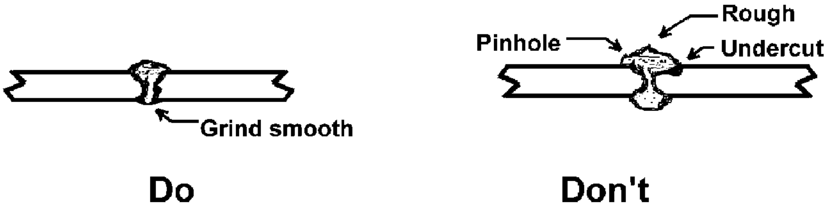


Figure 8.41 Dip tube. *(Courtesy Edlon Company.)*

Figure 8.42 Electrostatic powder application of an agitator. *(Courtesy General Plastics Corp.)*

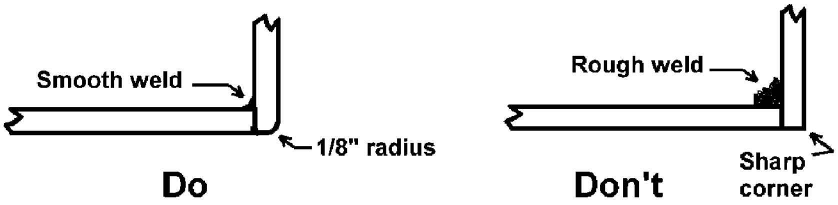


All construction involving pockets or crevices that will not drain or that cannot be properly abrasive-blasted and lined must be avoided.



All joints must be continuous solid welded. All welds must be smooth with no porosity holes, high spots, lumps, or pockets. Grinding is required to eliminate porosity, sharp edges, and high spots.

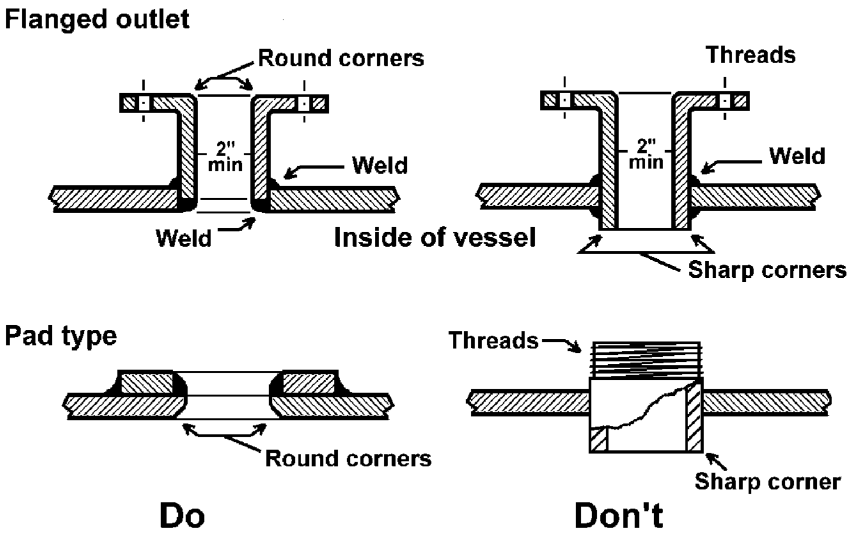
All weld spatter must be removed.



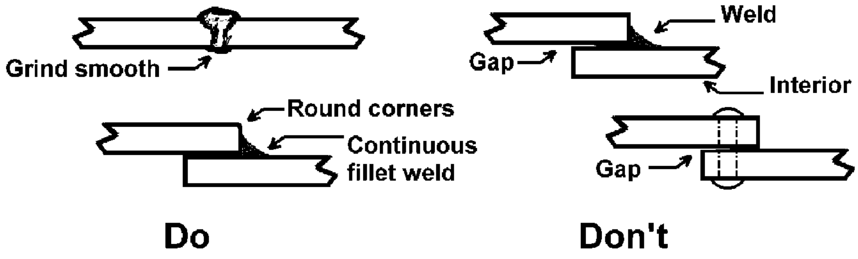
All sharp edges must be ground to a minimum 1/8" radius.

(Cont'd.)

Figure 8.43 Surface preparation for lined surface in vessels and internals. *(Courtesy Wisconsin Protective Coatings Co.)*



1. The outlets must be flanged or pad-type rather than threaded.
2. Within pressure limitations, slip-on flanges are preferred as the I.D. of the attaching weld is readily available for radiusing and grinding. If pressure dictates the use of weld neck flanges, the I.D. of the attaching weld is in the throat of the nozzle. It is therefore more difficult to repair surface irregularities such as weld undercutting by grinding.

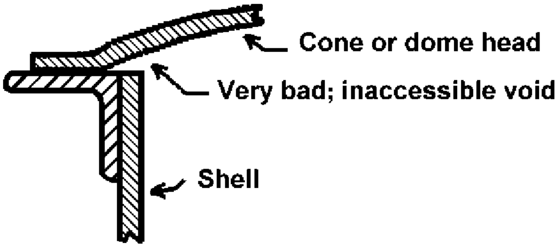


Butt welding should be utilized rather than lap welding or riveted construction.

Stiffening members should be on the outside of the vessel or tank.

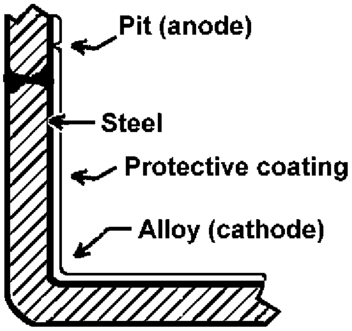
(Cont'd.)

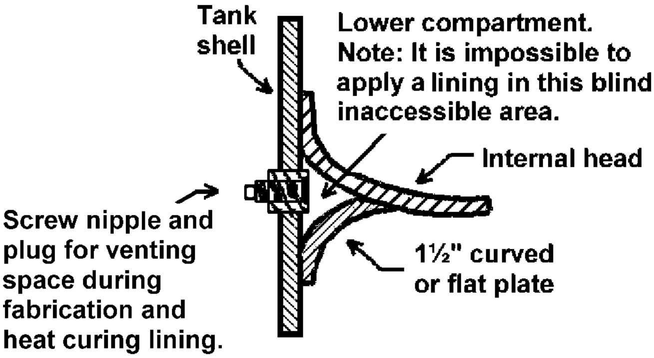
Figure 8.43 *(Cont'd.)* Surface preparation for lined surface in vessels and internals. *(Courtesy Wisconsin Protective Coatings Co.)*



Typical field storage tank head

Dissimilar metal (galvanic) corrosion will occur where an alloy is used to replace the steel bottom of a tank. If a lining is then applied to the steel and for several inches (usually 6"–24") onto the alloy, any discontinuity in the coating will become anodic. Once corrosion starts, it progresses rapidly because of the large exposed alloy cahtodic ares. Without the coating, galvanic corrosion would cause the steel to corrode at the weld area, but at a much slower rate. The recommended practice is to line completely the alloy as well as the steel thereby eliminating the possible occurrence of a large cathode to small anode surface.





A technique (detail of fabrication) to allow for good continuity of lining application for inaccessible areas for such as multi-compartment tanks.

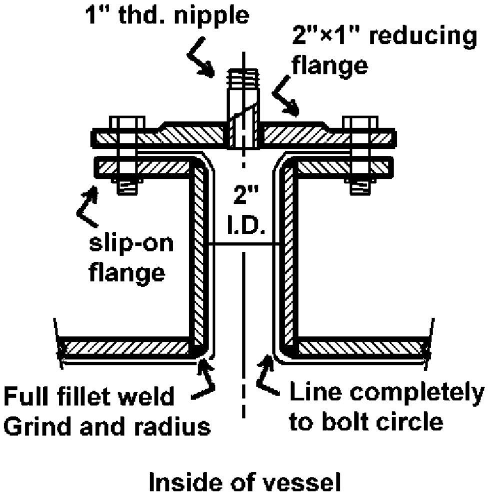


Figure 8.43 *(Cont'd.)* Surface preparation for lined surface in vessels and internals. *(Courtesy Wisconsin Protective Coatings Co.)*

Table 8.8. General Rules for Lining Surfaces

Description	Rubber Linings	Thin Plastic Linings	Glass-reinforced Plastic Linings	Sheet Linings*[3] (Adhesively Bonded) Proprietary
Butt welds permitted	Yes	Yes	Yes	Yes
Lap welds permitted	No	Yes	Yes	No
Welds must be flush	Yes	No	No*[1]	Yes
Welds must be smooth	Yes	Yes*[2]	Yes*[2]	Yes
Welds spattere permitted	No	No	No	No
Maximum nozzle length (in.)				
NPS 1	Not permitted	Not permitted	Not permitted	Unlimited*[4]
NPS 2	6	Not permitted	Not permitted	Unlimited*[4]
NPS 3	12	4	4	Unlimited*[4]
NPS 4	24	8	8	Unlimited*[4]
Minimum number of manholes in field-erected tanks	1	2 1	1 2	2
Grout tank bottom to minimize deflection or "oil-canning"	No	Yes	Yes	Yes
Use insulating or structural lightweight aggregate concrete for tank foundation	No	Yes No	No	No

*[1] Maximum height of weld bead shall be that permitted by ASME code or 1/8 inch, whichever is less. Welds shall blend into the adjacent surface so that the glass fabric saturated with plastic will be able to follow this contour and not leave a gap or air space.

*[2] Weld ripples are acceptable if they are shallow enough so that crevices and depressions can be cleaned by sandblasting to remove slag and oxides.

*[3] Generally 60 mils thick or greater.

*[4] Utilize insert linings. If loose linings are used for nozzles, venting is required.

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5. Martinez, F. V., and Huesmann, P. L. US Patent 6,518,349, assigned to DuPont (Feb. 11, 2003)
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7. Tatsushiro, Y., Takeshi, S., Shuhei, S., Masashi, W., US Patent 4,914,158 assigned to Daikin Industries, Ltd. (Apr. 3, 1990)
8. Perry, R. H., Green, D. W., Maloney, J. O., *Perry's Chemical Engineers' Handbook*, 7th Ed., McGraw-Hill Professional, New York (1997)

9 Operations and Maintenance

9.1 Operations

Operations of vessels and tanks require strict adherence to operating parameters of temperature, pressure, agitation, and flow rates. Any change, either deliberate or accidental, should be carefully recorded and evaluated for its effect on the lining system. Storage tanks are susceptible to differential exposures due to phase separation in multiphase liquids. Shutdown inspections should be carried out in a way that will not damage the lining. Ladders should have the legs protected by soft covers. Attention to safety is paramount. All established close chamber entry procedures should be followed.

Operations of piping should be carried out within the parameters set during the design stage. Close attention should be paid to temperature and pressure cycling since they affect the stability of the lining. Expansion joints should be installed within the deformation limits, i.e., axial stretch and compression, and axial misalignment and torsion. Hoses should be operated within the bend radius and with proper drying after chemical transfer.

9.2 Maintenance

Visual and other non-intrusive examinations are an essential part of maintenance. This typically begins with an inspection plan that outlines the type and frequency of inspection. The anticipated damage mechanism and the probability determine the type of inspection. The frequency is determined by the consequences associated with the damage. The consequences and the probability together constitute the risk-based inspection (RBI) strategy.

Broadly speaking, there are two categories of inspections. One is visual or assisted visual and the other is nondestructive examination. Where any of these examinations can be carried out with direct access to the surface and without shutting down the unit, the broad term “non-intrusive examination” is applied.

9.2.1 Visual Examination

Examination of a fluoropolymer surface visually shows the following types of degradation. They are based on visual manifestations only and do not refer to the underlying degradation mechanism. Underlying degradation mechanisms are covered in the failure analysis section (Ch. 10).

- Discoloration
- Blistering/bubbles/delamination
- Cracking
- Surface attack

Discoloration is usually due to permeation. Occasionally it is also due to surface reaction of the liquid and the polymer. Blistering, when within the polymer surface, is due to polymerization of the permeant. Localized separation of the polymer surface from the substrate will also manifest as blisters or, on a larger scale, bubbles. Bubbles, which continue to grow, will result in total delamination of the polymer surface. Blistering, or bubbling, is not a sufficient reason to discard the lining. Fluoropolymers are thermoplastic in nature and have high elongation. Blistering or bubbling becomes a serious problem only when it may be sheared off by the agitator. Cracking can result from overstressing or can be environmentally induced. Surface attack results from a chemical reaction between the chemical and the polymer.

9.2.1.1 Visual Inspections of Vessels

A true visual inspection of a vessel lining requires emptying of the vessel, cleaning it, and otherwise getting it ready for vessel entry. An alternative would be to use a remote visual inspection camera to view and record the images. All liners should be inspected for discoloration, cracked or separated weld seams, and blistering or bubbling. Blisters should be carefully recorded and monitored for growth. External ultrasonic examination of the metal substrate also needs to be carried out where corrosion of the metal substrate is suspected. Tapping for hollow spots is also a way of detecting blistering or bubbling. Spark testing should be avoided as much as possible and should be carried out only in the extreme case where a break in the lining is suspected, such as at the weld. Corners and flange flares should be closely examined for signs of tearing or cracking.

Vessel linings should be inspected within the first year of operation. The subsequent frequency of inspection is determined on the basis of the findings of the first inspection. The nature of the fluid being handled also plays a part in the decision.

9.2.1.2 Visual Inspection of Piping and Fittings

Visual inspection of lined piping involves looking at the flared ends for creep, cracking, and thinning of the flare face. Looking inside the pipe to detect evidence of collapse is necessary. Usually collapse can be a one-lobe or two-lobe type. External inspection for corrosion of the weep holes is important. Weep holes must be maintained free from pluggage. Elbows, T's, and crosses should be similarly inspected. Corrosion of flange bolts is evidence of leaks and should be addressed by use of gaskets, proper bolting using torque wrench, and using Belleville washers. In the case of traced and insulated piping, special attention should be given to corrosion under wet insulation.

9.2.1.3 Visual Inspection of Valves

Valves are very rarely removed from service for maintenance inspection. When the problem is detected it is usually too late. Therefore, where there is a past history of problems, it is a good idea to take the valve out of service for inspection.

The most common occurrence of failure in plugs, ball valves, and site glasses is cracking of liner. Butterfly valves typically fail by the degradation of the elastomer backing for the fluoropolymer liner. This is not possible to detect even after opening the valve. Diaphragm valves also fail due to degradation of the elastomer backing of the diaphragm.

9.2.1.4 Visual Inspection of Hoses

The most effective inspection of hoses is external where one looks for kinks, damage to the end fittings, and damage to the overbraiding. A boroscopic examination of the tube is very useful if it can be done regularly.

9.2.1.5 Visual Inspection of Expansion Joints

As in hoses, the most effective inspection of expansion joints is external where one looks for axial, angular, and torsional misalignment beyond the permissible limits. Obvious signs of bulging of the arches should be dealt with immediately by removing the unit and examining it internally.

9.2.2 Nondestructive and Destructive Examination

Metals respond to various nondestructive testing methods such as ultrasonic, magnetic particle, radiography, dye penetrant, and thermal imaging. Unfortunately, polymer-based materials do not respond to any of them. Efforts are under way to develop laser-based techniques, which can be used as a nonintrusive method of detecting flaws. However, the predominant method of nondestructive testing is still visual or assisted-visual such as using a remote access video camera. Looking for hollow spots, cracking, weld separation or rupture, and discoloration is the first step for evaluating real or potential damage. In cases where corrosion or other damage to the substrate is suspected, the thickness of the metal is ultrasonically measured from the outside. Direct access visual examination is subject to availability of the unit for internal examination.

Spark testing is technically a nondestructive test, although when carried out repeatedly, it can become destructive. Due to corona discharge, it can cause a treeing effect in the fluoropolymer leading to rupture of the lining. As far as possible, spark testing should be restricted to situations where a breach in the lining is suspected and confirmation is needed.

Destructive testing refers to a methodology where severe damage to the lining and the consequent damage to the substrate are suspected. In such cases, the lining is removed in a small area such as on a manway cover or a blind flange cover. Retention of adhesion, condition of the substrate, and condition of the lining system (adhesive, fabric backing, etc.) are examined. Destructive testing is usually carried out on surfaces that are easily replaceable such as the blind flange or manway covers. A new manway or blind flange is easily made up. This strategy works only once, unless there are multiple blind flanges available to track future changes. In some extreme cases, the lining on the vessel surface is removed to make similar examinations followed by weld repairs.

9.2.3 Non-Intrusive Examination

Unlike metals, which respond to various techniques, there are no methods of determining conditions of the fluoropolymer lining from the outside. This remains a major limitation in the use of fluoropolymers to replace metals. Initiatives are under way to address this gap at the research and development level.

9.2.4 Risk-based Inspection (RBI) Strategy

Determination of the type and frequency of inspection on the risk is what risk-based inspection (RBI) is all about. Risk is quantitatively determined by the probability of failure and the consequences thereof. This implies that the type of failure (blistering, cracking, etc.) and its rate are known through experience, testing, or other information. The owner, on the basis of the contained liquid, its amount, and its hazardous nature, determines the consequences. In almost all cases, fluoropolymers are used for corrosive and hazardous chemicals, and the consequences of failure are quite severe. This has led to the general guidelines for type and frequency of inspections shown in Table 9.1.

Table 9.1. Type and Frequency of Inspection of Fluoropolymer Lined Systems

	Ambient Temperature	**Temperature < 250°F**	**250 < Temp < 350**	**Tempperature and Pressure Cycling at Any Temp**
Vessels	First inspection after the first year of operation, thereafter as needed Spark test only if essential.	First inspection after the first year of operation, thereafter as needed External UT optional Spark test only if essential.	First inspection after the first six months of operation, thereafter every six months or as needed External UT recommended Spark test only if essential	Every six months External UT highly recommended Spark test only if essential
Hoses	Hydrotest every six months Replace as needed	Replace every six months		
Expansion joints	Visually inspect externally for exceeding misalignment specification Correct or replace as needed	Internal inspection every year Replace or upgrade as needed		
Piping	External inspection for flange flare and weep holes Internal inspection when available			
Pumps	Consider installed spare			

9.3 Repairs

Repairs to a damaged system are possible if the nature and extent of the damage permit it. Piping, expansion joints, valves, and pumps can be considered as maintenance items and therefore simply replaced rather than repaired. Vessel linings are a different matter. Replacing the lining is time-consuming and very expensive. Repairs, therefore, are carried out by locally welding or replacing an area with a patch. In both cases, repairability has to be determined.

Repairability is determined by welding a small bead on the lining at a location such as a manway cover or a blind flange. Adhesion of the weld bead is determined and any signs of foaming or other reaction between the heat input and the chemicals trapped in the fluoropolymer are noted. Once satisfied, weld repair can be carried out successfully. The repair area is then inspected by spark test.

10 Failure Analysis

10.1 Introduction

Failure of parts, irrespective of plastic type, is an inevitable fact of the operation of chemical plants. Fluoropolymers are no exception in spite of their excellent chemical, thermal, and mechanical properties. These plastics form the processing surfaces of equipment where they are exposed to the most aggressive and corrosive chemicals. The repeated exposure of fluoroplastics to these chemicals, in addition to other factors, can affect the integrity and surface quality of the parts. The chapters dealing with properties and part fabrication techniques of fluoropolymers should be consulted extensively. An understanding of the limitations of fluoropolymers and flaws created by fabrication methods is required for successful failure analysis of parts.

This chapter focuses on some of the techniques for determining the causes of failure of fluoropolymer parts. An approach for failure analysis has been proposed that includes conducting analytical tests on the specimen of interest. The results are then put together to create a composite picture of the damage to the part. The root cause(s) of the failure can be determined from the sum total of the analytic data and other observations. Inevitable gaps exist even in the most thoroughly conducted studies of failure. These gaps will have to be filled by sound judgment. It would be cumbersome and time consuming to attempt to eliminate all factual and analytic gaps and replace them with data. A discussion of the part manufacturing flaws is presented because many of the part failures encountered in operations begin as defects in the early stages of manufacturing.

10.2 Part Failure

Generally, parts fail for four reasons: incorrect design, inadequate material selection, fabrication flaws, and process excursions where part capability is exceeded. Here, the term *design* refers to the geometric shape of parts in contrast to the common use of the word design which is meant to include material selection and properties. This chapter deals with the determination of the causes of failures, assuming that the parts have been designed adequately. Analysis of the design of parts can be studied by referring to sources such as the *Mechanical Engineer's Handbook*,[1] which not only contains a great deal of information but numerous helpful references.

In chemical handling processes, parts are exposed to mechanical forces and chemicals. Fluoropolymer parts can fail for three reasons: mechanical, chemical, and physical changes, or their combinations. Failure often initiates at the location of fabrication flaws that arise from problems during manufacturing of the fluoroplastic part. These flaws often shorten the useful life of the part in service or form a starting point that can evolve into the failure point of the part.

Mechanical failures occur when the part is exposed to some type of force that exceeds its capability. A part may be exposed to three different types of forces: tensile, compression, and vacuum-generated stresses. Many processes require super- or subatmospheric pressure. In a fluoropolymer-lined vessel or a stand-alone vessel at elevated pressure, the walls are subjected to tensile stress. Compression stress develops in parts such as seals and gaskets where force is applied to the part, for instance, by placing it between bolted flanges. Vacuum can be a permanent or transient feature of a process and subjects a part to complex forces which could be a combination of tensile and compression.

Chemical changes occur when a fluoroplastic part is exposed to the few compounds and elements that can degrade them. Chemical attack over time can result in changes in surface or bulk composition, and a loss of mechanical properties such as tensile or burst strength. The loss of properties is because of a reduction in molecular weight or mass loss of the part. Degradation can introduce impurities into the process stream in the extreme case when massive chemical degradation takes place.

Physical changes are defined as those caused by permeation (or diffusion) of reaction components through the part. Fluoroplastics can be permeated, to varying extents, by different chemical compounds. The outcome can be swelling, formation of blisters, or localized polymerization that all result in the expansion of parts' volume. Crystallinity of the fluoroplastics, presence of voids in the part, and solubility of the substance in the fluoropolymer are some of the key variables of physical changes.

Break or fracture can take place due to *fatigue* or *impact*. Fatigue occurs slowly over a long period of time, often at loads well below the ultimate strength of the polymer. Impact fracture happens when a large load is abruptly applied to a part that can not absorb all the energy, thus it breaks. It is important to classify the type of fracture when examining failures. Ductile fatigue cracks occur in plastics that are easy to deform (or strain). This is in contrast to brittle fatigue cracks which occur in hard-to-deform polymers. The ductile cracks are elongated, folded, and usually do not have sharp edges. Brittle cracks often have sharp jagged edges such as one would observe in broken glass. A number of factors, such as the nature of polymer, nature and amount of additives and fillers, temperature, load, and strain rate, can change the nature of the crack from one type to the other. Fluoropolymers generally fail in the ductile mode except at extremely low temperatures. Ductility of fluoroplastics increases with an increase in the fluorine atom content of the polymer.

Both organic and inorganic compounds can permeate fluoroplastics. For example, perchloroethylene can swell PTFE, the extent and rate of which is dependent on temperature, pressure, and time. Monomers like styrenics and butadiene can permeate, swell the polymer, and polymerize in the void space created by swelling. Water in steam form can cause blister formation, especially when parts are exposed to thermal cycling. Temperature extremes experienced between steam and condensate result in the formation of blisters. Inorganic acids can also permeate fluoroplastics; some, like nitric acid, can form highly oxidizing mixtures and degrade fluoropolymers. Table 10.1 shows examples of defects and their associated causes. Temperature, pressure, and time are variables that expedite and intensify the permeation phenomenon. This means the symptoms of permeation may not be observable until the process has been operated for a period of time.

The outcome of part failures that result in release of process fluids falls in two categories: emission and corrosion. Emission causes environmental pollution, potential safety hazard to operating personnel, and economic loss. Corrosion usually occurs when corrosive acids and bases are released and contact equipment. Organic solvents could be corrosive to nonmetallic material, especially plastics. The consequences of long-term corrosion could include equipment damage, environmental pollution, health hazards, and aesthetic damage.

A variety of parts are made using fluoroplastics. A list of significant parts is presented in Table 10.2. Methods of manufacturing vary for producing parts, although some parts can be fabricated by more than one technique and from more than one fluoropolymer. Figures 10.1 through 10.4 show examples of parts made (or lined) with fluoroplastics.

10.3 Defect Analysis

Analysis of a defective part should ideally aim at determining the root cause of failure. Root cause analysis is based on the common causes of failure:

1. Part design
2. Material choice
3. Processing factors
4. End use conditions

Part analysis can be accomplished by different approaches but should always begin with visual inspection. The methodology presented in this book begins with visual observation and proceeds in an escalating manner; that is, the simpler analyses are to be conducted prior to more complex techniques. More

Table 10.1. Defects and Possible Causes

Defect	Possible Causes
Swelling	Sorption, permeation
Blistering	Permeation, localized polymerization
Discoloration	Thermal degradation, localized polymerization
Cracking	Stress, environmental stress cracking
Deformation	Creep (cold flow)
General degradation	Oxidation, chemical attack

Table 10.2. Typical Material and Fabrication Methods for Fluoropolymer Parts

Part	Fabrication Technique	Fluoroplastic Type
Lined pipe	Isostatic molding, melt extrusion, paste extrusion	PTFE, PVDF, PFA, ETFE, ECTFE
Vessels	Skived sheet lining, powder coating	PTFE, PVDF, PFA, ETFE, ECTFE
Pumps	Injection molding, machining stock shapes	PVDF, PFA, PTFE
Valves	Injection molding, transfer molding, thermoforming	PTFE, PVDF, PFA, ETFE, ECTFE
Hoses and expansion joints	Paste extrusion, melt extrusion	PTFE, PFA, FEP, ETFE
Seals and gaskets	Automatic molding, compression molding	PTFE
Column internals	Injection molding	PVDF, PFA, ETFE, ECTFE

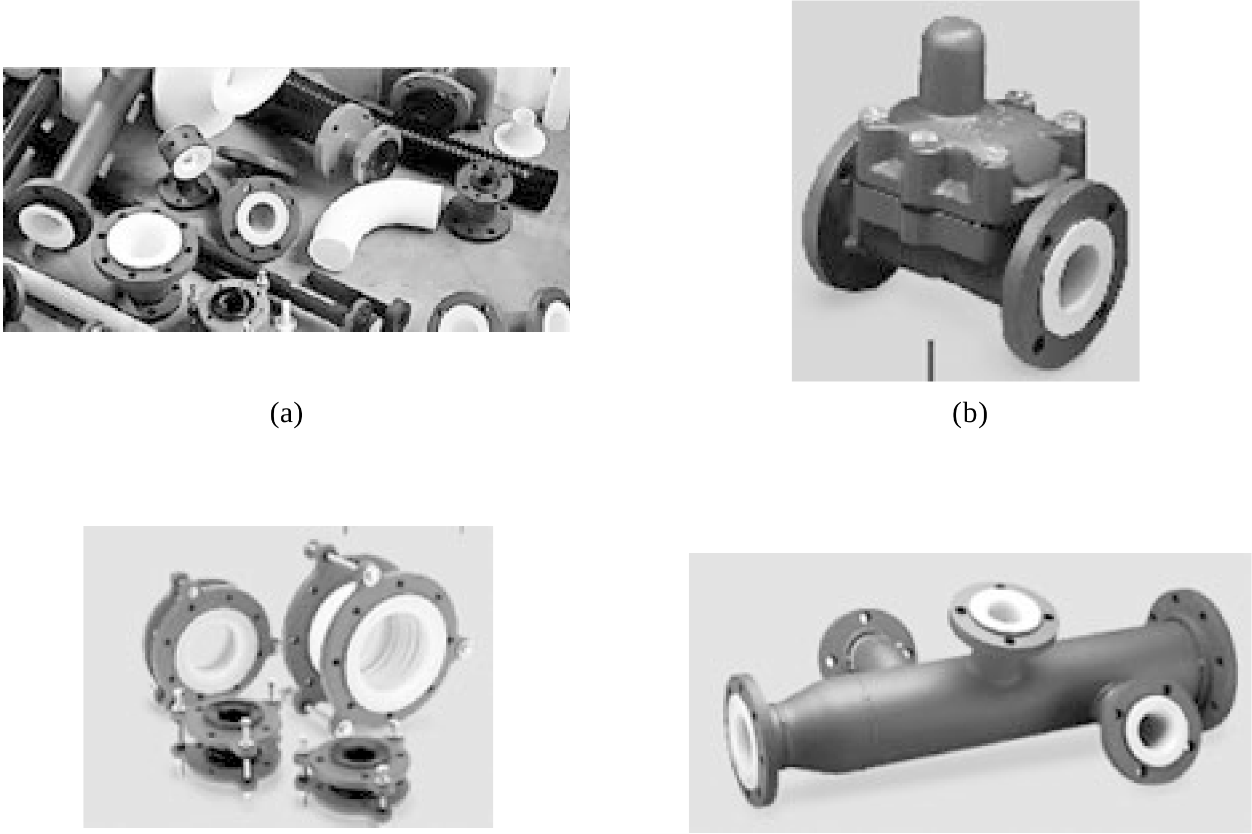

(a) (b) (c) (d)

Figure 10.1 Examples of fluoroplastics: (*a*) lined-pipe and liners, (*b*) valve, (*c*) expansion joints, and (*d*) a complex tee. *(Courtesy of Crane Resistoflex Corp.)*

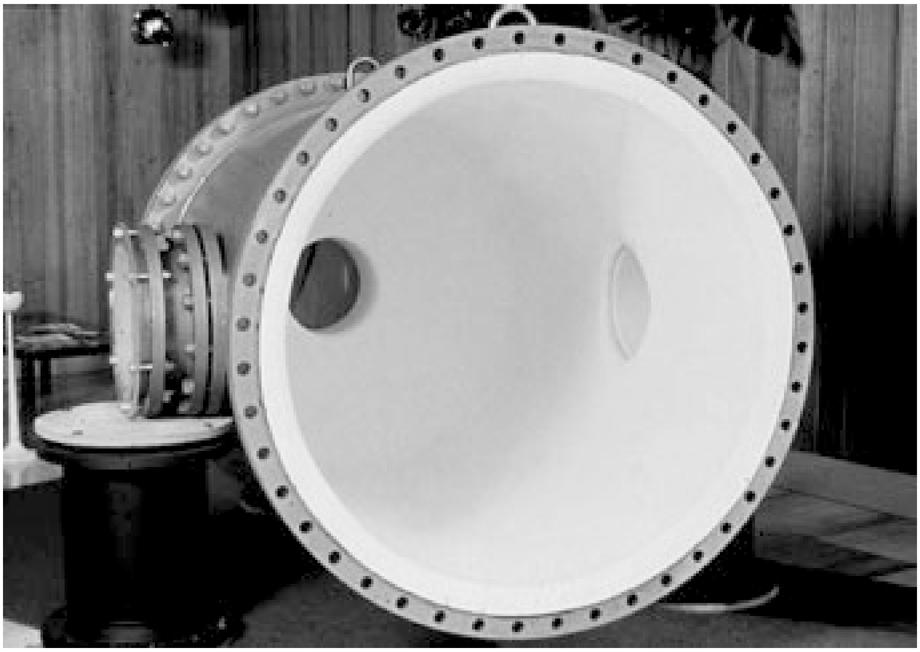


Figure 10.2 A chemical tank lined with skived and welded polytetrafluoroethylene. *(Courtesy of DuPont Co.)*

Figure 10.3 Injection-molded fluoroplastic tubing, tee, elbow, and valves. *(Courtesy of DuPont Co.)*

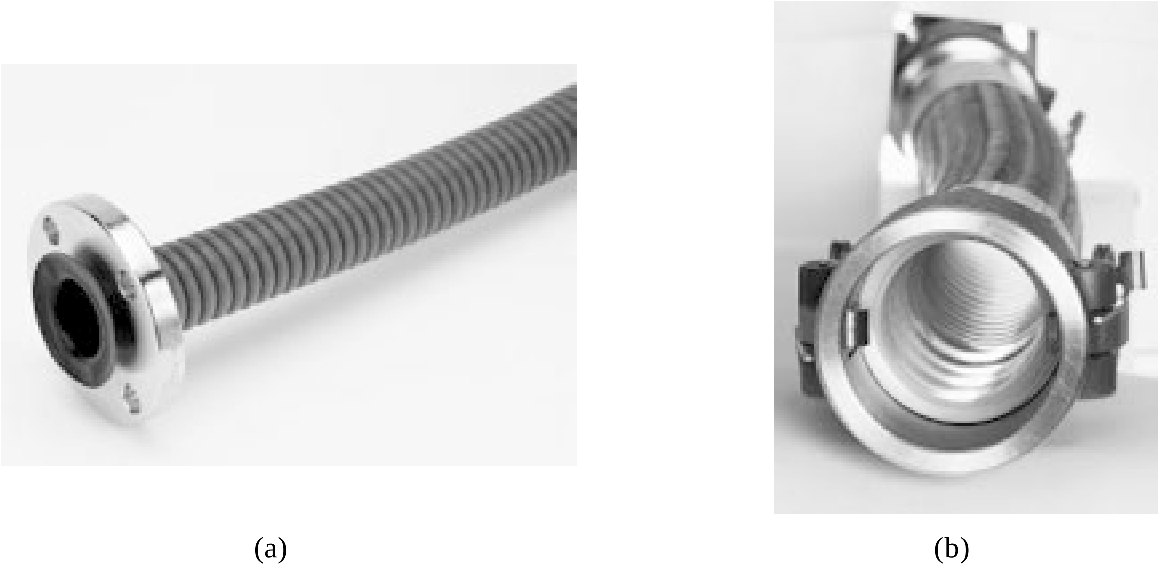

(a) (b)

Figure 10.4 PTFE hose: *(a)* convoluted, and *(b)* convoluted and braided. *(Courtesy of Crane Resistoflex Corp.)*

sophisticated analyses are usually more expensive, less available, and often require highly skilled expertise for interpretation of their results. It is advisable to resort to a simpler analytic technique to analyze defects.

Figure 10.5 shows a schematic of the methodology for defect analysis. The first step is visual and microscopic inspection. Optical microscopy (OM) and scanning electron microscopy (SEM) supplement the observations made by naked eyes. Small defects, depending on the size, should be viewed by OM or SEM. Table 10.1 gives some typical types of defects and the underlying phenomenon that can cause the occurrence of each defect. There are a number of other methodologies that have been utilized by government agencies or the industry to analyze defects and failures.

The question is “What are the visual signs that one could look for to recognize the type of defect in order to classify them?” (Figure 10.5.) Table 10.3 describes some of the observable clues that each class of defect exhibits. The corresponding figures (Figs. 10.6 through 10.10) elucidate the general appearance of defects graphically. The visual clues collected from the appearance of failures can greatly aid in the job of finding the cause of failure as the analyst gains experience.

The first consideration in defect analysis is whether the part has been handled after removal from service. Handling can alter the appearance or contaminate it to the point that either failure analysis could not be conducted or the root cause could not be determined. Surface analysis techniques are sensitive to handling and cannot distinguish between the changes caused by the failure and contamination. The best practice is to minimize handling the part and keep track of the history of the part. There are certain steps that frequently have to be taken such as decontamination of parts that have been in contact with corrosive, toxic, or flammable chemicals. A log should be considered to keep track of what has been done to the part, which may help explain any unforeseen consequences of part handling.

After visual inspection and prior to applying the rest of the methodology (Fig. 10.5), the available information must be reviewed. The objective is to determine whether failure has occurred as a result of exceeding any of the part and/or material capability during the service. It is important to identify the material from which the part has been made. A review of the properties of the part and a comparison with the service conditions will reveal whether the basic capabilities of the material have been exceeded; the properties include chemical, thermal, physical, mechanical, and electrical. For example, polytetrafluoroethylene (PTFE) degrades as a result of lengthy exposure to temperatures above 400°C. Properties such as tensile strength, flex life, and impact strength deteriorate, thus providing clues about, for example, a mechanical failure such as rupture or stress cracking. Exposure of polyvinylidene fluoride (PVDF) to strong amines and bases, especially at elevated temperatures, may result in part failure because of the chemical attack on PVDF by these compounds.

Other examples include operations that exceed the design of a part. For example, failure of a weld line that met the design criteria indicates insufficient strength at the weld line. A redesign may be required including increasing the *weld factor*[2] and replacement of the plastic.

In the cases that one can identify that material or part design limits have been exceeded, assignment of cause to the failure is relatively simple. The effects of excess condition(s) on the part and the material can be determined by following the methodology in Fig. 10.5.

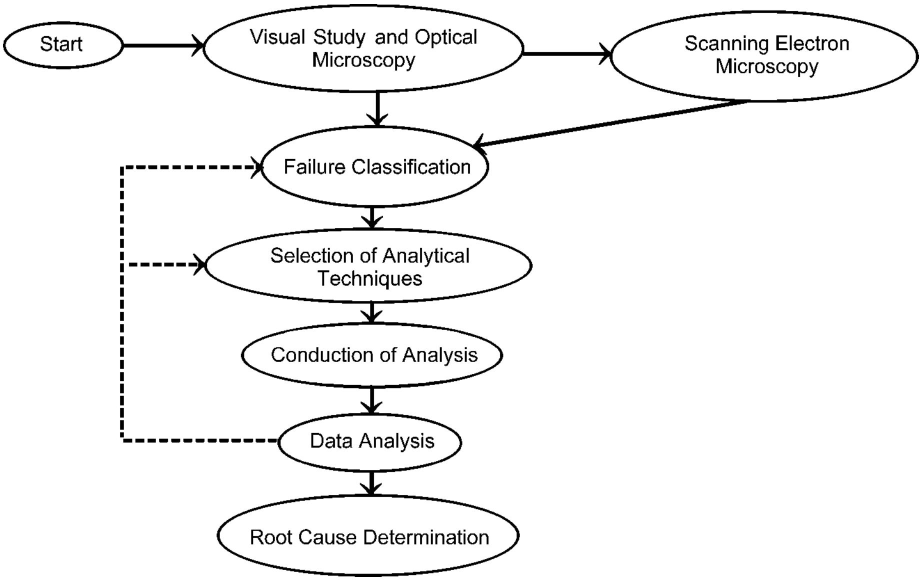


Figure 10.5 Methodology for defect analysis.

Table 10.3. Observable Clues of Different Classes of Defects

Defect Class	Observable Clues	Figure
Swelling	General enlargement of the part	10.6
Blistering	Formation of small or large blisters on the part surface	10.7
Discoloration	Darkening of part color – yellow to brown to black for white parts	—
Fracture (Cracking)	Surface or volume crack	10.8
Break	Part divides into two or more pieces	10.9
Deformation	Enlargement of one or more dimensions of parts	10.10
General Degradation	Combinations of different classes of defects	—

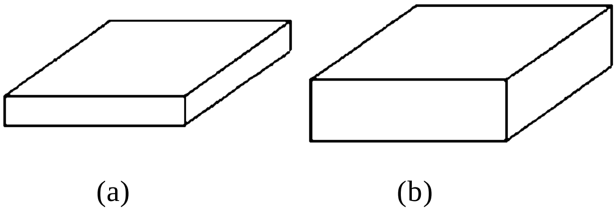


Figure 10.6 Appearance of a part *(a)* before, and *(b)* after swelling.

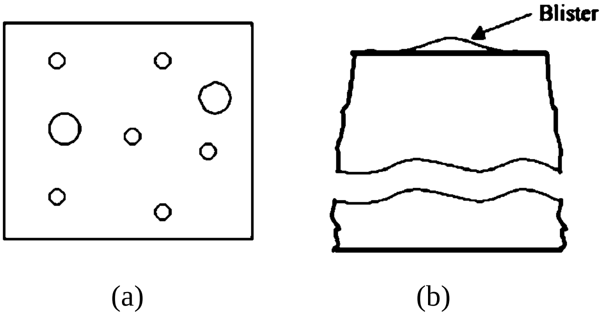


Figure 10.7 View of a blistered surface: *(a)* top, and *(b)* cross section.

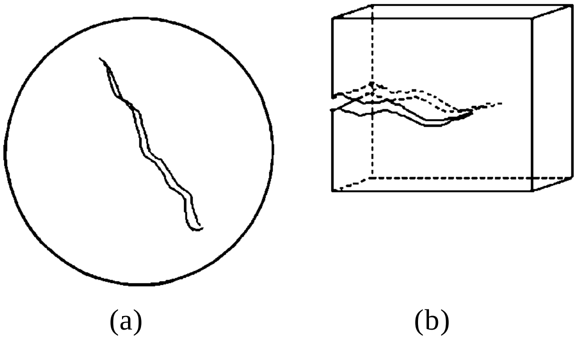


Figure 10.8 Schematic diagram of *(a)* a surface crack, and *(b)* a mass or volume crack.

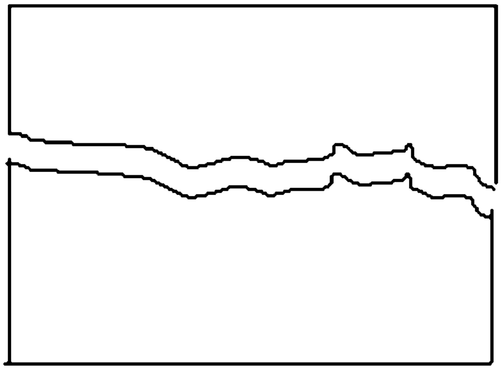


Figure 10.9 Depiction of a part fractured into two pieces.

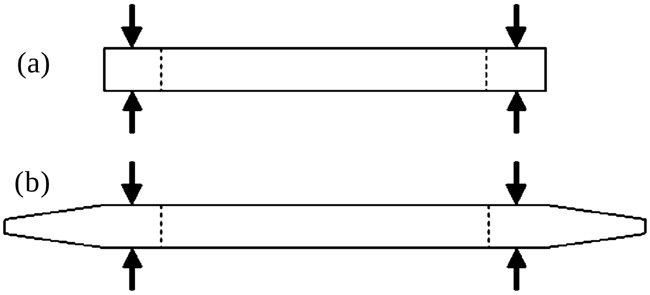


Figure 10.10 Example of deformation of a gasket under compression force: *(a)* at the onset of force application, and *(b)* after sufficient elapsed time.

10.4 Application of Failure Analysis Methodology

The methodology in Fig. 10.5 is a simplified sequence of steps for the analysis of fluoroplastics failure. There are other schemes for failure analysis such as those used by General Electric Company and the United States Air force.[3] These schemes all aim at guiding the analysis through logical and escalating analytic steps, utilizing more complex and costly techniques as further steps need to be taken to determine the cause of the failure. The test methods need to be capable of differentiating between the defective and acceptable areas. It does not need to be a complex or expensive measurement because simple tests often provide the most useful results for solving problems.

The goal of failure analysis is to characterize the fluoroplastic at the point of defect to compare with material characteristics in unaffected areas. The latter is referred to as "control," which can also include the basic properties of the fluoropolymers where the effects of fabrication and service have been taken into account. Table 10.4 presents general tests that have been recommended for the characterization of plastics in failure analysis. Table 10.5 provides examples of specific methods of analysis.

A fundamental requirement for successful use of this methodology to determine the root cause of failures is complete familiarity with material properties, part fabrication, and process fluids, conditions, and excursions. A majority of the failures involve one or more variables related to the process

The pure scientific approach in failure analysis is to proceed without any presupposition of a possible cause. Accordingly, the analyst would make various measurements to collect sufficient data to analyze and then develop a cause for the failure. This approach is preferable whenever possible. In the majority of practical situations, time and resources do not allow the analyst to follow the pure scientific approach. The analyst should then develop a list of potential causes that could result in the observed defect. The most likely cause(s) should then be selected based on all the available information.

Table 10.4. Plastics Characterization Test Methods

Category	Characterization
Material Composition	1. Analysis of composition of the polymer and additives 2. Degree of crystallinity, molecular weight, molecular weight distribution, and degree of fusion 3. Identification of contaminants at the failure point 4. Surface analysis
Physical Properties	1. Density/specific gravity 2. Melting point 3. Glass transition temperature 4. Melt viscosity/melt flow rate (MFR)
Mechanical Properties	1. Plastic properties 2. Tests on the failed material, e.g., tensile and environmental stress crack resistance (ESC)
Chemical Resistance and ESC	1. Chemical resistance of plastics 2. ESC
Non-destructive Evaluation	1. Determination of failure location 2. Acoustic and ultrasonic methods
Microscopy and Fractography	Determination of origin and direction of fracture, e.g., optical microscopy (OM), scanning electron microscopy (SEM)
Stress Analysis	1. Effect of residual stresses 2. Effect of external stresses

Table 10.5. Major Characterization Test Methods for Fluoropolymers

Characteristic	Examples of Test Methods
Analysis of Composition of the Polymer and Additives	Infrared Spectroscopy (IR), Energy Dispersive X-Ray Spectroscopy (SEM-EDX)[1], Mass Spectrometry (MS), Gas Chromatography (GC), Nuclear Magnetic Resonance NMR)
Fluorine Content	
Solubility	
Degree of Crystallinity, Molecular Weight, Molecular Weight Distribution and Degree of Fusion	Differential Scanning Calorimetry (DSC), Gel Permeation Chromatography (GPC)
Identification of Contaminants at the Failure Point	IR, EDX, X-ray Fluorescence
Surface Analysis	Attenuated Total Internal Reflectance (ATIR), EDX, Rutherford Backscattering (RBS), Electron Spectroscopy for Chemical Analysis (ESCA) also known as X-ray Photoelectron Spectroscopy (XPS), Secondary Ion Mass Spectrometry (SIMS), Ion Scattering Spectroscopy (ISS)
Thermal Stability	Thermogravimetric Analysis (TGA)
Density/specific gravity	ASTM D792 and D1505
Refractive Index	ASTM D542 (using Abbe refractometer)
Melting point	DSC, ASTM D4591, D3418
Glass transition temperature	DSC, ASTM D4591
Melt viscosity/melt flow rate (MFR)	ASTM D3307, D2116, D3159, D1238
Mechanical Properties:	ASTM Test:
Tensile	D4894, D638
Compressive	D695
Flex Modulus	D790
Flex Life	D2176, D671
Chemical Resistance of Plastics	ASTM D543, D2299
Environmental stress crack (ESC) resistance.	Simulate end-use conditions (ideal), ASTM D1693, (Ethylene Plastics), ISO 4600, ISO 6252, ISO 4599
Determination of Failure Location	Optical Microscopy (OM), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM).
Determination of Origin and Direction of Fracture.	OM, SEM, TEM
Effect of Residual Stress.	ASTM D1939
Deformation-under-load	ASTM D621[2], Dynamic Mechanical Analysis (DMA)

[1] Both analyses are usually conducted in conjunction with scanning electron microscopy (SEM).

[2] This method is obsolete but is useful for comparing different plastics.

The analyst can then pursue an experimental plan to measure characteristics of the material that may have been affected by the proposed cause(s). It is vitally important that the failure analyst avoid pursuing a proof of a presupposed cause. Instead, the data obtained from the measurements should be reviewed carefully to look for clues that are incompatible with the presupposed cause and may point to other potential causes. An example will help clarify this point.

Let's assume a fluoroplastic part used in a relatively high-temperature process has failed due to microcrack formation. Examination under an optical microscope reveals the presence of dark spots on the surface at the defective location. Energy dispersive x-ray, in conjunction with scanning electron microscopy (these techniques are described in Sec. 10.4.2), reveals the identity of the dark spots as metal oxides. The analyst could reasonably assume that catalytic degradation of the plastic by the metal oxides has reduced the mechanical strength of the plastic part, resulting in cracking. Suppose that surface analysis by ESCA (electron spectroscopy for chemical analysis, see Sec. 10.5.1) shows little evidence of oxidation or defluorination which are the expected results of degradation of a fluoroplastic. The analyst should reasonably question the starting "theory" of catalytic oxidation and look in a different direction. Measurement of the melt flow rate (MFR) showed a significant increase, most likely as a result of overheating during part fabrication. The dark spots came from the contact of a metal part, forming a hot spot on the fluoroplastic part. The surface of the part softened because of the high MFR, resulting in crack formation under stress.

Selected testing and analytic techniques (Table 10.5) are briefly described in the following sections. An understanding of each method is necessary for the proper application and interpretation of results. Some of these techniques are specific to non-fluorinated thermoplastics and may require modification when applied to fluoropolymers. Examples of the results of applying some of these techniques to fluoroplastic are presented to illustrate their use. The reader is referred to ASTM methods for additional details regarding the measurement of properties and characterization of the plastics.

10.4.1 Infrared Spectroscopy

In infrared spectroscopy (IR), a sample is subjected to electromagnetic radiation in the infrared region of the spectrum. Certain specific wavelengths are absorbed by a sample, depending on the nature of the chemical groups present. These wavelengths are defined by a wave number (cm^{-1}) which is obtained by dividing the number 10,000 by the wavelength in microns. The ranges of various wave numbers are given in Table 10.6. Absorbance is defined per Eq. (10.1) and varies from 0 (100% transmission) to 100% (0% transmission). Absorbance is related to concentration of the absorbing species by Beer's law [Eq. (10.2)].

Eq. (10.1) $$\text{Absorbance} = \log \frac{100}{\%\ \text{transmission}}$$

Eq. (10.2) $$\text{Absorbance} = Kcl$$

where K is a constant that is occasionally called the *extinction coefficient*, c is the concentration of the absorbing species, and l is the sample thickness.

Equation (10.2) can be used to determine the concentration of a compound in a solution if the value of K is known for that compound. Chemical bonds, such as C–C, C–F, etc., absorb different amounts of infrared energy over various wavelengths. Absorption patterns vary from sharp to broad for different bonds. Peak IR absorption wavelength (wave number) is a characteristic of chemical bonds. Absorption over a range of wavelengths called the infrared spectrum is a fingerprint characteristic of an organic material. Qualitative identification can be achieved

Table 10.6. Definition of Electromagnetic Wave Ranges

Definition of Range	Wave Number (10^4 cm^{-1})	Wavelength (µm)
Ultraviolet	5–2.5	0.2–0.4
Visible	2.5–1.42	0.4–0.7
Near IR	1.42–0.4	0.7–2.5
IR	0.4–0.02	2.5–50
Far IR	0.02–0.0012	50–830

by obtaining and analyzing the IR spectrum of a material. Figures 10.11 through 10.16 show the characteristic IR spectra of a few fluoropolymers.

Infrared spectra can also be obtained by reflecting the IR beam on the surface of a sample. This technique is applied when it is not possible to obtain an IR spectrum by a transmission technique. Attenuated total reflectance (ATR) also known as ATIR (attenuated total internal reflectance) is based on multiple internal reflectance of the IR beam on the sample surface using a high refractive index crystal (e.g., thallium bromo-iodide). The IR beam is entered into the crystal at an angle and after about 25 internal reflections (5 cm), a spectrum similar to that of transmission is obtained. The sample is in tight contact with both surfaces on the crystal as seen in Fig. 10.17.

Modern infrared spectrometers use Fourier Transform for the calculation of results. The method is called Fourier Transform Infrared Spectroscopy, abbreviated FTIR.

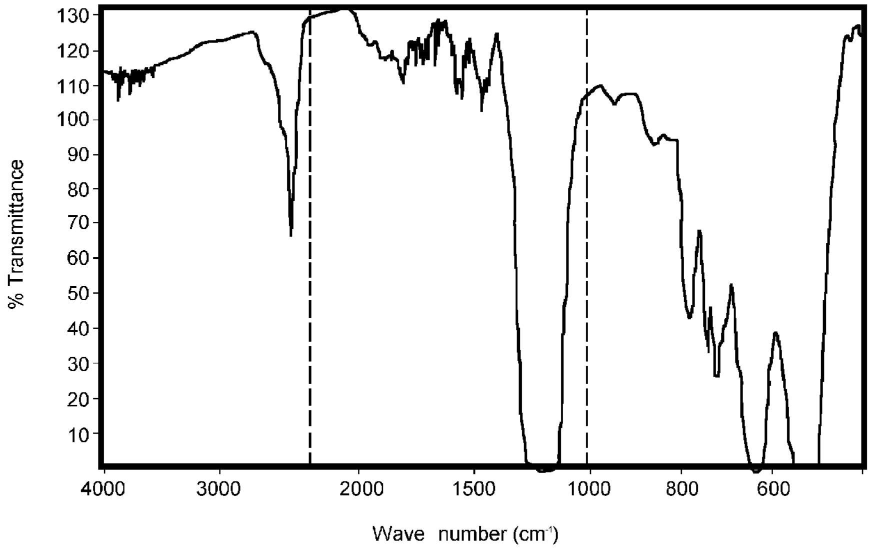


Figure 10.11 IR spectrum of PTFE.

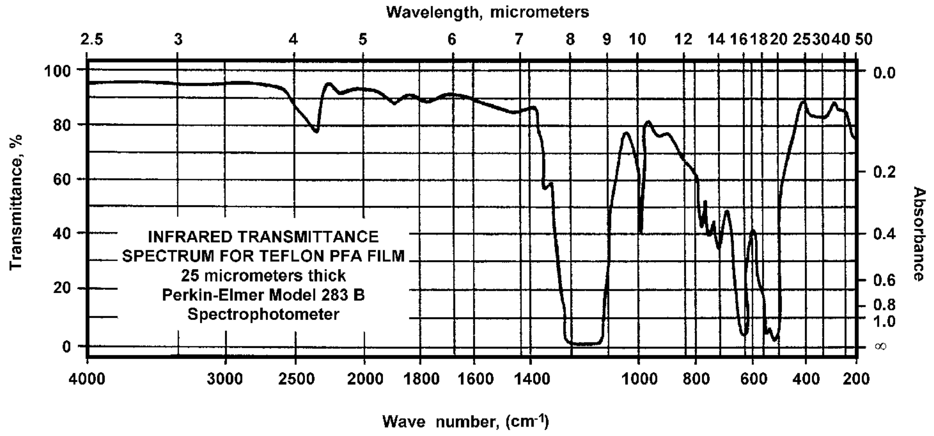


Figure 10.12 IR spectrum of PFA.[4]

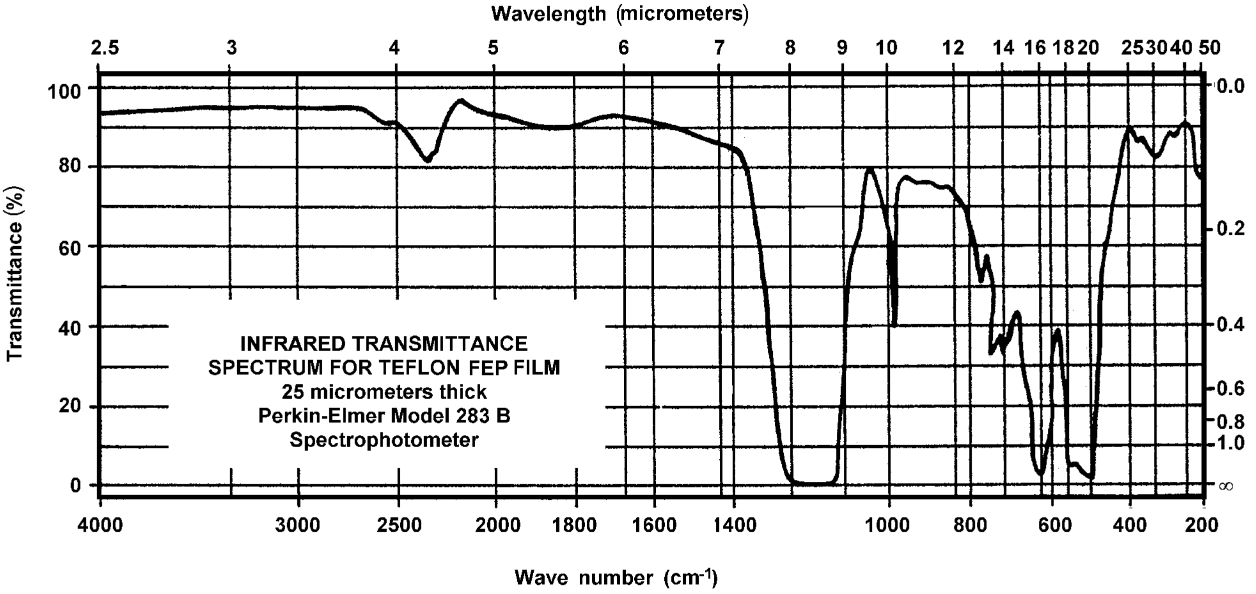


Figure 10.13 IR spectrum of FEP.[4]

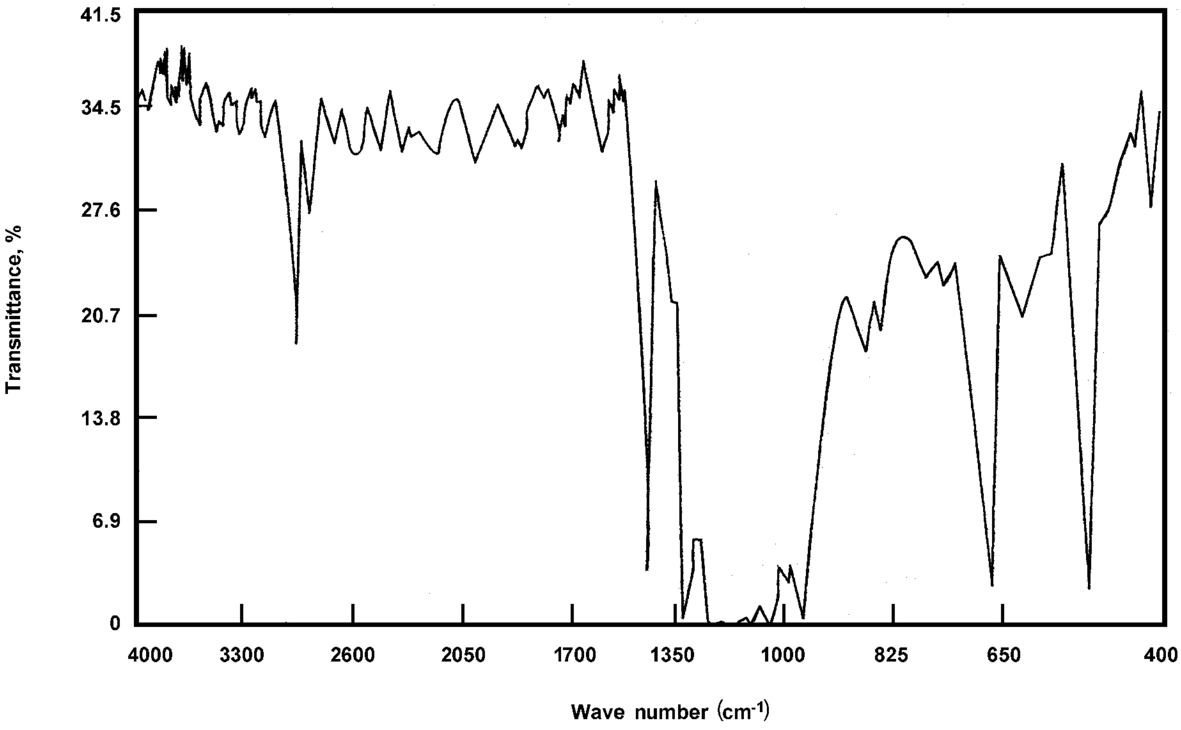


Figure 10.14 IR spectrum of ETFE.[5]

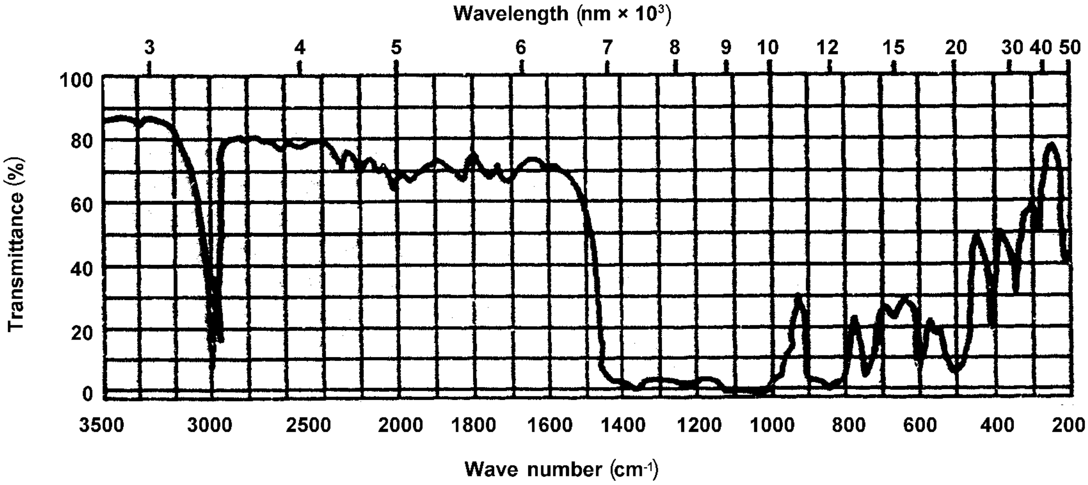


Figure 10.15 IR spectrum of PVDF.[6]

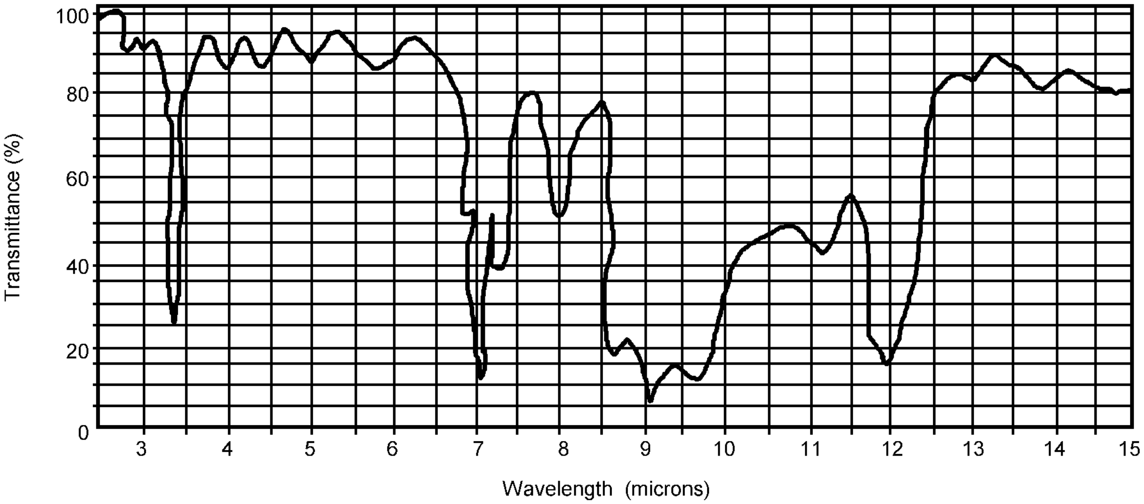


Figure 10.16 IR spectrum of PVF.[7]

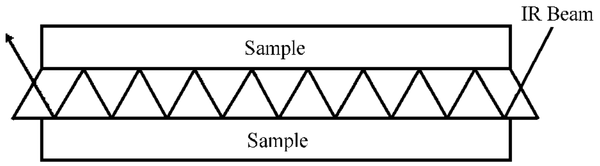


Figure 10.17 Schematic of sample configuration relative to reflective crystal in attenuated total reflectance IR.

10.4.2 Electron Microscopy Techniques

10.4.2.1 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a useful technique for the analysis of plastic surfaces. It involves a finely collimated beam of electrons that sweeps across the surface of the specimen being analyzed. The beam is focused into a small probe that scans across the surface of a specimen. The beam's interactions with the material results in the emission of electrons and photons as the electrons penetrate the surface. The emitted particles are collected with the appropriate detector to yield information about the surface. The final product of the electron beam collision with the sample surface topology is an image (Fig. 10.18).

For example, Fig. 10.18 shows the result of topical SEM analysis of particular PTFE tubing that had developed leaks during pressure testing. Scanning electron microscopy of the leak point created the images at 10,000 and 20,000 times magnification. There are aggregates containing particles that have generally round outlines resembling primary PTFE particles. The presence of these aggregates is accompanied by a significant number of voids. Incomplete sintering was determined as the cause for the presence of these aggregates and voids.

10.4.2.2 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is similar to SEM except that the beam passes through the sample. A high-voltage (80–200 keV) highly focused electron beam is passed through a thin solid sample, typically 100–200 nm in thickness. Electrons undergo coherent scattering or diffraction from lattice planes in the crystalline phase of materials, thus yielding phase identification. Characteristic x-rays that are generated can be detected in a separate detector, permitting qualitative elemental analysis.

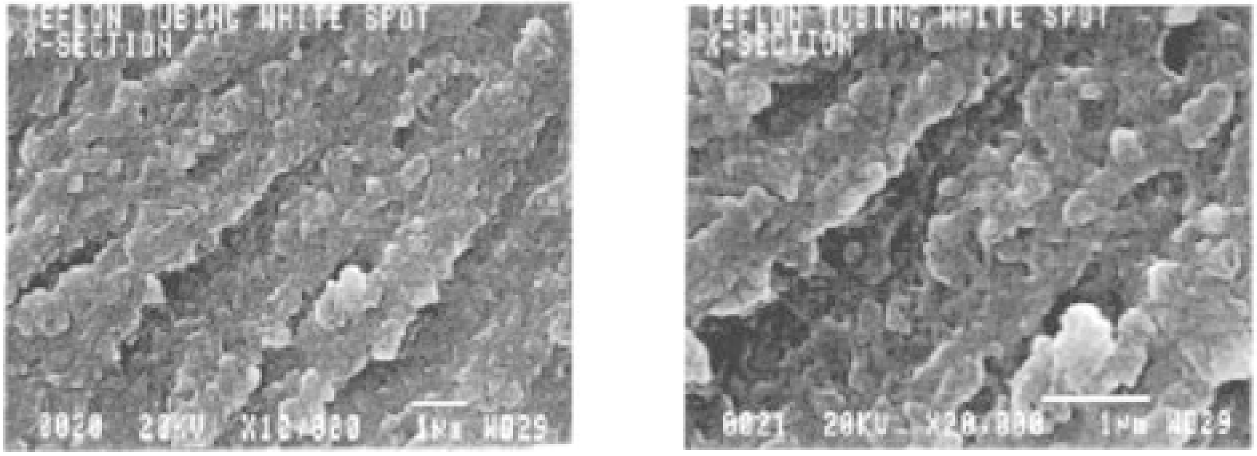
Figure 10.19 shows a TEM micrograph of particles of polyvinylidene fluoride that have been produced by emulsion-polymerization in an aqueous phase. Figure 10.20 shows an example of the capability of TEM in revealing the structure of the material, as illustrated for graphite. Lattice thickness and interplanar spacing of graphite can be measured from the micrograph because of its excellent resolution.

10.4.2.3 Energy Dispersive X-Ray (EDX) Spectroscopy

Energy dispersive x-ray (EDX) spectroscopy is a standard method for identifying and quantifying elemental compositions in a very small sample, as small as a few cubic micrometers. In a properly equipped SEM, the atoms on the surface are excited by the electron beam, thus emitting back specific wavelengths of x-rays that are characteristic of the atomic structure of the elements. The x-ray emissions can be analyzed using an energy dispersive detector, which is a solid state device that discriminates among x-ray energies. Appropriate elements are assigned, thus yielding the composition of the atoms on the specimen surface. This procedure is called energy dispersive x-ray or EDX and is useful for analyzing the composition of the surface of a specimen (Fig. 10.21).

10.4.3 Mass Spectroscopy (MS)

Mass spectroscopy (MS) is applicable to both organic and inorganic substances. Mass spectroscopy is a quantitative technique that allows the study of the structure of organic matter. A sample is degraded, often bombarded with electrons, into fragments which are identified through fractional mass differences in atoms of the same principal mass number.[10] The method requires high vacuum and the fragments must be volatile. The determination relies on the pattern of fragmentation of a molecule upon ionization. These patterns are distinct, can be reproduced, and are additive for mixtures. A mass spectrum is basically a graph that shows the measured values of ion intensities per unit charge (*m/e*, mass divided by



(a)

(b)

Figure 10.18 SEM micrographs of the surface of an incompletely sintered PTFE tubing at magnifications of (*a*) 10,000X, and (*b*) 20,000X. *(Courtesy of DuPont Fluoroplastics.)*

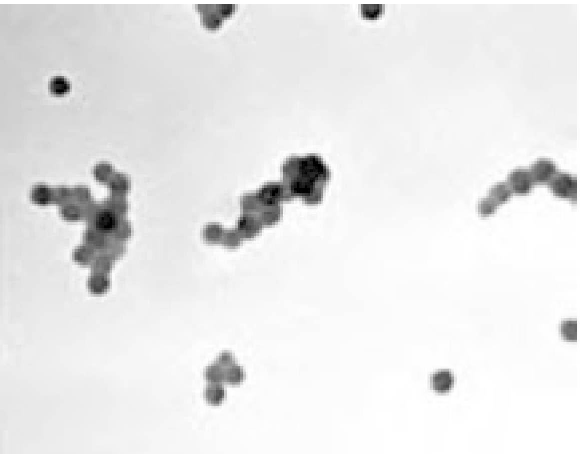


Figure 10.19 Transmission electron micrograph of particles of emulsion-polymerized PVDF particles (D_p = 128 nm).[8]

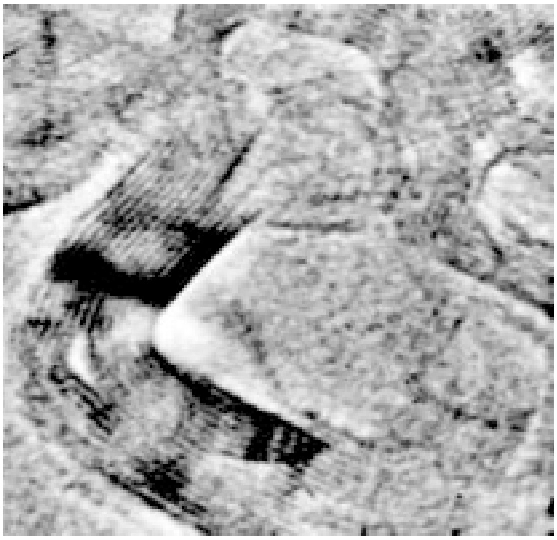
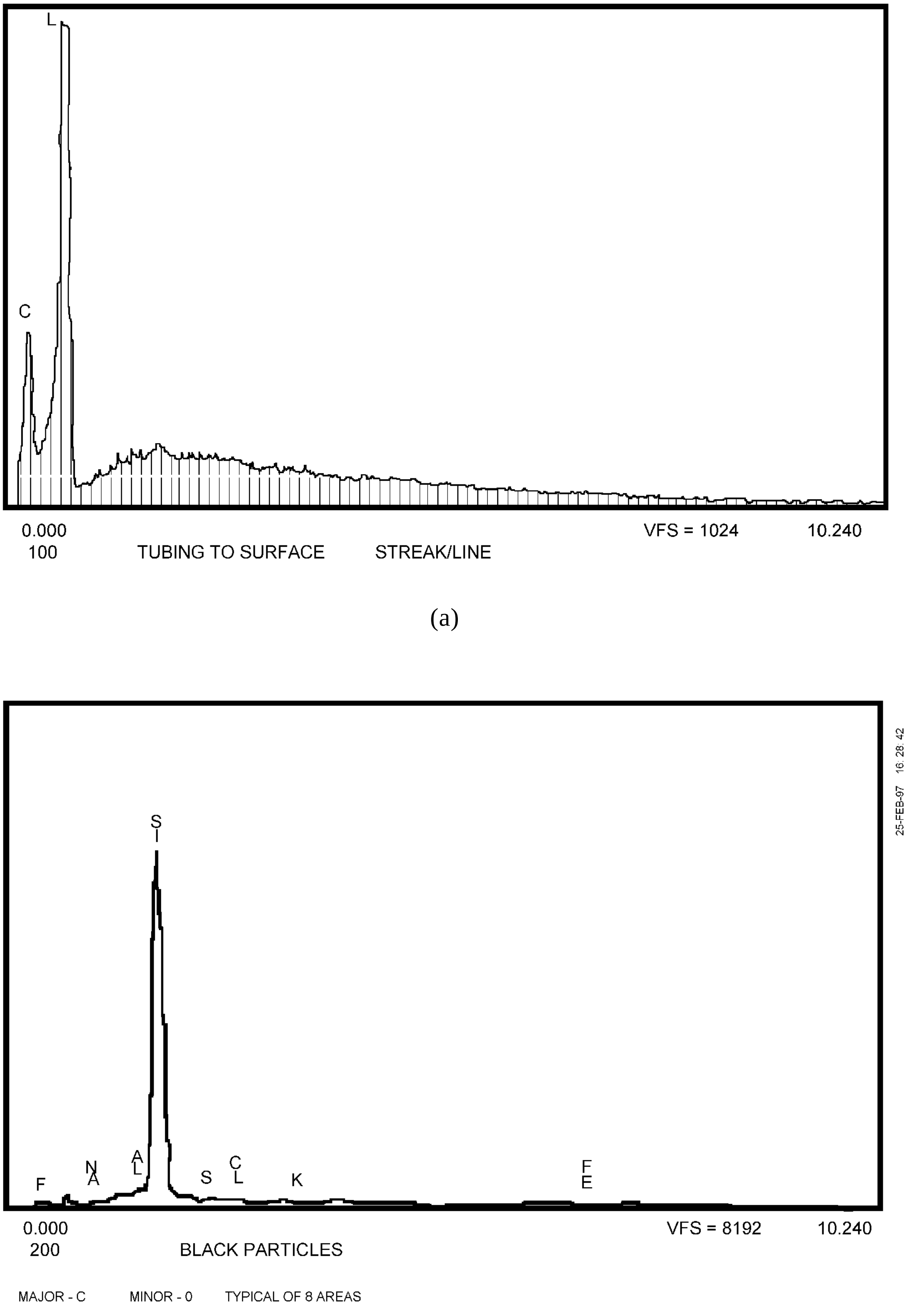


Figure 10.20 Graphite is used as a control to demonstrate the resolution capabilities of the Phillips 420 TEM. The periodic structure shown above represents the 3.354 Å interplanar spacing of the graphite lattice. Each lattice plane has a thickness equivalent to one carbon atom, which is 1.7 Å. The image has been averaged four times (0.33 sec exposure), normalized, scaled, and low pass filtered for subtraction of background noise (× 4,500,000).[9]



(a)

(b)

Figure 10.21 EDX elemental analysis of (*a*) a clean PTFE surface, and (*b*) a contamination spot on the PTFE surface. *(Courtesy DuPont Fluoroproducts.)*

charge). The mass spectrum is unique for each compound. In a high resolution spectrum, the deviation of the molecular weight of each fragment from an integral value is used to determine the elemental composition.

There are several methods of ionizing organic materials such as particle bombardment, chemical and field ionization, electron impact, field desorption, and laser pulse. For example, in the laser micro-mass analysis method, a laser pulse is used to supply the necessary energy to volatilize a sample from the surface for mass spectroscopy.[3] Mass spectrometry is often used in conjunction with gas chromatography to identify the separated components. The working technology of mass spectrometry is quite complex.

10.4.4 Gas Chromatography (GC)

Chromatography separates mixtures into its components which are then analyzed by one of many detectors. In gas chromatography (GC), the sample is passed in vapor phase through an appropriate solid bed placed in a column. An oven supplies heat to the column through which the vapor is carried using a constant stream of a gas like nitrogen or helium. The time required to elute each component (called *retention* time) is monitored for about 30 minutes. GC refers to the use of solid absorbent or molecular sieve columns. In the majority of GC columns, the packing is coated with a stationary liquid phase. Separation takes place by partitioning between the liquid coating and the carrier gas.

There are a variety of column packing materials and liquid phases. Sometimes a very long capillary column is used without a solid packing and only coated with a liquid on the wall. The oven can be operated isothermally at a given temperature or according to a program where temperature is varied as a function of time.

There are different types of detectors, including thermal conductivity and electron capture types. The most common detector is the *flame ionization* variety (FID). A hydrogen flame is utilized to combust the column effluents. Thermal conductivity detectors do not degrade the effluents and are not as sensitive as flame ionization. Electron capture detection is especially sensitive to halogenated compounds.

Retention time of a compound is a characteristic of that compound under a set of conditions. To resolve an overlap of retention time, a combination of GC with MS or IR is employed.

10.4.5 Nuclear Magnetic Resonance (NMR)

Nuclear magnetic resonance (NMR) is a unique technique that depends on the magnetic nature of a few isotopic nuclei, primarily ^{1}H, ^{13}C, ^{19}F, and ^{31}P. In a strong magnetic field, a nucleus precesses about the direction of the magnetic field with a frequency proportional to the field strength. A nucleus is bombarded with radio frequency electromagnetic waves at the right angles to the magnetic field. When the spinning nucleus and the radio frequency become equal, resonance takes place. The energy transfer is the basis of the NMR spectrum of the nucleus and is measured and depicted as a band. The resonance frequency at which the energy absorption occurs depends on the chemical nature of the sample and the environment (e.g., solvent). The nature of the bonds in a molecule can be identified by NMR with the use of reference spectra and characteristic frequencies for different types of chemical bonds.

10.4.6 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) is one of the best known techniques among a group called thermal analysis methods; others include differential thermal analysis, dynamic mechanical analysis, and thermogravimetric analysis methods; all of which are covered in the following sections.

DSC is a thermal analysis technique that is used to measure the temperatures and energy flows related to transitions in materials as a function of time and temperature.[11] These measurements provide qualitative and quantitative information about physical and chemical changes that involve endothermic or exothermic processes or changes in heat capacity. Any event, such as loss of solvent, phase transitions, crystallization temperature, melting point, and degradation temperature of the plastic sample, result in a change in the temperature of the sample. The systems available cover a wide temperature range, e.g., -60°C to >1,500°C.

Two types of systems are commonly used: power compensation and heat flux DSCs. In the power compensation apparatus temperatures of the sample and the reference are controlled independently by using separate but identical furnaces. The power input to the two furnaces is adjusted to equalize the temperatures. The energy required for the temperature equalization is a measure of the enthalpy or heat capacity in the sample relative to the reference. In *heat flux* DSC, the sample and the reference are interconnected by a metal disk that acts as a low-resistance heat-flow path. The entire assembly is placed inside a furnace. The changes in the enthalpy or heat capacity of the sample cause a difference in its temperature compared to the reference. The resulting heat flow is small because of the thermal contact between the sample and the reference. Calibration experiments are conducted to correlate enthalpy changes with the temperature differences. In both cases, the enthalpy changes are expressed in the units of energy per unit mass.

A typical DSC is run isothermally or with the temperature changing at a constant rate under an atmosphere of air or other gases. In the isothermal case, the heat flow, or enthalpy changes, is plotted against time. In the latter case, heat flow, or enthalpy, is plotted against temperature or time. Figure 10.22 shows an example of an enthalpy peak generated by an exothermic event or an endothermic event such as melting of the crystalline phase of semicrystalline or crystalline polymer. Heat of fusion (H_{f0}) represents the enthalpy change at the crystal melting point of T_0. The weight fraction of the crystalline phase (W) can be determined by comparing the measured heat with H_{f0}. A sample of the polymer is heated in a DSC from a temperature of T_1 to T_2 where the polymer becomes amorphous at a temperature of T_0 prior to reaching T_2 as shown by the baseline shift in Fig. 10.22. The enthalpy changes are determined according to the following procedure.

H_a represents the simple enthalpy change during the heating of the polymer sample from T_1 to T_0. At T_0 the crystalline phase completely melts; that is, it becomes amorphous. The enthalpy of fusion is expressed in Eq. (10.3). The increase in the enthalpy of the amorphous phase as a result of heating from T_0 to T_2 is designated as H_c. If the enthalpy change calculated from the separation of the DSC curve from the baseline (i.e., area under the curve) is designated as H_T, then Eq. (10.4) can be derived to calculate the weight fraction of the crystalline phase.

$$H_b = W \cdot H_{f0}$$

Eq. (10.3)
$$H_T = H_a + H_b + H_c$$
$$H_T = H_a + W \cdot H_{f0} + H_c$$

Eq. (10.4)
$$W = \frac{(H_T - H_a - H_c)}{H_{f0}}$$

Examples of DSC graphs for different fluoropolymers are presented in Figs. 10.23 through 10.28.

DSC analysis can be used to determine whether a plastic has been completely melted or sintered. For example, PTFE parts sometimes fail because of incomplete sintering, which appears as a second peak during the heat-up cycle of DSC. This peak appears at 342°C in contrast to the remelt peak at 327°C. A comparison of second heat cycles for three different molecular weight PTFE samples indicates the highest molecular weight resin has the lowest heat of fusion. This is expected because the high molecular weight PTFE is expected to recrystallize the least after being melted.

10.4.7 Differential Thermal Analysis (DTA)

Differential thermal analysis (DTA) measures the temperature difference between a sample and a reference as the temperature is increased. A plot of the temperature difference (thermogram) reveals exothermic and endothermic reactions that may occur in the sample. The temperature for thermal events such as phase transitions, melting points, crystallization temperatures, and others can be determined

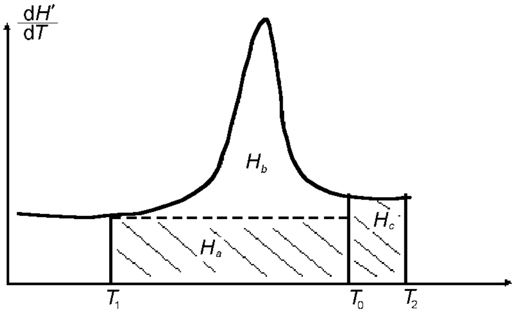
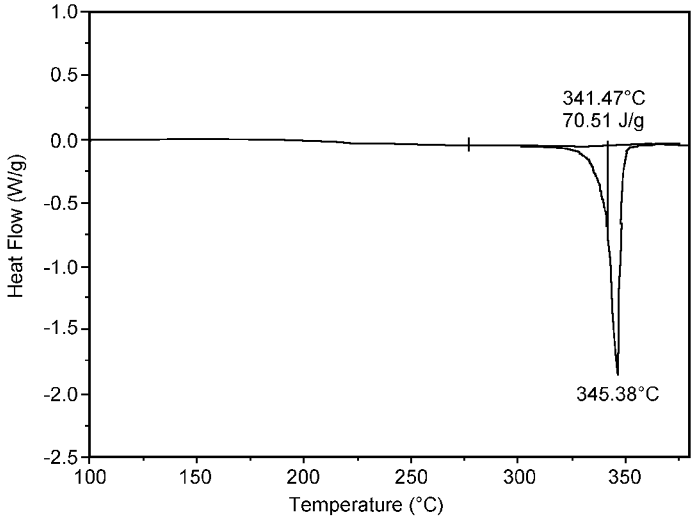
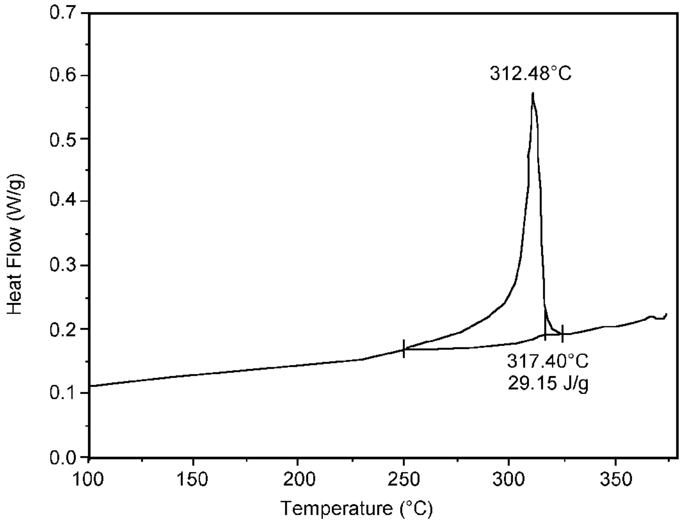


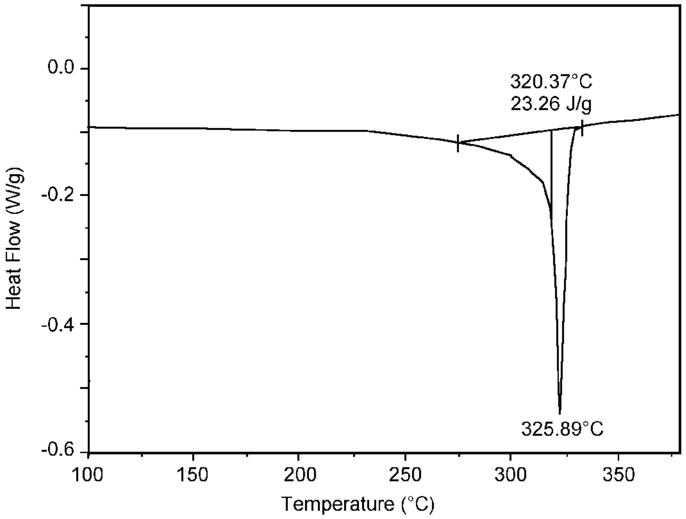
Figure 10.22 Example of a DSC peak.



(a) First heat cycle

(b) Cooling cycle

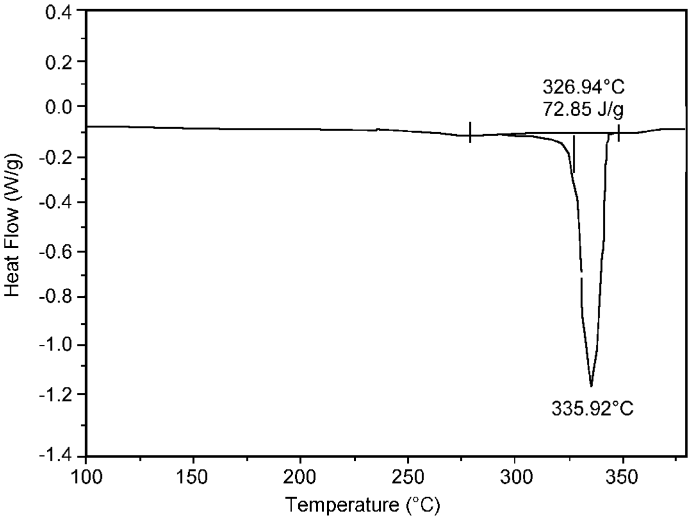


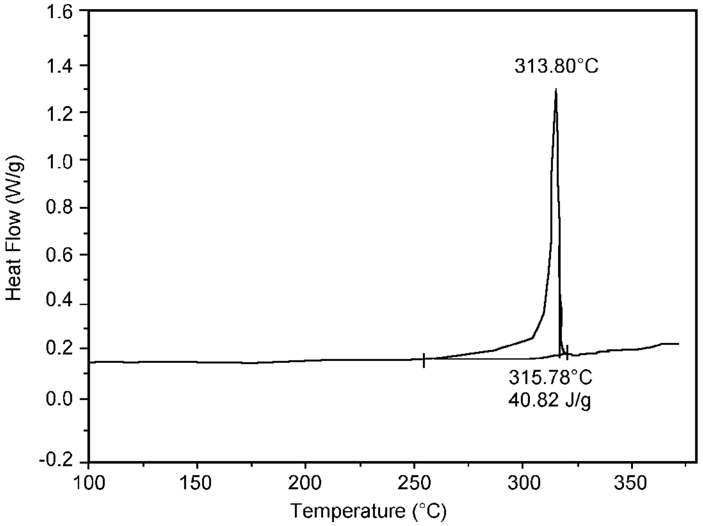


(c) Second heat cycle

Figure 10.23 DSC thermograms of a high molecular weight PTFE (standard specific gravity = 2.155): (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*

(a) First heat cycle





(b) Cooling cycle

(c) Second heat cycle

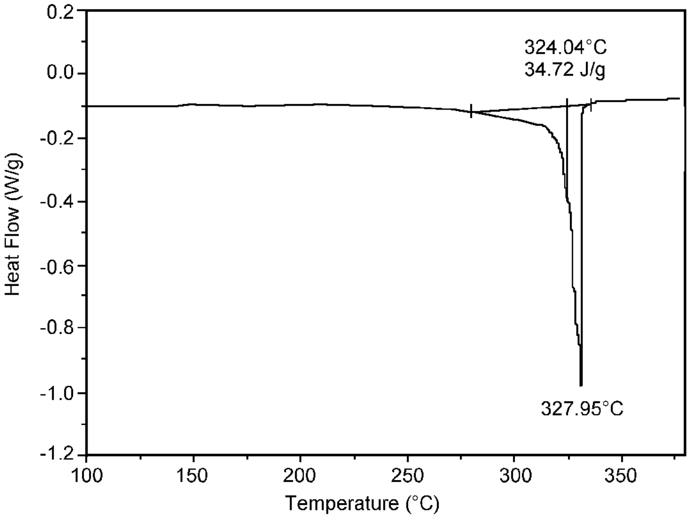
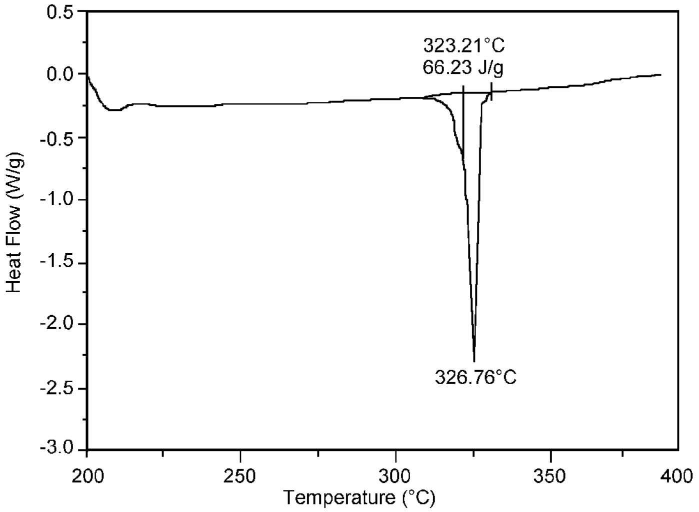
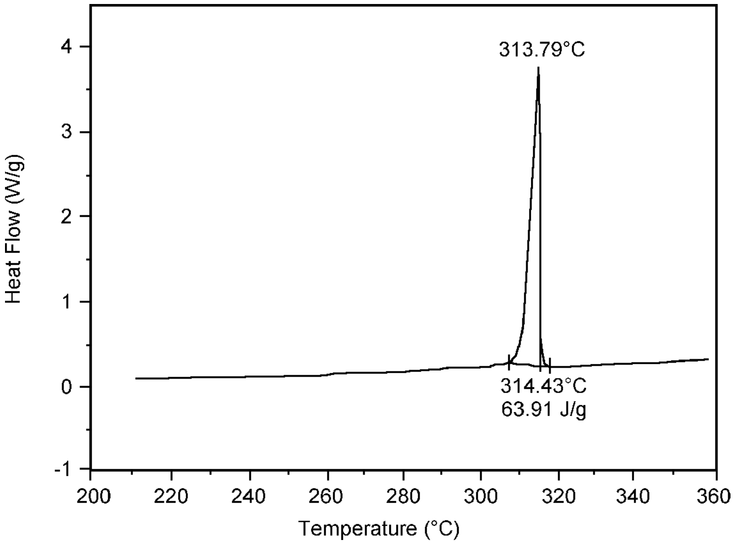


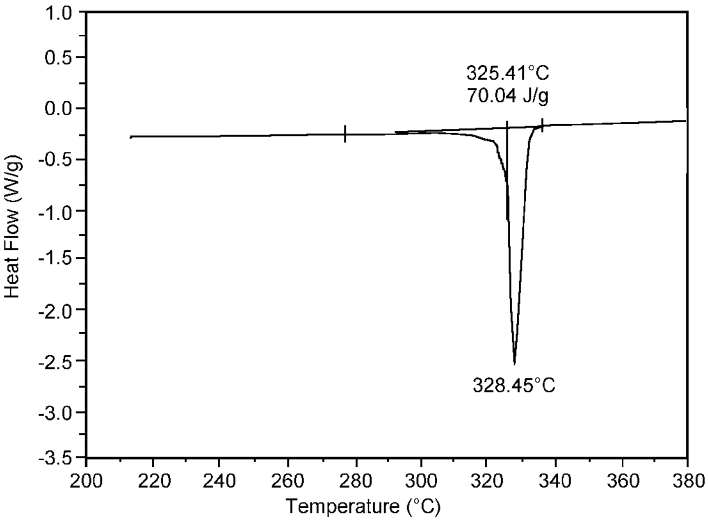
Figure 10.24 DSC thermograms of a medium molecular weight PTFE (standard specific gravity = 2.200): (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*



(a) First heat cycle

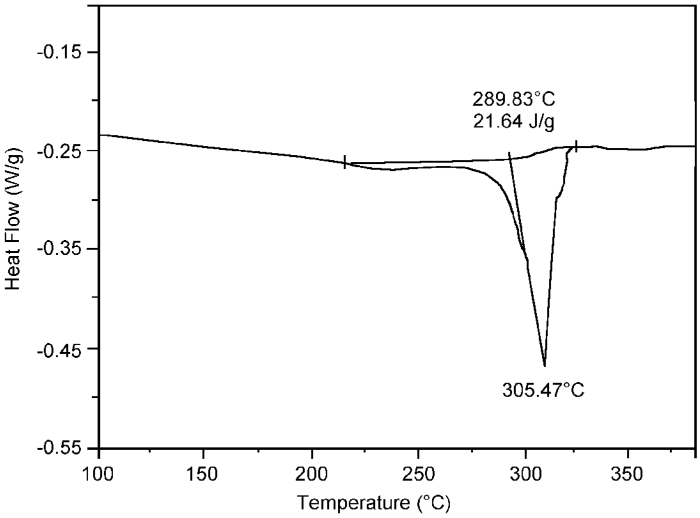


(b) Cooling cycle

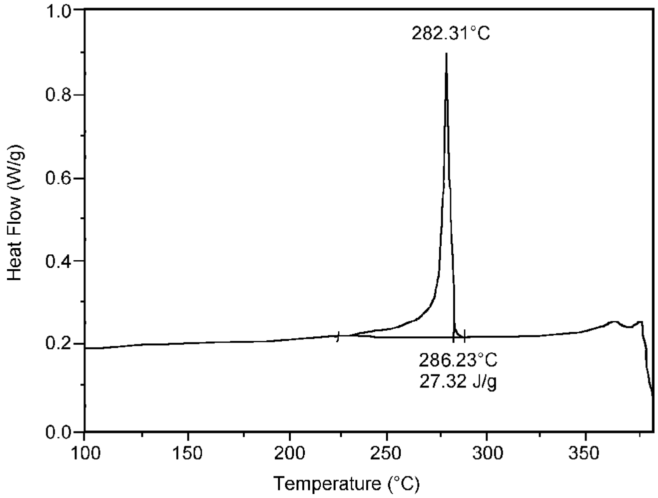


(c) Second heat cycle

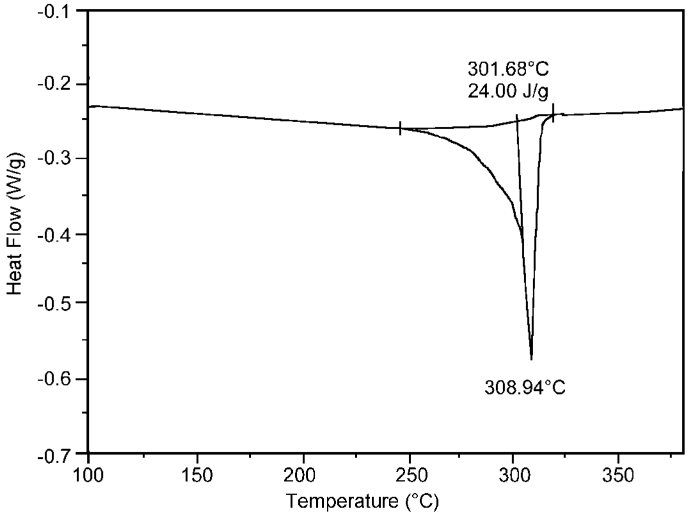
Figure 10.25 DSC thermograms of a low molecular weight PTFE (standard specific gravity = 2.225): (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*



(a) First heat cycle

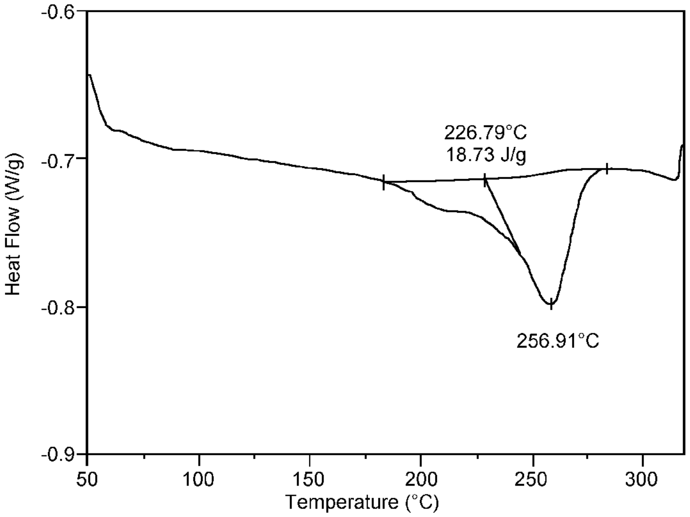


(b) Cooling cycle



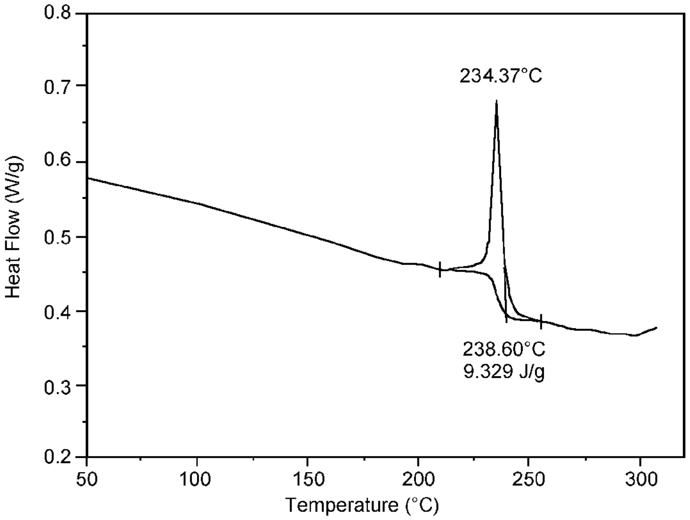
(c) Second heat cycle

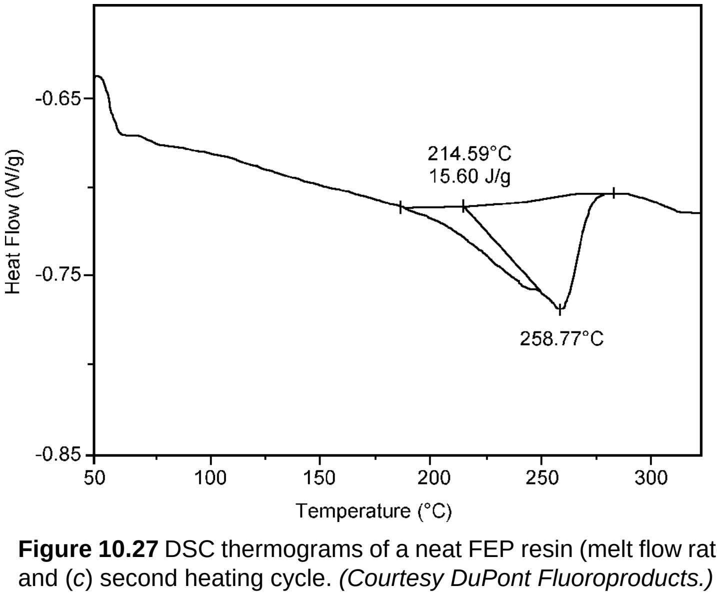
Figure 10.26 DSC thermograms of a PFA resin: (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*



(a) First heat cycle

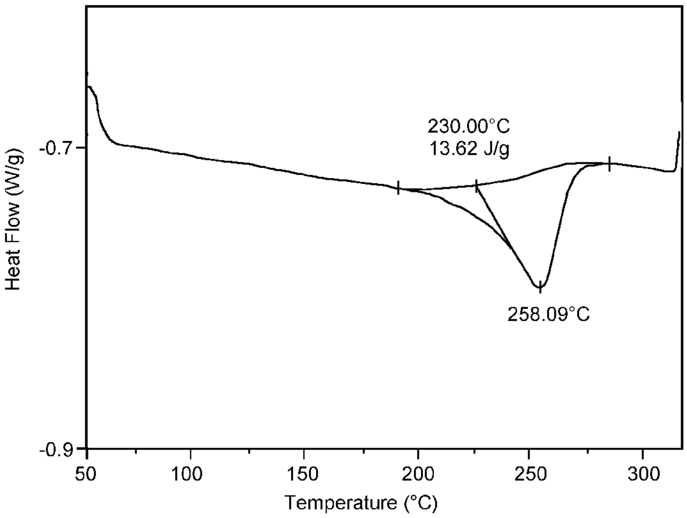
(b) Cooling cycle



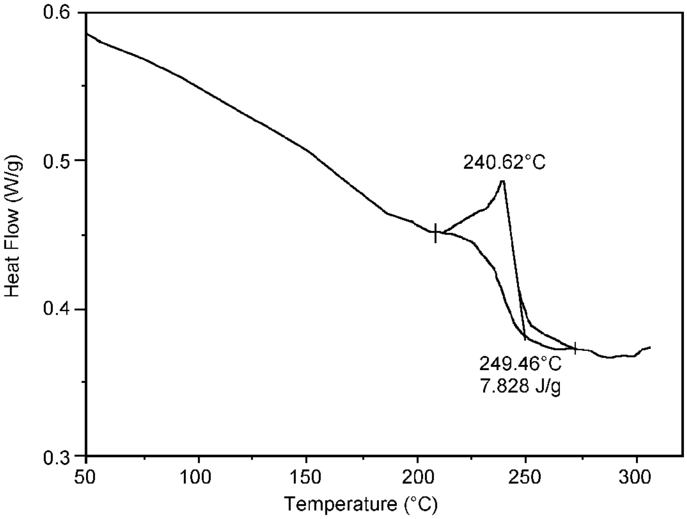


(c) Second heat cycle

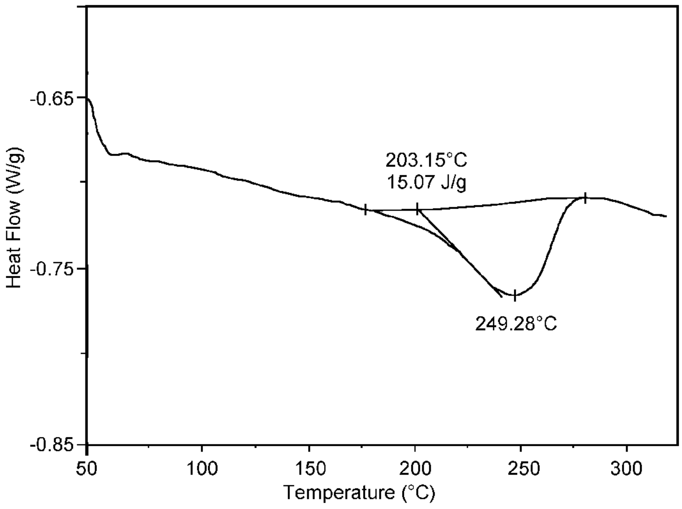
Figure 10.27 DSC thermograms of a neat FEP resin (melt flow rate = 30 g/10 min): (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*



(a) First heat cycle



(b) Cooling cycle



(c) Second heat cycle

Figure 10.28 DSC thermograms of a pigmented FEP resin (melt flow rate = 30 g/10 min for base resin): (*a*) first heating cycle, (*b*) cooling cycle, and (*c*) second heating cycle. *(Courtesy DuPont Fluoroproducts.)*

by this method. The maximum temperature of DTA is in excess of 1,000°C under air or other gas atmospheres. A typical heating for DTA is in the range of 10°C–20°C/min, although slower rates are possible using a typical optimum sample weight of 50–100 mg. The sample should be ground to smaller than 100 mesh.

The melting of a semicrystalline or crystalline polymer exhibits itself as an endothermic peak. The peak temperature is correspondent to the actual melting point of the polymer. As in DSC, the area under the peak is proportional to the crystalline fraction of the sample. Mixtures of polymers can be characterized by DTA because the melting points of individual polymers are, for the most part, unaffected by the mixture. Similar polymers, such as high and low density, are distinguishable by DTA while infrared spectroscopy would not be able to easily resolve such subtle differences. Figure 10.29 shows a thermogram of a mixture of polytetrafluoroethylene (PTFE) and perfluoroalkoxy polymer (PFA).

10.4.8 Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis (DMA) is generally a more sensitive technique for detecting transitions than differential thermal analysis and differential calorimetry methods. This is because the properties measured are dynamic modulus and damping coefficient, both of which change significantly when crystalline structure changes, such as when a transition to the amorphous phase occurs. The operating principle is that, in these transitions, a proportionally larger change occurs in the mechanical properties of a polymer than in its specific heat. Dynamic mechanical analysis is, thus, the preferred method of measurement for glass transition temperature and other minor phase/structure changes of polymers.

The dynamic mechanical analysis method determines[12] elastic modulus (or storage modulus, G´), viscous modulus (or loss modulus, G´´), and damping coefficient (tan Δ) as a function of temperature, frequency or time. Results are usually in the form of a graphical plot of G´, G´´, and tan Δ as a function of temperature or strain. DMA may also be used for quality control and product development purposes.

The forced non-resonance technique[13] is one of the simpler dynamic mechanical methods. In the majority of commercially available DMAs, a force is applied to a sample, and the amplitude and phase of the resultant displacement are measured. These instruments utilize a linear actuator where the applied force is calculated from knowledge of the input signal to the electromagnetic coils in the driver.

An alternative to the above is using a force transducer to measure the applied load, with the sample held between this transducer and the magnetic driver. These are the two types of arrangements that are found with the forced non-resonance technique. In each case, the sample is driven at a frequency below that of the test arrangement. The typical frequency range of instruments is 0.001 to 1000 Hz. Any measurements below 0.01 Hz takes too long for most analytical experiments, especially if data are required as a function of temperature. Resonance often occurs at frequencies greater than 100 Hz, depending upon the sample stiffness.

In a DMA test,[13] it is the sample stiffness and loss that are being measured. The sample stiffness is a function of its modulus of elasticity and geometry or shape. The modulus measured depends on the choice of geometry, Young's (E*) for tension, compression, and bending, and shear (G*) for torsion. The modulus is defined as the stress per unit area divided by the strain resulting from the applied force. It is, thus, a measure of the material's resistance to deformation. A higher modulus value is an indication of more rigidity of the material.

The above modulus definition does not take time into account. For materials that exhibit time-dependent deformation, such as polymers, the reported modulus must include, to be valid, a time factor. This

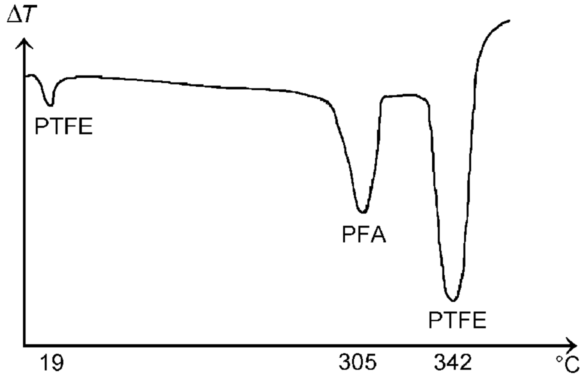


Figure 10.29 Examples of DTA thermograms for PFA and PTFE.

attribute is a powerful advantage that DMA offers. Dynamic mechanical analyzers apply a periodic stress or strain to a sample and measure the resulting strain or stress response. The resultant response is out-of-phase with the applied stimulus because of the time-dependent nature of polymers. The *complex modulus* is defined as the instantaneous ratio of the stress/strain. To understand the deformational mechanisms occurring in the material, this is resolved into an inphase and out-of-phase response. This analogy is equivalent to a complex number where M' is the inphase or elastic response also known as the recoverable or stored energy. M'' is the imaginary or viscous response that is proportional to the irrecoverable or dissipated energy ($M^* = M' + M''$).

For a completely elastic material, $M^* = M'$, while for a perfectly viscous material, $M^* = M''$. The factor "Δ" is the measured phase lag between the applied stimulus and the response. Tan Δ is given by the ratio M''/M' and is proportional to the ratio of energy dissipated to energy stored, called the loss tangent or damping factor, which is one of the key parameters in DMA. Loss tangent is observed to increase during transitions between different deformational mechanisms.

Table 10.7 provides definitions of the most common nomenclature for parameters of dynamic mechanical analysis.

Figure 10.30 shows an example of DMA output for polytetrafluoroethylene. Samples of PTFE were analyzed by DMA in shear mode at a length to thickness ratio of 4:1. Figure 10.30a shows the DMA output of stress versus time versus temperature which has been converted to Fig. 10.30b by the *time-temperature superimposition* technique.

The time-temperature superimposition technique allows the prediction of material properties that normally would require measurements over many months or years. To collect the necessary data, measurements of a time-dependent variable are made at a number of temperatures. The curves are shifted mathematically along the time axis until some overlap occurs and a continuous curve is formed covering several decades of time; this curve is called a *master curve*. A master curve can be used to determine the time-dependent property as a function of time. Figure 10.30c shows total strain as a function of time and temperature for PTFE.

Readers interested in a more in-depth understanding of data obtained from DMA measurements can refer to polymer rheology textbooks. Some of the available helpful books published in this area as listed in Refs. 14–16.

The choice of geometry will be dependent on the sample under investigation. For example, thin films can only be measured accurately in tension. Good dynamic mechanical testers perform well in tension and should apply the required pretension forces automatically, including those associated with large modulus changes that may occur at the glass transition. *Pretension* is necessary in order to maintain the sample under a net tension to prevent buckling that would otherwise occur. Tension should be the first choice for any sample less than one millimeter thick. Samples thicker than one millimeter will likely be too stiff for the instrument in tension; the bending mode would be preferable in this case. Materials that creep excessively, such as polyethylene, may be difficult to test in tension due to creep under the pretension force.

The bending mode is the most accommodating geometry, in that common-sized bars (50 × 10 × 2 mm) of material are readily tested. Such sizes are within the ranges of most commercial dynamic mechanical testers. Clamped modes will yield better results over the whole temperature range, but suffer from clamping effects, while simply supported modes (3-point bending) yield the most accurate modulus. Torsion is a good choice of geometry, but since this has a low inherent stiffness, it requires reasonably large samples. Also, few dynamic mechanical testers have torsional capability. Simple shear is an excellent means of measuring low modulus materials such as rubbers, gels, and pastes. Glassy materials will be

Table 10.7. Common Nomenclature for Dynamic Mechanical Analysis

In-phase or Storage (Real) Properties	Out-of-Phase or Loss (Imaginary) Properties
Young's (Pa) $E' = \|\sigma/\varepsilon\| \cos\delta$	$E'' = \|\sigma/\varepsilon\| \sin\delta$
Shear (Pa) $G' = \|\tau/\gamma\| \cos\delta$	$G'' = \|\tau/\gamma\| \sin\delta$
Compliance $D' = \|\varepsilon?\sigma\| \cos\delta$	$D'' = \|\varepsilon/\sigma\| \sin\delta$
(m^2N^{-1}) $D' = E' / (E'^2+E''^2)$	$D'' = E'' / (E'^2+E''^2)$
Viscosity (PaS) $\eta' = G''/\omega$ where $\omega ?= 2\pi f$	$\eta'' = G'/\omega$ where $\omega = 2\pi f$

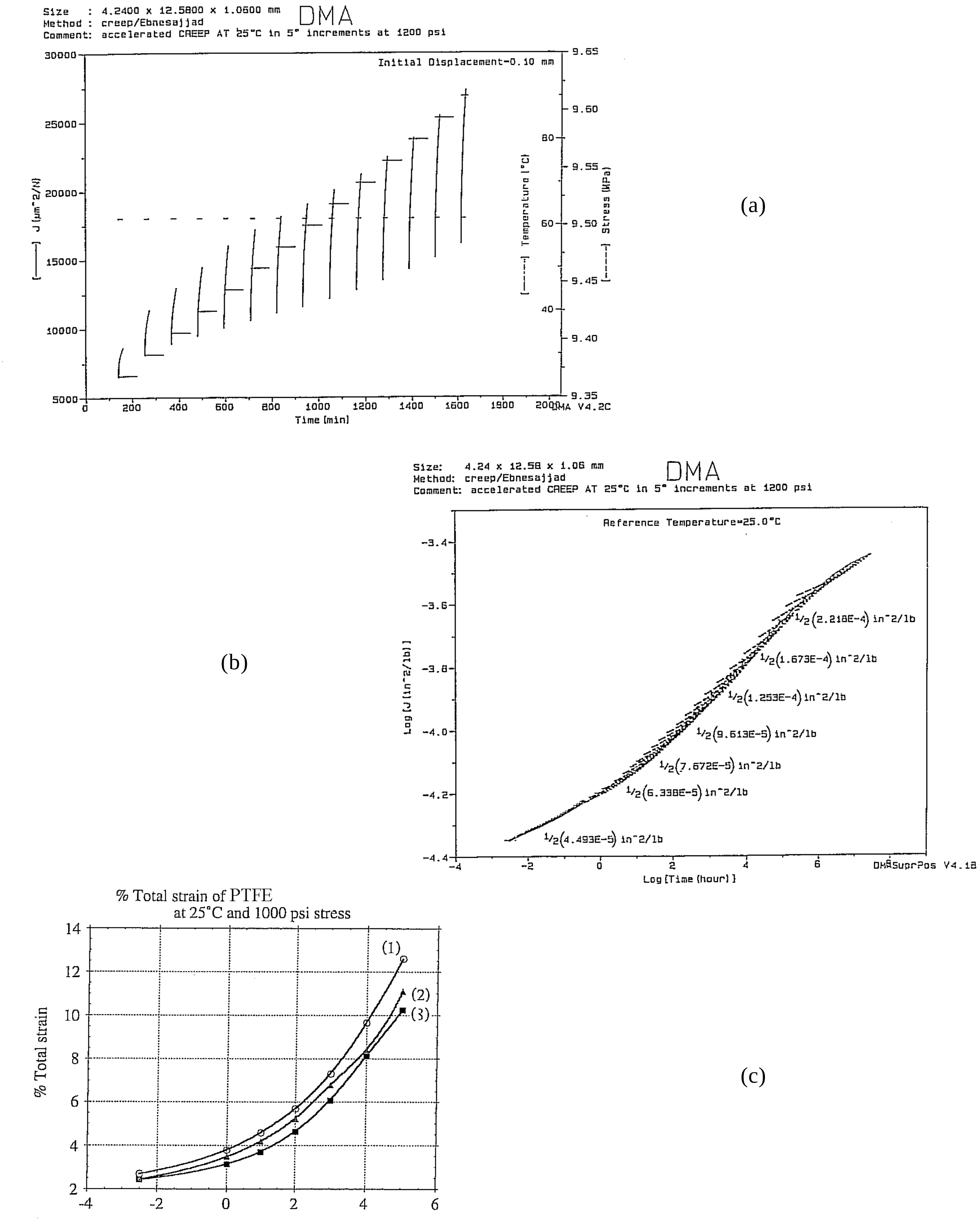


Figure 10.30 Examples of DMA graphs for three grades (1, 2, and 3) of PTFE: (*a*) DMA output, stress vs. time vs. temperature; (*b*) superimposed time-temperature data from (*a*); (*c*) total strain as a function of time and temperature. *(Courtesy DuPont Fluoroproducts.)*

too stiff for most dynamic mechanical testers in this mode. Compression is the worst choice for any sample. It is the mode with the most geometrical errors (assumption of perfect lubrication at surface), but is often the only way to measure irregularly shaped samples.

10.4.9 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is a powerful technique for measuring the thermal stability of polymers. In this method, changes in the weight of a specimen are measured while its temperature is being increased. Moisture and volatiles contents of a sample can be measured by this method. The apparatus basically consists of a highly sensitive scale to measure weight changes and a programmable furnace to control the heat-up rate of the sample. The balance is located above the furnace and is thermally isolated from the heat. A high-precision hang-down wire is suspended from the balance into the furnace. At the end of the hang-down wire is the sample pan, the position of which must be reproducible. The balance must be isolated from the thermal effects (e.g., by use of a thermostatted chamber) to maximize the sensitivity, accuracy, and precision of weighing. The addition of an infrared spectrometer to TGA allows analysis and identification of gases generated by the degradation of the sample.

The TGA apparatus is equipped with a microfurnace, which can be rapidly cooled. The heating element is made of platinum (for temperatures up to 1,000°C). An external furnace with a heating element made of an alloy of platinum and 30% rhodium can extend the temperature range to almost 1,500°C.

A modern apparatus is usually equipped with a computer that can calculate the weight loss fraction or percentage. A commercial TGA is capable of greater than 1,000°C, 0.1 μg balance sensitivity and variable controlled heat-up rate under an atmosphere of air or another gas. The heat-up rate capability of TGA can vary from 0.1°C–200°C/min.

Figures 10.31 and 10.32 show the TGA spectra for the FEP resins, DSC's of which have been shown in Figs. 10.27 and 10.28. A comparison of these figures indicates deterioration in the thermal stability of FEP after incorporation of pigment. Figure 10.33 represents the TGA thermogram for a PTFE (31%wt) compounded with carbon black (18%wt) and silica (50.5%wt). The 0.5% difference (from 100%) is due to the evolved volatile gases, which have not been shown in Fig. 10.33.

10.5 Surface Analysis

Surface science is an invisible yet exceedingly important branch of physics and organic chemistry that studies the behavior and characteristics of molecules at or near the surface or interface. The interface can be between solids, liquids, gases, and combinations of these states. Sophisticated apparatus have been developed to identify and quantify surfaces and interfaces. Polymer surfaces are of special interest in industrial and biological applications; examples of the latter include dental implants and body part prosthetic devices. Modification of surfaces of these devices allows formation of controlled interfaces to achieve characteristics such as bondability and compatibility.

A variety of techniques and apparatus have been developed to study and measure surface properties of polymers and other materials. Three of the most useful techniques for such measurements are electron spectroscopy for chemical analysis (ESCA) also known as x-ray photoelectron spectroscopy (XPS), secondary ion mass spectroscopy (SIMS) and ion scattering spectroscopy (ISS). Table 10.8 shows a comparison of the sampling depth of traditional methods and the new techniques. These analyses can focus on a much shallower thickness of the surface and virtually yield analyses of the outermost layers of a polymer article. Some of these methods and examples of their application to fluoroplastics are discussed below.

10.5.1 Electron Spectroscopy for Chemical Analysis (ESCA)

Electron spectroscopy for chemical analysis (ESCA) is the most widely used analytic technique for characterizing fluoropolymer surfaces. ESCA is also called x-ray photoelectron spectroscopy (XPS) and is able to detect all elements except for hydrogen. A sample is irradiated by x-ray beams, which inter-

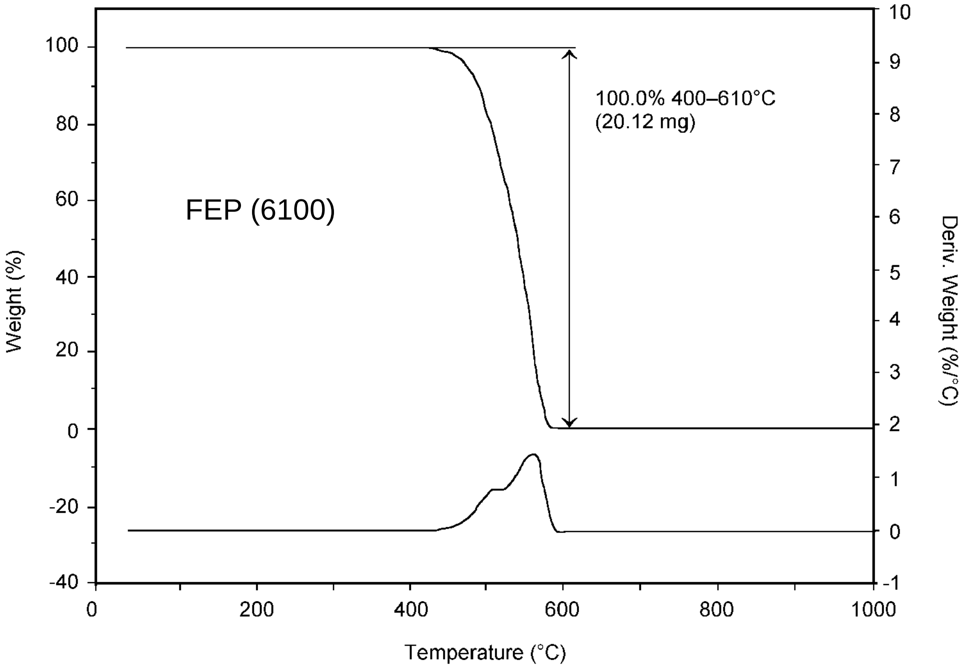


Figure 10.31 TGA thermogram of a neat FEP resin. *(Courtesy DuPont Fluoroproducts.)*

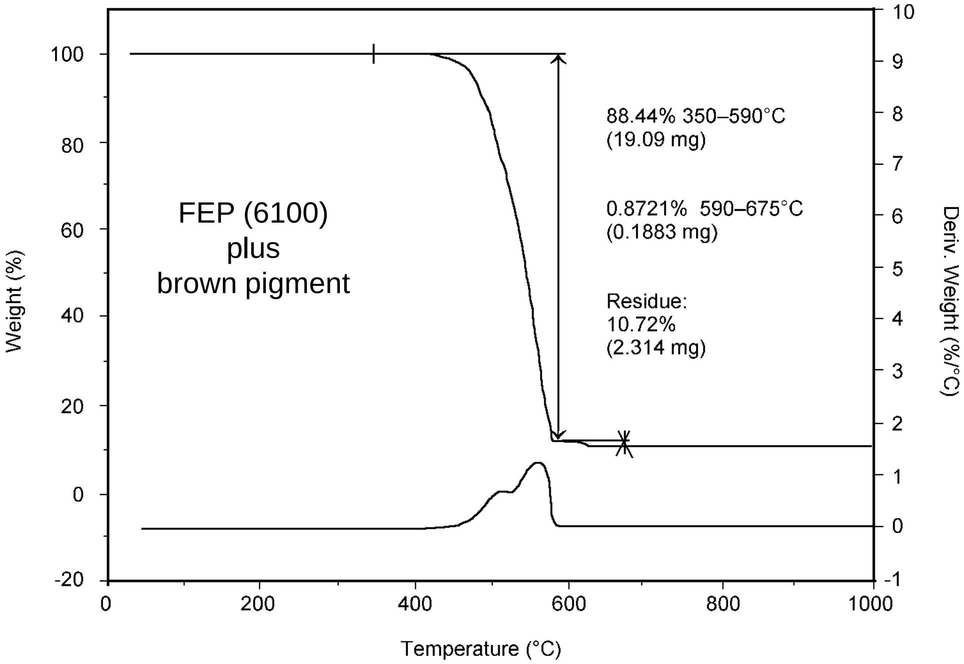


Figure 10.32 TGA thermogram of a pigmented FEP resin. *(Courtesy DuPont Fluoroproducts.)*

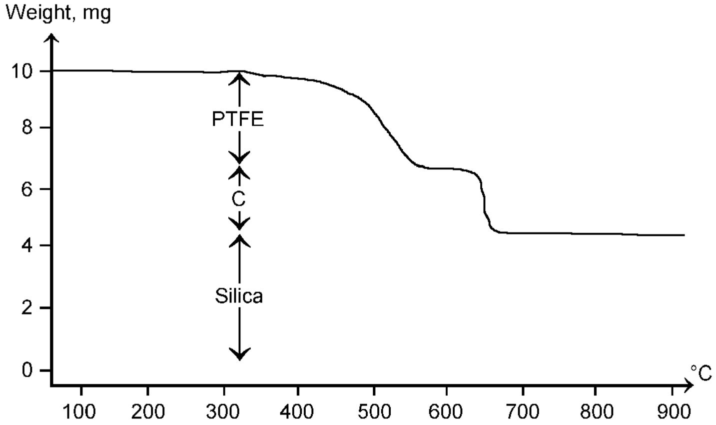


Figure 10.33 Examples of TGA thermogram for PTFE compounded with carbon black and silica.[17]

Table 10.8. A Comparison of Average Sample Depth for Various Surface Analysis Techniques[18]

Analysis Method	Sampling Depth
Infrared Spectroscopy (IR)	<2 µm
Energy Dispersive X-ray (EDX)	<5,000 Å
Rutherford Back Scattering (RBS)	<400 Å
Electron Spectroscopy for Chemical Analysis (ESCA) and Auger	<40 Å
Second Ion Mass Spectroscopy (SIMS)	<4 Å
Ion Scattering Spectroscopy (ISS)	<2 Å

act with the inner electronic shells of atoms. The x-ray's photon energy is transferred to an electron in the inner shell, enabling it (the photoelectron) to escape from the sample surface. An analyzer measures the kinetic energy of the photoelectron which is equal to its binding energy. A knowledge of the binding energy allows identification of the element. The chemical bonding of an atom to another element shifts the bonding energy of the photoelectron to higher or lower values. This shift in binding energy provides structural information about a molecule.

The operation and maintenance of ESCA equipment and interpretation of its data are quite complex. Samples intended for ESCA and other surface analysis methods should be handled carefully because minute contamination can mask the surface structure of the samples. To alleviate this type of complication, the sample surface can be washed with volatile solvents such as methanol, acetone, hydrocarbons, and fluorocarbons using an ultrasound bath. Typically, analysis is conducted before and after surface wash in studying a sample that has been handled and/or contaminated. The working details and data interpretation for ESCA are outside the scope of the present book. The interested reader is encouraged to refer to other sources to gain an in-depth understanding of electron spectroscopy for chemical analysis.[18]–[23]

A typical spectrum of ESCA shows peaks as a function of binding energy such as that shown in Fig. 10.34 for polytetrafluoroethylene. The presence of C1s and F1s peaks on a "clean" surface (b, c, d in

Fig 10.34) indicate that the PTFE surface is comprised of only carbon and fluorine. The energy shift can be curve-fitted by trial and error to determine the functional groups on the surface. The most simplified report that ESCA generates is the atomic composition of the surface elements with the exception of hydrogen. A helpful tool for investigating surface changes of a polymer is the ratio of other elements to carbon. Table 10.9 shows the effect of sodium etching on the surface composition of a few different fluoropolymers.

10.5.2 Secondary Ion Mass Spectroscopy (SIMS)

Secondary ion mass spectroscopy (SIMS) is a valuable technique for identifying the structure and composition of polymer surfaces and complements ESCA. Similar spectra are difficult to resolve by ESCA, while SIMS can differentiate among different polymers. This is partly due to the smaller sampling depth required by SIMS. In a typical analysis, the surface of the polymer sample is bombarded by a primary ion at low current density, mainly intended to minimize alteration of the sample surface. A polymer surface generates positive and negative ions that are analyzed using a mass analyzer. The results of detailed analysis provide chemical structure and composition information about the surface. A traditional shortcoming of SIMS is its inability to perform quantitative analysis.

A different type of analyzer called *Time of Flight* (TOF) SIMS can be utilized to determine the structure of the sample as a function of "sampling depth." TOF SIMS can be useful in determining stratification of resins in coatings or diffusion of atoms into a part underneath a surface.[25][26]

10.6 Examples of Failure Analysis

In this section, examples of failure analysis are discussed where the methodology and analytic techniques, described earlier in this chapter, have been applied to some actual cases. Certain aspects of these actual cases have been altered to insure confidentiality of the sources.

10.6.1 Case 1: Failed Lined Pipe

A plastic-lined pipe was removed from service due to severe cracking as seen in Fig. 10.35. Severe cracking and corrosion were the two visual features of the liner. Pieces of the plastic liner could be broken off by hand indicating essentially no strength. Why did this failure occur?

An investigation of the failure indicated that the lined pipe transported a process stream containing hydrofluoric acid (HF). Normal practice requires the use of perfluoropolymer-lined pipe, e.g., PTFE or PFA, neither of which are expected to be attacked by HF in the process stream. The rational question to ask is "Is the liner actually a perfluoropolymer?" This question can be answered by performing infrared spectroscopy and differential scanning calorimetry on a sample of the liner.

Figure 10.36 shows the infrared spectra of the liner. It matches the spectra of polyvinylidene fluoride which is a partially fluorinated fluoropolymer and is susceptible to chemical attack by HF. DSC analysis measured a melting temperature of 165°C for the liner sample. Follow-up discussions with the plant personnel revealed that the wrong spool piece had been installed instead of a PTFE-lined pipe.

10.6.2 Case 2: Failed Check Valves

Two PFA-lined ball valves failed after six years in service, which is considered premature failure. In the most recent period, the orientation of both valves had been changed from horizontal to vertical. The process stream operated at a temperature of 90°C and contained a mixture of acids including nitric, sulfuric, oxalic, picric, and styphinic at a pH of 1.3. The failure manifestation was unexpected and there was excessive "audible" pinging during the process operation. This case is an example of a failure where analysis has to be conducted by knowledge of the material, equipment, and the process, in contrast to the collection of definitive data. The ball had a diameter of 17 cm and weighed over 5.5 kilograms.

The valve had a PFA liner, which was the appropriate material for this application from a chemical resistance standpoint. A close-up picture of the interior surface of the valve is seen in Fig. 10.37. One of

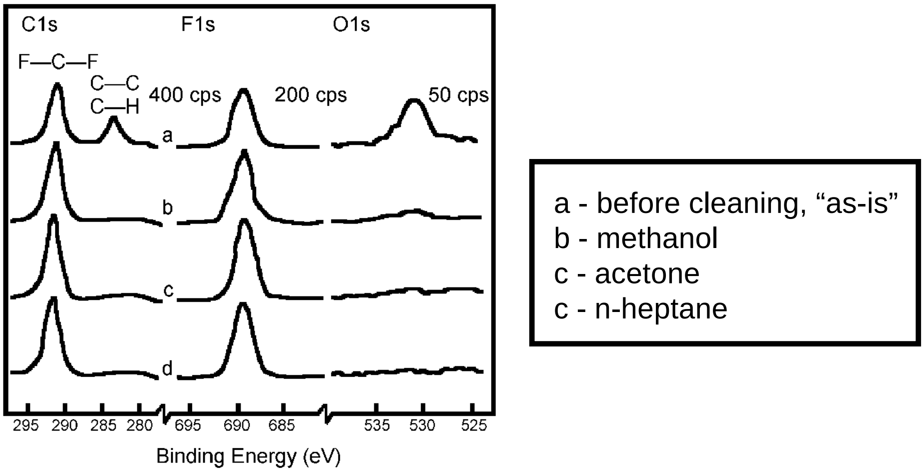


Figure 10.34 ESCA spectra for PTFE before and after cleaning. *(Reprinted by permission from Ref. 18.)*

Table 10.9. Effect of Sodium Etching on the Surface Composition and Adhesion Bond Strength of Fluoropolymers[24]

Polymer	Treatment	Surface Chemical Analysis (%) by ESCA						
		F/C Ratio	Cl/C Ratio	O/C Ratio	Cl	C	F	O
PTFE	None	1.60	—	—	—	38.4	61.6	—
PTFE	Tetra-Etch®* (1 minute)	0.011	—	0.20	—	82.2	0.9	16.9
PTFE	N/1 min**	0.005	—	0.14	—	87.2	0.4	12.4
PVF	None	0.42	—	—	—	70.4	29.6	—
PVF	Tetra-Etch®* (30 minute)	0.21	—	0.026	—	80.7	17.2	2.1
ECTFE	None	0.64	0.27	—	14.1	52.5	33.4	—
ECTFE	Tetra-Etch®* (1 minute)	0.16	0.05	0.12	3.8	74.9	12.2	9.1

* Supplied by WL Gore Corporation.

** Treatment with a 1 mole solution of sodium naphthalenide in tetrahydrofuran at room temperature.

Figure 10.35 Photograph of the cracked lined-pipe spool. *(Courtesy DuPont Fluoroproducts.)*

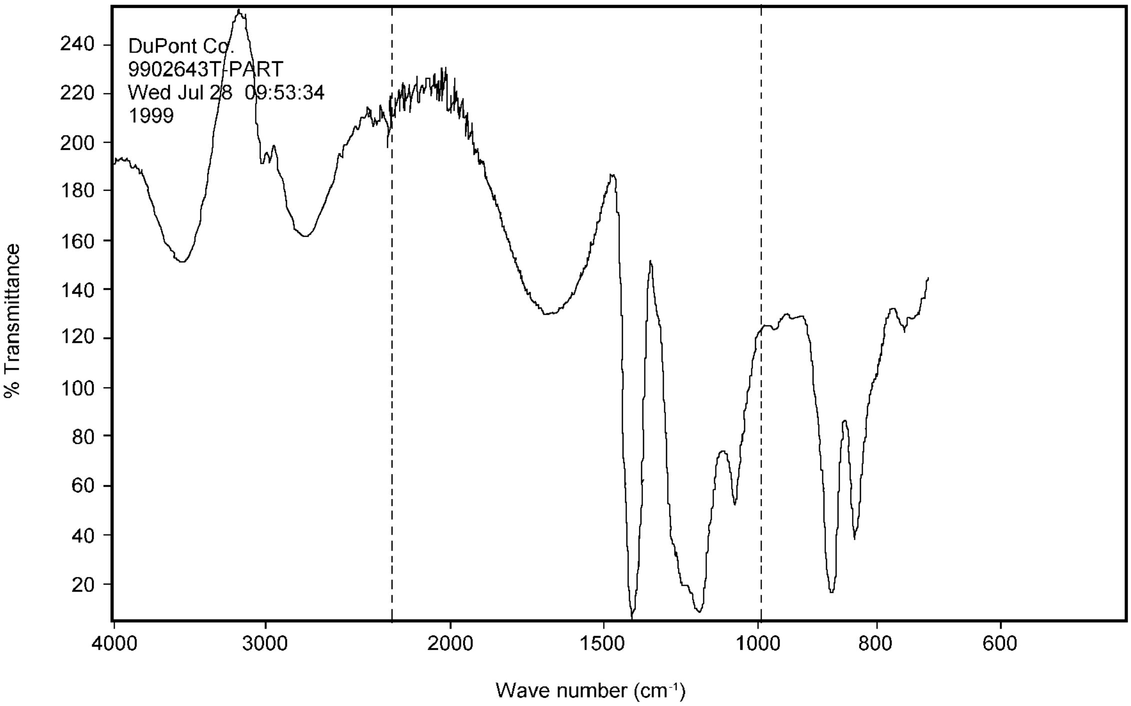


Figure 10.36 Infrared spectra of the failed pipe liner (Case 1). *(Courtesy DuPont Company.)*

Figure 10.37 Photograph of the PFA-lined valve body (Case 2). *(Courtesy DuPont Company.)*

the six protruding fingers or ball supports had broken off from the valve body and the others had been worn away at their bases. The uneven support for the ball explains the excessive noise. The wear pattern appeared to have changed after reorientation of the valve. This is likely to have caused uneven impact of the ball on the fingers, thus breaking off the one that had carried most of the load. The PFA liner was significantly thinner at the area of the broken-off finger than the rest of the liner. This was probably caused by the hammering impact of the ball on the liner in the absence of the support finger. The horizontal crack that developed in the liner was due to the stress to which the liner had been subjected.

Close inspection of the valve prior to installation and measurement of the dimensions at the installation of the new valve and during periodic inspection were the recommended corrective actions.

10.6.3 Case 3: Black Spots on FEP Coating

A glass-cloth coated with FEP exhibited contamination in the form of black spots resembling carbon black. The coating process did not use any carbon black, thus ruling it out as a source of contamination. What was the nature of contamination and its possible sources?

Analysis by scanning electron microscopy (SEM) revealed that the contamination was beneath the top surface of the coating. This observation suggested that the contamination had occurred prior to the application of the coating. Next, the surface was analyzed by electron spectroscopy for chemical analysis (ESCA). Chemical compositions typical of contamination spots and an adjacent uncontaminated point are listed in Table 10.10.

The uncontaminated area analysis in Table 10.10 shows the presence of other atoms where normally only 67% F and 33% C (F/C ratio 2) would be expected. Significant/detectable quantities of O, N, Cl, Si, Zn, and Cr were present, which could indicate broad contamination of the coating. The differences between contaminated and uncontaminated areas showed large increases in O, N, Si, Cr, P, and Cu. The most likely compounds were mixtures of chromium and copper oxides and probably phosphates.

10.6.4 Case 4: Braided Hose Failure

A hose assembly in fluorine service failed because of forming a leak (Fig. 10.38). The hose consisted of a PTFE tube (liner) at its core which had been reinforced with a stainless steel braiding. The failure occurred in the PTFE tube below and near the lower edge of the collar, away from the joint. The failed hose handled fluorine that had been diluted by a neutral gas. A lengthy analysis was performed to determine the cause of the failure because of the safety concerns about fluorine service.

Braid surfaces at the failure point and a spot away from that area were analyzed. The external and internal surfaces of the braid at the failure area were mildly discolored because of oxidization, similar to the effect of overheating a metallic object. Optical microscopy and scanning electron microscopy showed no disturbance to the weave pattern, no deformation of metal wires, and no surface defects, based on the comparison of defective and normal areas. Energy dispersive x-ray (EDX) showed similar concentrations of iron (Fe), nickel (Ni), chromium (Cr), and molybdenum (Mo) in both areas, indicating stainless steel. A small amount of silicon (Si) was detected that was attributable to environmental contamination such as dust and dirt.

Analysis of a liner sample by FTIR confirmed that the tube was made of PTFE. A peak was detected for perfluoropropyl vinyl ether (PPVE) indicating that PTFE was modified by a small amount of PPVE. No differences were found between the failure and normal areas after analysis by optical and scanning electron microscopy and EDX except for the small crack in the PTFE tube at the failure point. EDX detected similar amounts of F and C in both areas, as expected.

OM and SEM analysis of the interior of the crack (1.7 mm wide) gave interesting results. Scanning electron micrographs at 100–500× magnification revealed that the inside of the crack was filled with agglomerates that had an irregular shape resembling crushed stone. Beginning at a magnification of 5,000, small round particles could be seen that resembled primary PTFE fine powder particles both in shape and size (Fig. 10.39). Another unusual observation was the presence of PTFE fibrils (<0.050 µm in width). These observations were unexpected because a properly sintered part should not contain any uncoalesced PTFE particles and fibrils.

Table 10.10. Composition (Atom%) of Contaminated Spots on FEP Coating ***(Courtesy DuPont Company)***

	F	C	F/C Ratio	O	N	Cl	Si	Zn	Cr	P	Cu
Contaminated Spot	36	47	0.77	12	1.6	0.3	0.6	0.2	1.9	-	-
Contaminated Spot	20	41	0.49	27	2.7	0.4	0.6	0.3	3.7	4.1	0.6
Uncontaminated Spot	50	42	1.12	5.6	1.1	0.2	0.3	0.1	0.6		

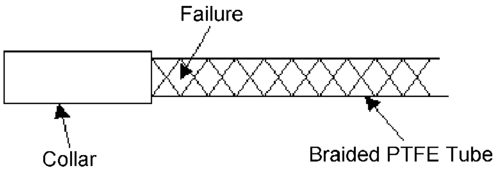


Figure 10.38 Schematic diagram of failed hose.

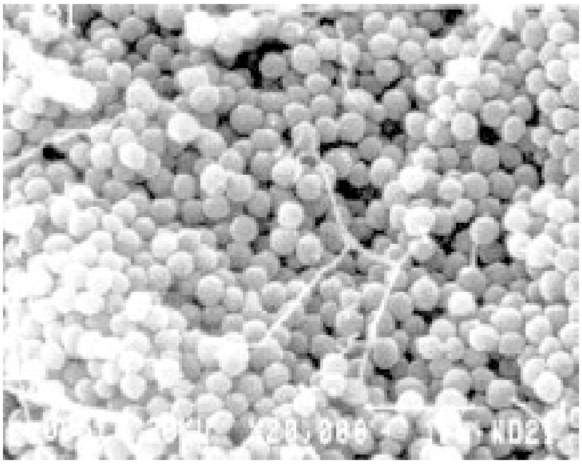


Figure 10.39 SEM micrograph of unsintered particles. *(Courtesy DuPont Fluoroproducts.)*

EDX analysis results showed that iron, nickel, and chromium, all typical components of stainless steel, were present. The fluorine peak was weaker in this area than in the normal areas. No evidence of an external piece of metal or wire being trapped in the crack was detected. All data suggested that the source of contamination must have been mixed with the PTFE prior to or during the fabrication of the tube.

ESCA was conducted on the internal surface of the failure area and a normal area. The theoretical result calls for 33 atomic% C and 67 atomic% F for a PTFE surface with an F/C ratio of 2. The actual data for “as-is” surfaces yielded an F/C ratio of 1.3 and an O/C ratio of 0.05 for the normal area and an F/C ratio of 0.9 and an O/C ratio of 0.09 for the failure area. “As-is” means that the surfaces were not washed with any cleaning solvents prior to measurement. This implies that surface debris, oils, and anything else arising from the handling could mask the surface of PTFE because of the relatively shallow depth of sampling (Table 10.8). Nevertheless, the ratio difference between the two areas indicated a significant difference in the composition of the two areas. Both F/C and O/C ratios indicated severe defluorination at the failure point because loss of fluorine from the surface is accompanied by oxidation.

Differential scanning calorimetry (DSC) was used to determine the heat of fusion and melting points of normal and failure areas. The normal area had a first heat of 22.6 J/g and a melting point of 321°C, both of which are considered acceptable values for a PPVE-modified PTFE. The defective area exhibited two melting points at 309°C and 318°C with corresponding heats of fusion of 30.9 J/g and 12.5 J/g. Both of these values suggested the presence of fairly low molecular weight (MW) polymer species at the point of failure. Lowering the MW of PTFE could depress the melting point to 318°C but not down to 309°C. A melting point of 309°C suggested the presence of another fluoropolymer such as PFA (the most likely).

The findings in the defective area point to a complex event resulting in the failure of the hose and cracking. The presence of fibrils and PTFE particles mean that, in the defective area, the polymer had not coalesced completely. Contamination probably prevented normal fibrillation and sintering of the PTFE part. PFA resin brings along a small amount of metals originating from the extrusion step used to palletize the polymer. Fluorine, probably over time, reached the PFA contamination by diffusing through the gap created by the incomplete PTFE sintering. After contact with the metals, fluorine is likely to have reacted with the metal contamination in a highly exothermic reaction. The heat from the metal/fluorine reaction was responsible for defluorination, subsequent oxidation, and degradation of PTFE, thereby depressing the melting point to 318°C.

10.7 Physical Defects Due to Part Fabrication

Crystallinity affects a great number of properties of semicrystalline thermoplastics such as fluoropolymers. The degree of crystallinity in a fabricated part is dependent on the processing conditions such as the length of exposure to temperature above the melting point and the cooling. Elimination of bubbles, trapped air, and voids during processing have a major impact on a number of properties of a part including mechanical, electrical, and resistance to permeation of chemicals. Partially fluorinated fluoroplastics contain hydrogen or chlorine and can undergo significant thermal degradation if they are overexposed during the processing. Thermal degradation will alter many of the properties of partially fluorinated fluoroplastics.

10.7.1 Polytetrafluoroethylene (PTFE)

A great deal of parts used in the chemical processing industry are made of polytetrafluoroethylene (PTFE), which is fabricated by non-melt techniques. These resins are semicrystalline and highly stable at temperatures up to 400°C. The degree of crystallinity in a fabricated part is dependent on the processing conditions. Different processing conditions such as the length of exposure to sintering temperatures affects some of the properties of the resin.

Three steps are common to fabrication conditions of PTFE. They include preforming, sintering, and cooling. All three steps can influence properties of the part such as flex life, permeability, stiffness, resiliency, and impact strength.

Process conditions affect five different variables, which influence the functional properties of any part.

1. Macroscopic flaws such as impurities, cracks, charge-to-charge adhesion, and bubbles.
2. Microscopic flaws or *microporosity* are voids that are created by poor coalescence of particles.
3. Crystallinity is a measure of the orderly packing of the molecules.
4. Molecular weight is an indication of the size of the polymer molecules.
5. Degree of orientation which is an indicator of the alignment of polymer molecules in a specific direction.

These five factors are difficult to measure and control routinely due to a need for special equipment and procedures. A number of indirect properties have been defined to measure the impact of the five parameters. They include specific gravity, tensile strength, break elongation, dielectric breakdown strength, and heat of fusion. These properties are measured by relatively simple and quick methods.

Dielectric breakdown strength is a function of microporosity but not molecular weight or crystallinity. The number and size of the microvoids affect the dielectric strength. Table 10.11 shows the relationship of dielectric breakdown strength to microporosity.

Table 10.11. PTFE Granular Resin: Relation of Dielectric Strength to Degree of Microporosity[27]

Sample	Appearance of Cross Section in Microscope	Dielectric Strength, kV/mm
A	No visible voids at 100× magnification	30.4
B	Scattered 25 µm voids between particles	23
C	Scattered 125 µm voids	17.8
D	Numerous 125 µm voids	10

Specific gravity (SG) is easily measured by gradient-tube or water displacement as described in ASTM D1505 or D792. The value of specific gravity of a sample is affected by microvoids. It is important to correct the measured value of specific gravity for the void content. The following formula [Eq. (10.5)] can be used to calculate the inherent specific gravity of a part:

Eq. (10.5)

$$\text{SG (inherent)} = \frac{\text{SG (measured)}}{(1 - 0.01 \times \%\ \text{void content})}$$

Inherent specific gravity of a PTFE part free of voids can be calculated from Eq. (10.6) as a function of crystalline content.

Eq. (10.6)

$$\text{SG (inherent)} = \frac{(2.302 \times \%\ \text{crystalline} + 2.00 \times \%\ \text{amorphous})}{100}$$

Eq. (10.7) % amorphous = 100 – % crystalline

After substituting from Eq. (10.7) into (10.6), the relationship between crystallinity and inherent specific gravity is reached.

Eq. (10.8)

$$\text{Inherent SG} = \left[\frac{2.302 \times \%\ \text{crystalline} + 2.00 \times (100 - \%\ \text{crystalline})}{100}\right]$$

Figure 10.40 graphically illustrates the relationship between inherent specific gravity and crystallinity of a part. Equations (10.5) and (10.8) can be used to calculate specific gravity of a part at different void contents, as shown in Fig. 10.40.

Break elongation and tensile strength are affected by all of the above five factors. Tensile properties are reduced due to microvoids. An increase in crystallinity results in a reduction in the tensile strength. Elongation rises with crystallinity up to a point and then falls. The impact of microvoids is particularly significant on high tensile strength (i.e., low crystallinity) samples. Table 10.12 shows the effect of microporosity on tensile strength and break elongation at four levels.

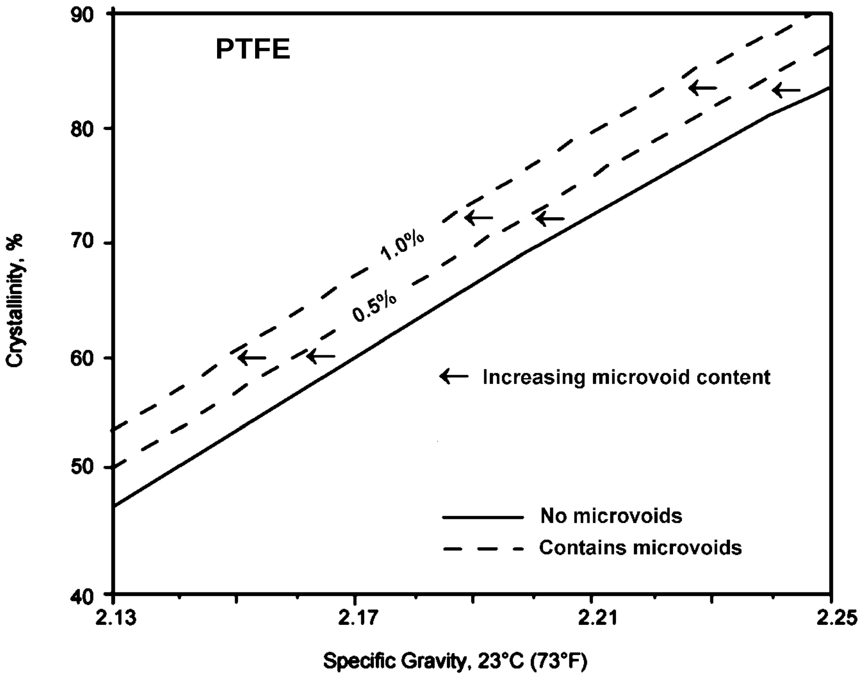


Figure 10.40 Relation of percent crystallinity to specific gravity.[27]

Table 10.12. PTFE Granular Resin: Effect of Microporosity on Tensile Strength and Elongation[27]

Sample*	Extent of Microporosity	Tensile Strength, Mpa	Ultimate Elongation, %
A	Negligible	24.8	390
B	Slight	17.4	350
C	Moderate	13.9	300
D	Severe	12.4	170

* Free-cooled, 1/16 inch specimens with relative crystallinity of 65%–68%, tested using ASTM D4894/4895.

Tensile properties are also influenced by the degree of orientation. Tensile strength is greater in the oriented direction, but break elongation is lower than the unoriented specimen.

10.7.2 Melt-processible Fluoropolymers

Aside from PTFE and PCTFE, copolymers of TFE and a few other fluorocarbon polymers are processed by melt-processing methods. Commercial fluoropolymers that have found application in chemical processing industries include PFA, FEP, ETFE, ECTFE, and PVDF. These plastics are fabricated into parts by common techniques such as injection molding, transfer molding, blow molding, compression molding, rotational molding, and extrusion (Table 10.13). Physical flaws that can occur in these plastic parts are primarily dependent on the fabrication technique and are common to all the resins. Flaws arising from each molding technique are reviewed.

10.7.2.1 Injection Molding

Injection molding is one of the most important processes for mass production of objects from thermoplastics, usually without additional finishing being required. Today, most injection molding machines are the universal types, which can accept all types of molds, within limits. The economics of this process are excellent for articles with complex geometry, giving this process an advantage over other techniques. Cost per molding improves with scale, despite the sizable initial cost of acquisition of injection molding machines.

The principle of injection molding is very simple. The plastic material is heated above its melting point, resulting in the conversion of the solid polymer to a molten fluid with a reasonably low viscosity. It is then forced into a closed mold that defines the shape of the article to be produced. There, the material is cooled until it reverts to a solid, then the mold is opened and the finished part is extracted. Although the principle may be simple, the practice of injection molding is anything but simple. This is a consequence of the complex behavior of plastic melts and the ability of the process to encompass complicated products. The essential mechanisms of injection molding are heat transfer and pressure flow.

The complexity of the injection molding process, and the interdependence of the many variables involved, means that any molding defect may have several different causes, of which more than one may be present at any given time. Table 10.14 shows a list of the defects that one may encounter in injection molding.

10.7.2.2 Rotational and Transfer Molding

Rotomolding and transfer molding are also affected by a number of variables that are difficult to control and hard to scale when the size and design of the part changes. It is important to follow a set of troubleshooting guidelines to take corrective action when the part is defective. Tables 10.15 and 10.16 provide lists of problems and suggested corrective actions.

10.7.3 Measurement of Flaws

It is clear that macroscopic and microscopic flaws affect the properties of PTFE parts. It is important to characterize their impact quantitatively. These flaws can be directly measured by a number of techniques. The measurement methods are complex and not suitable for routine quality control. Macroscopic flaws are frequently detectable visually or by a simple magnifying glass. Internal defects can be detected by x-ray techniques such as radiography. ASTM E94 can be applied as a guideline in establishing procedures.

Table 10.13. Comparison of Molding and Extrusion Techniques for Thermoplastic Polymers

Molding Technique	Advantages	Disadvantages	Typical Process Shear Rate (sec^{-1})
Injection Molding	The most precise control of shape and dimensions, highly automatic process, fast cycle time; the widest choice of materials.	High capital cost; is only good for large numbers of parts; large mold pressures (140 MPa).	1,000–10,000
Compression Molding	Lower mold pressures (7 MPa); does minimum damage to reinforcing fibers (in composites); large parts are possible.	Requires more labor; longer cycle than injection molding; less shape flexibility than injection molding; each charge is loaded by hand.	<1
Transfer Molding	Good for encapsulating metal parts and electronic circuits.	Some scrap with every part and each charge is loaded by hand.	1–100
Blow Molding	Can make hollow parts (such as bottles); stretching action improves mechanical properties, fast cycle; requires low labor.	No direct control over wall thickness; cannot mold small details with high precision; requires a polymer with high melt strength.	–
Rotational Molding/Lining	Labware that's shatterproof and won't contaminate samples; small to very large lined vessels; valve lining; bellows; items with complex geometry; containers.	A slow process; requires labor and involves numerous moving parts. A great deal of cleaning and surface conditioning is necessary.	<100
Extrusion	Used for films, wraps, or long continuous parts (i.e., pipes).	Must be cooled below its glass transition temperature to maintain stability.	100–1,000

Table 10.14. Defect Deformation in Injection Molding Process *(Courtesy DuPont Co.)*

Problem	Possible Causes
Sink marks	Melt temperature too high Insufficient material injected Insufficient dwell time Premature gate freezing Sharp variations in wall thickness Wrong gate location Part ejected too hot Cavity pressure too low
Flash	Excessive injection pressure Excessive melt temperature Mold parting face faulty Insufficient clamp force Foreign matter on mold parting face Flow restriction in one or more cavities of multicavity mold
Voids	Volatiles from overheated material Condensation on granules Premature freezing of flow path to thick section
Surface defects near gate	Mold too cold Mold too hot
Flow marks	Melt temperature too low
Weld lines	Incorrect gate location
Bad surface finish	Incorrect gate type Injection pressure too low Inadequate venting Mold cavity soiled Mold temperature too low Flow length too great Excessive use of mold lubricant

(Cont'd.)

Table 10.14. *(Cont'd.)* Defect Deformation in Injection Molding Process

Problem	Possible Causes
Brittleness	Melt temperature too low Mold too cold Melt degraded by excessive heating Material contaminated Incorrect part design Excessive use of regrind
Silver Streaks	Melt temperature too low Mold too cold Condensation on mold Entrapped volatiles
Burn Marks	Incorrect filling pattern
Warping	Melt temperature too low Incorrect part design Overpacking near gate Sharp variations in wall thickness Flow length too great Unbalanced multiple gates Part ejected too hot Inadequate or badly located ejectors Temperature variations between the mold halves
Nozzle Drool	Excessive nozzle temperature Excessive melt temperature

Table 10.15. Rotational Molding Troubleshooting Guideline for Fluoropolymers

Part Problem	Possible Causes
Poor part release from the mold	Insufficient draft angle Roughness of the mold surface Resin decomposition Insufficient application of release agent Undercuts are trapped
Rough part surface	Resin degradation Presence of foreign particles on the mold surface
Warping	Vacuum development inside the part due to poor venting Non-uniform cooling Part has pulled away from the mold surface because it cooled too quickly
Wall thickness uniformity	Incorrect mold rotation because of equipment problems or the wrong rotation ratio Variation in the thickness of the mold wall resulting in uneven heat transfer, thus improper melting and fusion rate of the resin Variation in heat transfer to the mold
Poor mechanical properties	Cooling too slowly leads to excessive crystallinity Resin fusion is incomplete Poor filler dispersion in the polymer
Incomplete resin sintering	Short heating cycle Low mold temperature Slow heat transfer due to excessive wall thickness of the mold Improper oven air flow

Table 10.16. Defect Formation in Transfer Molding Process ***(Courtesy DuPont Co.)***

Part Problem	Possible Causes
Black Specks in Part	Excessive Melt Temperature Contamination Mold Materials of Construction Cross Contamination of Resin Contaminated Fitting.
Part Discoloration	Excessive Melt Temperature Contamination Mold Materials of Construction Cross Contamination of Resin
Voids in Part	Injection Pressure too Low Excessive Injection Rate Short Injection Time Low Melt Temperature Low Mold Temperature Cooling Rate too Low Gate Size too Small Incorrect Pad Size
Poor Weld Lines	Injection Pressure too Low Short Injection Time Low Melt Temperature Low Mold Temperature Incorrect Pad Size
Flange Warping	Injection Pressure too Low Excessive Injection Rate Short Injection Time Low Melt Temperature Low Mold Temperature
Surface roughness	Excessive Injection Rate Low Melt Temperature Low Mold Temperature Gate Size too Small

Part Problem	Possible Causes
Delaminations in Part	Excessive Injection Pressure Excessive Injection Rate Short Injection Time Low Melt Temperature Low Mold Temperature Gate Size too Small Cross Contamination of Resin Fitting is not Clean
Sink Marks	Injection Pressure too Low Excessive Injection Rate Short Injection Time Low Melt Temperature Low Mold Temperature Cooling Rate too High Gate Size too Small Incorrect Pad Size
Ripples on Part	Short Injection Time Low Melt Temperature Low Mold Temperature Cooling Rate too High Gate Size too Small
Skins on Mold Side of Part	Low Melt Temperature Low Mold Temperature Cooling Rate too Low Contamination Cross Contamination of Resin Contaminated Fitting
Cracks in Part	Excessive Injection Pressure Excessive Injection Rate Low Melt Temperature

Excessive microporosity can be detected visually by a trained observer. Other detection methods do not depend on the experience of the observer. The skills needed for the visual technique are difficult to describe due to its heavy dependence on experience. A few steps can be taken to increase the likelihood of successful inspection of parts for microporosity. The best approach is to compare a series of samples that have been processed by the same sintering and cooling cycles. These samples will have the same inherent specific gravity. A thin section should be obtained due to the ease of light passage. A powerful transmitted light source should be employed for the observation of the voids.

Another way to detect the microvoids is by dye penetration. In this technique, bright-colored dyes are placed on the surface of the PTFE part (thickness <1.5 cm) being tested. An “acceptable” sample is compared with the one in question in this method. A porous sample will have an appearance of fluorescent spots similar to stars in the sky. ARDROX P135E is one of the common fluorescent dyes and can be purchased from ARDROX, Inc., La Mirada, California. Another dye is formulated by mixing 1 g "Calco" Red A-1700 dye (supplied by Cyanamid, Division of American Home Products), 100 ml of reagent grade turpentine, and 5 g $CaCl_2$.

A quantitative way of measuring microporosity is by an indirect technique using specific gravity and crystalline content. From Eq. (10.9), obtained by rearranging Eq. (10.5), void content can be calculated.

Eq. (10.9)

$$\%\text{ void content} = 100 \times \frac{\text{SG (inherent)} - \text{SG (measured)}}{\text{SG (inherent)}}$$

Inherent SG can be calculated from Eq. (10.8), provided that crystalline content of the sample could be measured. A few techniques are available for the measurement of crystallinity. They include infrared spectroscopy,[4] torsional damping,[5] x-ray diffraction,[6] and ultrasonics.[7]

Infrared spectroscopy and torsional damping are the most reproducible techniques for the measurement of crystallinity. The former is most flexible in accommodating different sample shapes. Averages of duplicate measurements yield the best results. Orientation introduces significant errors into these methods, thus prohibiting their application for paste extruded PTFE samples; however, the void content of most paste-extruded PTFE is usually low.

Gases and liquids permeate fluoropolymers to different extents depending on variables such as temperature, pressure, and the composition of the processing fluid. An increase in temperature accelerates the rate of permeation into the polymers. Thermal cycling can cause a part to "stress-crack" or form blisters because of successive evaporation and condensation of permeated chemicals. Steam is a well-known permeant of polytetrafluoroethylene and can create blisters upon cycling.

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11 Modeling and Mechanical Analysis of Fluoropolymer Components

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11.1 Introduction

Fluoropolymers are used in critical applications where failure may have serious safety, environmental, and/or financial consequences. Modeling is an important tool in determining the root cause of the failure and its correction. The modeling of fluoropolymer components, like other polymer materials, continues to evolve in sophistication. This chapter introduces current and developing methodologies for mechanical analysis. These methodologies promise increasingly accurate predictions and analysis of fluoropolymer materials.

Modeling of fluoropolymers can be based on several approaches, ranging from simple to complex and from phenomenological to those based on physical deformation processes. This chapter does not discuss all of the tools available for analysis. It does, however, provide a comparison and discussion of the values and ranges of applications for numerous analytical tools so an engineer or scientist can make informed decisions about how much effort and sophistication is appropriate for a given analysis.

11.2 Review of Modeling Techniques

As stated in the introduction, there are numerous available techniques for modeling fluoropolymers. These can be divided into analytical and computational techniques, using more or less sophisticated material models within each technique. Table 11.1 provides a brief description of different modeling approaches with associated advantages and disadvantages. Each technique can use increasingly complex models for polymer behavior, ranging from linear elastic to involved viscoplastic constitutive models.

Finite element analysis involves the discretization of a geometry into smaller areas (in two-dimensional problems) or smaller volumes (in three-dimensional analyses). This discretization permits the solution of complicated boundary-value problems involving very complex geometries and similarly complex material behavior. It is the technique of choice for complicated polymer analyses.

Finite element analysis has become particularly useful due to developments in recent years. These developments include the following:

- Increased processor speed permitting more complicated analyses with large deformations and complex constitutive behavior.
- Development of robust explicit finite element codes that can reliably accommodate contact between surfaces and time dependence.
- Robust methods for handling large deformations.
- Meshing and remeshing software that ease the development of finite element models for complex geometries.
- Physically based constitutive models that accurately capture the behavior of fluoropolymers.
- Development of finite element codes that can work on parallel processors, accelerating analysis times.

Appropriate use of finite element analysis methods require three sets of inputs: loading conditions, geometry, and material behavior. The loading conditions consist simply of the displacements, loads, temperatures, and stresses that a component is expected to experience. These loading conditions do not change between analyses. Geometry simply replicates the shape of a component and, therefore, the geometry difference between modeling efforts depends on how accurately one needs capture that shape. Material behavior provides the greatest opportunity for choice and variation between modeling methods. There are many material models available for fluoropolymers, ranging from very simple (frequently inaccurate), to very complex, requiring material testing that ultimately results in more accuracy.

Table 11.1. Summary of Available Modeling Approaches

Technique	Advantages	Disadvantages
Linear elastic solutions from stress analysis handbooks	Relatively quick with validated results.	Does not account for polymer nonlinearity. May underestimate strains and stresses and underestimate deformations. Standard geometries only.
Linear viscoelastic solutions from stress analysis handbooks	Relatively quick.	Small strain effects only. Simple, accepted material laws. Standard geometries only. Some material testing may be required.
Analytical viscoplastic solutions	More accurate than elastic or viscoelastic for simple geometries.	No standard solutions available. Requires some numerical analysis given complexity of material model. Some material testing may be required.
Linear elastic finite element analysis	Accommodates complex geometries. Rapid analysis possible.	Does not account for FP nonlinearity. May underestimate strains and stresses and underestimate deformations. Good only for small strains.
Hyperelastic finite element analysis	Accommodates complex geometries. Can handle nonlinearity in material behavior and large strains. Rapid analysis possible. Standard material models available.	Does not include rate-dependent behavior. Cannot predict permanent deformation. Does not handle hysteresis. Some material testing may be required. Can produce errors in multiaxial stress states.
Standard plasticity finite element analysis	Provides nonlinear behavior with large strains and permanent deformations. Standard material model.	Does not include rate-dependent behavior. Does not handle hysteresis. Not accurate for polymers.
Finite element analysis with polymer-specific material or constitutive laws	Accommodates complex geometries. Can handle nonlinearity in material behavior and large strains. Rapid analysis possible. Can predict very complicated polymer behavior, including filled polymers and complex temperature-loading histories.	Requires the most computing power. Requires the most material testing.

11.3 Currently Available Material Models

Fluoropolymers, as well as other thermoplastics, exhibit a complicated nonlinear response when subjected to loads. The behavior is characterized by initial linear viscoelasticity at small deformations, followed by distributed yielding, viscoplastic flow, and material stiffening at large deformations until ultimate failure occurs. The response is further complicated by a strong dependence on strain rate and temperature, as illustrated in Fig. 11.1. It is clear that higher deformation rates and lower temperatures increase the stiffness of the material.

Thermoplastics are unique and typically exhibit a broad range of behaviors. This is illustrated by comparing their mechanical responses to the responses of other structural materials such as metals. The observed behavior is a manifestation of the different microstructures of the two types of materials and the different micromechanisms controlling the deformation resistance. It is, therefore, not surprising that different material models should be used when representing fluoropolymers instead of metals. Specifically, traditional material models for metals (e.g., the J_2-plasticity model[1]), although convenient and often familiar to the simulation engineer, should be used with great caution. They are rarely, if ever, a good choice for thermoplastics such as fluoropolymers. As an example, Fig. 11.2 shows that the magnitudes of the true stress in tension and compression, at the same magnitude of applied strain, are very different for fluoropolymers. However, stress predictions based on the J_2-plasticity model are always symmetrical in the strain, clearly in disagreement with the experimental data. There are models that can more accurately capture the difference between tension and compression.

There are a number of candidate materials models for predicting the behavior of fluoropolymers. Since the models have varying degrees of complexity, computational expense, and difficulty in determining the material parameters, it is a good idea to use the simplest material model that captures the necessary material characteristics for the application and situation at hand. Unfortunately, it is often difficult to determine, in advance, the required conditions needed by the material model. Hence, it is recommended that a more advanced model be used in order to ensure accuracy and reliability of the predicted data. At a later stage, a less advanced model can be attempted if the computational expense is too great. At that time, the accuracy of the different model predictions can also be tested and validated.

Given their obvious advantages, development of advanced constitutive models for fluoropolymers and other thermoplastics is an active area of research that is continuously evolving and improving. In the last few years, models capable of predicting a majority of the experimentally observed characteristics have been developed.[2]–[4] Some of the modeling approaches are summarized later in this section. A number of traditional models can also be used to predict different aspects of the fluoropolymer behavior. These models are often easier to use but have a limited domain of applicability. The three main models of this category are linear elasticity, hyperelasticity, and linear viscoelasticity. These models also have the added benefit of being directly available in all commercial finite element software packages. The next few sec-

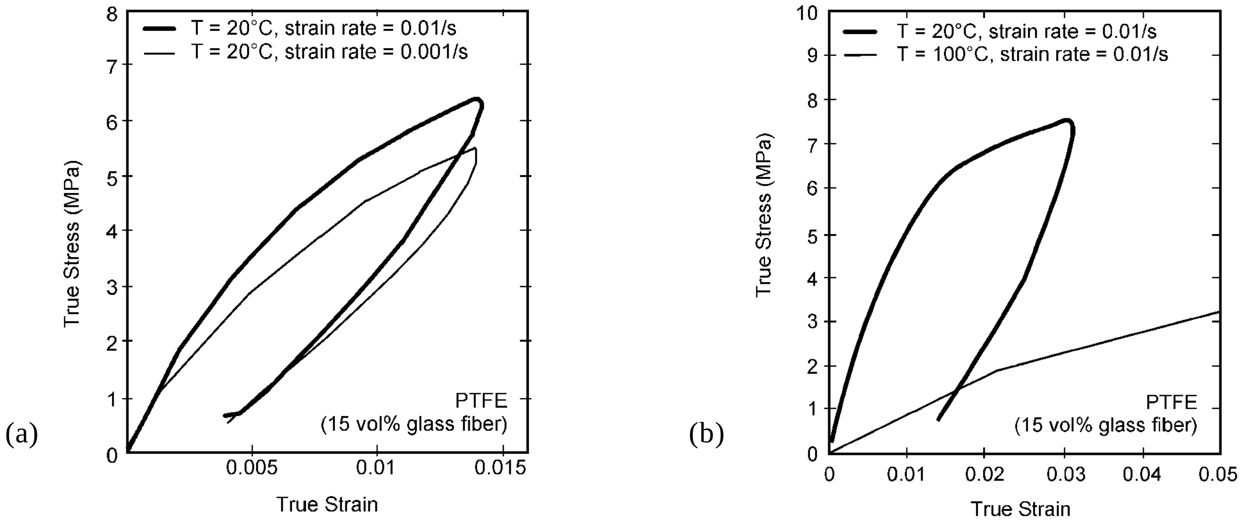


Figure 11.1 Exemplar stress-strain curves for PTFE filled with 15 vol% glass fiber; *(a)* Illustrates the strain-rate dependence at small deformations, *(b)* illustrates the influence of temperature on the mechanical response.

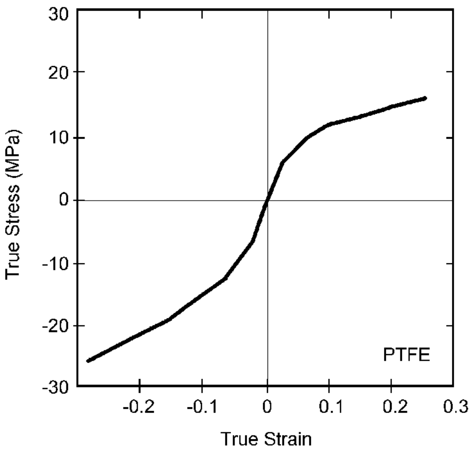


Figure 11.2 The magnitude of the stress response at intermediate and large strains is very different in tension and compression for fluoropolymers.

tions present these traditional models and how they apply to fluoropolymers. Then, as an example of a more advanced material model, the Dual Network Fluoropolymer (DNF) model[5] is presented.

11.3.1 Linear Elasticity

Linear elasticity is the most basic of all material models. Only two material parameters need to be experimentally determined: the Young's modulus and the Poisson's ratio. The Young's modulus can be directly obtained from uniaxial tension or compression experiments, and typical values for a few select fluoropolymers at room temperature are presented in Table 11.2.

The Poisson's ratio can be determined by measuring the transverse strain during uniaxial tension or compression experiments. Due to the small magnitude of the transverse strain, it is difficult to accurately determine the Poisson's ratio. Instead, it is often sufficient to assume a value for the Poisson's ratio of about 0.4. Unless the fluoropolymer component is highly confined, the Poisson's ratio has only very weak influence on the predicted material response.

Fluoropolymers can rarely be represented with a high degree of accuracy using linear elasticity. As exemplified in Fig. 11.3, only if the applied strains are less than about 0.4% can linear elasticity be taken as a reasonable model.

Another situation where a linear elastic representation can be of value is if the fluoropolymer component is part of a larger system and the response of the fluoropolymer component is not the focus of the study and has little influence on overall response.

Table 11.2. Representative Values of the Young's Modulus at Room Temperature for a Few Select Fluoropolymers

Materials	Young's Modulus (MPa)
PTFE (unfilled)	400–800
PTFE (15% glass fiber)	700–1200
FEP	300–600
TFE	300–600

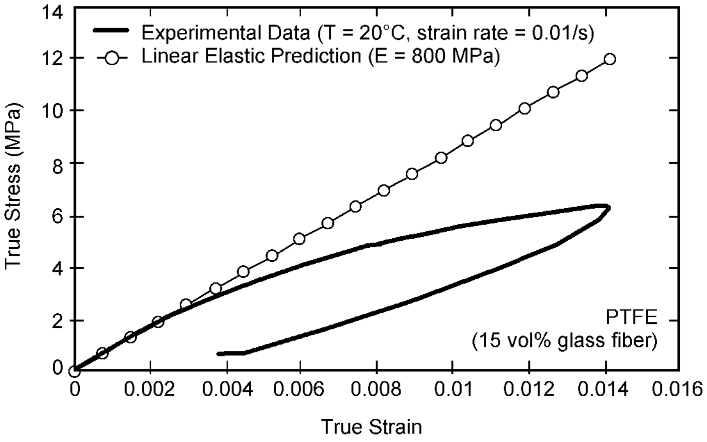


Figure 11.3 Comparison between experimental data for PTFE (with 15 vol% glass fiber) and predictions from a linear elasticity model.

11.3.2 Hyperelasticity

A natural extension of linear elasticity is hyperelasticity.[6] Hyperelasticity is a collective term for a family of models that all have a strain energy density that only depends on the applied deformation state. This class of material models is characterized by a nonlinear elastic response, and does not capture yielding, viscoplasticity, or time-dependence. The strain energy density is the energy that is stored in the material as it is deformed, and is typically represented either in terms of invariants of the deformation gradient: $\hat{I}_1$, $\hat{I}_2$, and J, where

Eq. (11.1) $$\hat{I}_1 = \hat{\lambda}_1^2 + \hat{\lambda}_2^2 + \hat{\lambda}_3^2$$

Eq. (11.2) $$\hat{I}_2 = \hat{\lambda}_1^{-2} + \hat{\lambda}_2^{-2} + \hat{\lambda}_3^{-2}$$

Eq. (11.3) $$J = \det[F] = \lambda_1 \lambda_2 \lambda_3$$

or directly in terms of the distortional principal stretches:

$$\hat{\lambda}_1, \hat{\lambda}_2, \text{and } \hat{\lambda}_3$$

The distortional stretches can be obtained from the applied principal stretches by

$$\hat{\lambda}_i = J^{-1/3}\lambda_i,\ i = 1, 2, 3$$

The two main types of hyperelastic models are the polynomial model and the Ogden model. In the polynomial model, the strain energy density is given by

Eq. (11.4)

$$W = \sum_{i+j=1}^{N} C_{ij}\left(\hat{I}_1 - 3\right)^i \left(\hat{I}_2 - 3\right)^j \sum_{i=1}^{N} D_i \left(J - 1\right)^{2i}$$

and, in the Ogden model, the strain energy density is given by

Eq. (11.5)

$$W = \sum_{i=1}^{N} C_i \left(\lambda_1^{a_i} + \lambda_2^{a_i} + \lambda_3^{a_i} - 3\right) + \sum_{i=1}^{N} D_i \left(J - 1\right)^{2i}$$

Commercial finite element software packages typically contain a number of other hyperelastic representations that can also be used.

Hyperelastic models are often used to represent the behavior of crosslinked elastomers where the viscoelastic response can sometimes be neglected compared to the nonlinear elastic response. Since fluoropolymers behave significantly different from elastomers, there are only specific cases when a hyperelastic representation is of value for fluoropolymer simulations. One case is when the loading is purely monotonic and at one single loading rate. Under these conditions it is not possible to distinguish between nonlinear elastic and viscoplastic behavior, and a hyperelastic representation might be considered. If a hyperelastic model is used in an attempt to capture the stress-strain response that is observed at large strains, including yielding, then it is a significant risk that the model is not unconditionally stable, also referred to as not being Drucker-stable.[1] This means that even if a hyperelastic model can be fit to uniaxial experimental data, it is possible that predictions of multiaxial deformation states are very inaccurate. It is, therefore, often safer to use a more advanced model than can capture the yielding and the flow behavior in a more robust and accurate way.

Hyperelastic models within finite element codes should be used carefully when a component experiences multiaxial stresses.

11.3.3 Linear Viscoelasticity

Linear viscoelasticity is an extension of linear elasticity and hyperelasticity that enables predictions of time-dependence and viscoelastic flow. Linear viscoelasticity has been extensively studied for many different materials[7] and can be very useful when applied under the appropriate conditions. Another added benefit of linear viscoelasticity is that it is available in all commercial finite element packages and therefore easy to use.

The basic foundation of linear viscoelasticity theory is the Boltzmann's superposition principle which states:

> *Every loading step makes an independent contribution to the final state.*

This idea can be used to formulate an integral representation of linear viscoelasticity. The strategy is to perform a thought experiment in which a step function in strain is applied, $\varepsilon(t) = \varepsilon_0 \cdot H(t)$, where $H(t)$ is the Heaviside step function, and the stress response $\sigma(t)$ is measured. Then a stress relaxation modulus can be defined by $E(t) = \sigma(t)/\varepsilon_0$. Note that ε_0 does not have to be infinitesimal due to the assumed superposition principle. To develop a model capable of predicting the stress response from an arbitrary strain history, start by decomposing the strain history into a sum of infinitesimal strain increments:

Eq. (11.6) $$\varepsilon(t) = \sum_{i=1}^{N} \Delta\varepsilon_i H(t - \tau_i)$$

The stress response can then be written

Eq. (11.7) $$\sigma(t) = \sum_{i=1}^{N} \Delta\varepsilon_i E(t - \tau_i)$$

In the limit as the number of strain increments goes to infinity, the stress response becomes

Eq. (11.8)

$$\sigma(t) = \int_{-\infty}^{t} E(t-\tau)\,d\varepsilon(t) = \int_{-\infty}^{t} E(t-\tau)\frac{d\varepsilon(t)}{d\tau}\,d\tau$$

This equation can be generalized to a three-dimensional deformation state for an isotropic material as follows:

Eq. (11.9)

$$T(t) = \int_{0}^{t} 2G(t-\tau)\,\dot{e}\,d\tau + \mathrm{I}\int_{0}^{t} K(t-\tau)\,\dot{\phi}\,d\tau$$

where $G(t)$ is the stress relaxation shear modulus, $\dot{e}$ is the rate of change of deviatoric strains, $K(t)$ is the stress relaxational bulk modulus, and $\dot{\phi}$ is the rate of change of volumetric strains. Only two relaxation moduli need to be determined to predict any arbitrary deformation. The relaxation moduli can be determined from stress relaxation tests and are typically specified into finite element packages as a power series of exponential functions (prony series):

Eq. (11.10) $$G(t) = G_\infty + \sum_{i=1}^{N} G_i e^{-t/\tau_i}$$

The theory behind linear viscoelasticity is simple and appealing. It is important to realize, however, that the applicability of the model for fluoropolymers is restricted to strains below the yield strain. One example comparing predictions based on linear viscoelasticity and experimental data for PTFE with 15 vol% glass fiber in the very small strain regime is shown in Fig. 11.4.

The figure shows that the model predictions are in reasonable agreement with the experimental data. For example, the model quantitatively captures the unloading behavior and hysteresis. An illustration of what happens when linear viscoelasticity is applied to a deformation history that goes past yield is illustrated in Fig. 11.5. This figure shows that linear viscoelasticity is incapable of capturing the yielding behavior of fluoropolymers. Either the large strain behavior is captured, completely ignoring the yielding behavior, or the model can be made to fit the small pre-yield behavior.

Another interesting aspect of linear viscoelasticity is that it can be extended to enable predictions at different temperatures. The basis for this approach is based on a time-temperature superposition principle.[7] This approach has been shown to work well in a restricted temperature range, but does not change the requirement of small strains.

11.3.4 Dual Network Fluoropolymer (DNF) Model

A number of more advanced and general models attempting to predict the yielding, viscoplastic flow, time-dependence, and large strain behavior of fluoropolymers and other thermoplastics have recently been developed.[2]–[4] In this section, we discuss the Dual Network Fluoropolymer (DNF) model.[5]

The DNF model incorporates the experimentally observed characteristics by using a micromechanism-inspired approach in which the material behavior is decomposed into a viscoplastic response, corresponding to irreversible molecular chain sliding due to the lack of chemical crosslinks in the material, and a time-dependent viscoelastic response. The viscoelastic response is further decomposed into the response of two molecular networks acting in parallel: the first network (A) captures the equilibrium response and the second network (B) the time-dependent deviation from the viscoelastic equilibrium state. A one-dimensional rheological representation of the model framework and a schematic illustrating the kinematics of deformation are shown in Fig. 11.6.

In this constitutive framework, the total deformation gradient $\mathbf{F}$ is decomposed into viscoplastic and viscoelastic components: $\mathbf{F} = \mathbf{F}^{ve}\mathbf{F}^{p}$. The viscoelastic deformation gradient acts on both the equilibrium network A, and on the time-dependent network B, i.e., $\mathbf{F}^{ve} = \mathbf{F}_A = \mathbf{F}_B$. The Cauchy stress acting on network A is given by the eight-chain representation:[8][9]

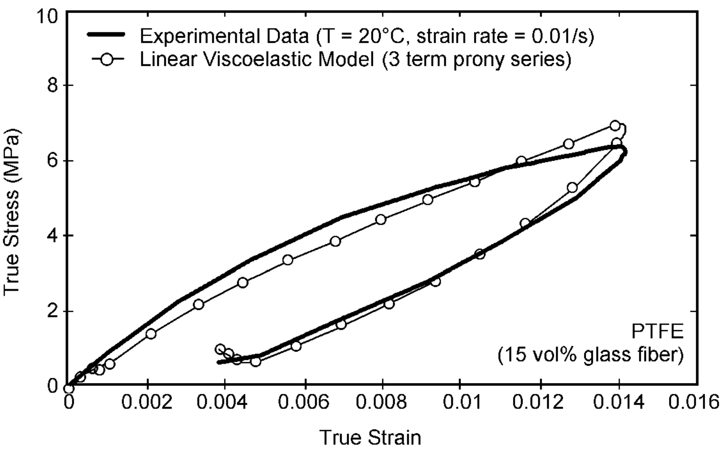


Figure 11.4 Comparison between experimental data for PTFE (15 vol% glass fiber) and predictions from linear viscoelasticity theory.

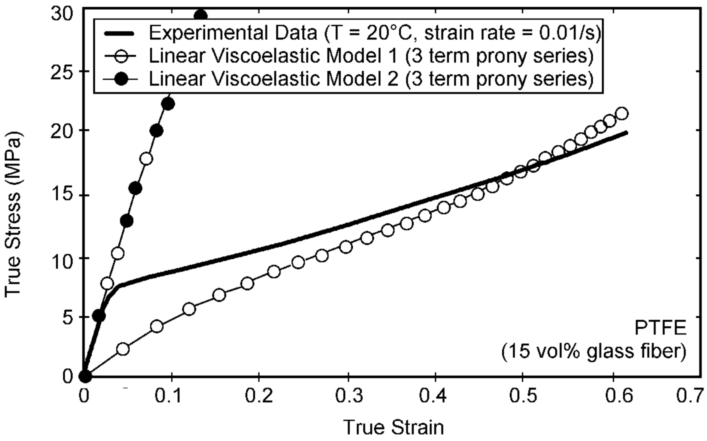
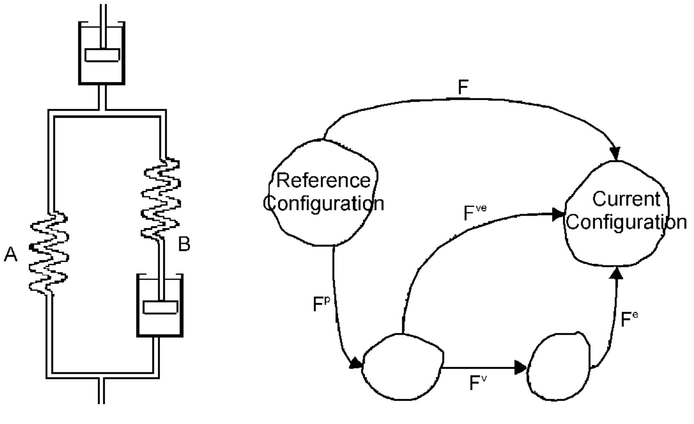


Figure 11.5 Comparison between experimental data for PTFE (15 vol% glass fiber) and predictions from linear viscoelasticity theory.



(a) (b)

Figure 11.6 *(a)* Rheological representation of the constitutive model; *(b)* kinematics of deformation.

Eq. (11.11)

$$J^{ve}\mathbf{T}_A = \frac{\mu_A^0(\theta)}{\overline{\lambda}*}\,\frac{L^{-1}\left(\dfrac{\overline{\lambda^{ve*}}}{\lambda^{lock}}\right)}{L^{-1}\left(\dfrac{1}{\lambda^{lock}}\right)}\,\mathrm{dev}\left[\mathbf{B}^{ve*}\right] + \kappa\left[\ln J^{ve}\right]\mathbf{1}$$

where $J^{ve} = \det[\mathbf{F}^{ve}]$, $\mu_A^0\,(\theta)$ is a temperature dependent shear modulus, λ^{lock} is a chain locking stretch, $\mathbf{B}^{ve*} = (J^{ve})^{-2/3}\mathbf{F}^{ve}(\mathbf{F}^{ve})^T$, and

$$\overline{\lambda^{ve*}} = \sqrt{\frac{\mathrm{tr}\left(\mathbf{B}^{ve}\right)}{3}}$$

is the effective chain stretch based on the eight-chain topology assumption.[9] By explicitly incorporating the temperature dependence of the shear modulus it is possible to capture the stiffness of the material over a wide range of temperatures. The following expression is found to accurately capture the experimentally observed[10] temperature dependence of the shear modulus for temperatures between 20°C and 200°C:

Eq. (11.12) $$\mu_A^0(\theta) = \mu_A \exp\left[\frac{\theta_0 - \theta}{\theta_{base}}\right]$$

where $\theta_0 = 20°\mathrm{C}$ is a reference temperature, and μ_A and θ_{base} are material parameters.

The viscoelastic deformation gradient acting on network B is decomposed into elastic and viscous parts**:** $\mathbf{F}^{ve} = \mathbf{F}^e\mathbf{F}^v$. The Cauchy stress acting on network B is obtained from the eight-chain network representation using the same procedure that was used for network A:

Eq. (11.13)

$$J^{e}\mathbf{T}_B = \frac{\mu_B^0(\theta)}{\overline{\lambda^{e*}}}\,\frac{L^{-1}\left(\dfrac{\overline{\lambda^{e*}}}{\lambda^{lock}}\right)}{L^{-1}\left(\dfrac{1}{\lambda^{lock}}\right)}\,\mathrm{dev}\left[\mathbf{B}^{e*}\right] + \kappa\left[\ln J^{e}\right]\mathbf{1}$$

where $J^e = \det(\mathbf{F}^e)$, and

$$\overline{\lambda^{e*}} = \sqrt{\frac{\mathrm{tr}\left(\mathbf{B}^{e*}\right)}{3}}$$

The volumetric response is governed by the bulk modulus κ, which is taken to be the same for both networks A and B. The temperature dependence of the shear modulus $\mu_B^0\,(\theta)$ is captured using the same temperature dependence as was used for μ_A^0. Using this framework, the total stress in the system is given by $\mathbf{T}_A + \mathbf{T}_B$.

The total velocity gradient of network B,

$$\mathbf{L}^{ve} = \dot{\mathbf{F}}^{ve}\left(\mathbf{F}^{ve}\right)^{-1}$$

can similarly be decomposed into elastic and viscous components:

$$\mathbf{L}^{ve} = \mathbf{L}^e + \mathbf{F}^e\mathbf{L}^v\mathbf{F}^{e-1} = \mathbf{L}^e + \tilde{\mathbf{L}}^v$$

where

$$\mathbf{L}^v = \dot{\mathbf{F}}^v\mathbf{F}^{v-1} = \mathbf{D}^v + \mathbf{W}^v$$

and

$$\tilde{\mathbf{L}}^v = \tilde{\mathbf{D}}^v + \tilde{\mathbf{W}}^v$$

The unloading process relating the deformed state to the intermediate state is not uniquely defined since an arbitrary rigid body rotation of the intermediate state still leaves the state stress-free. The intermediate state can be made unique in different ways;[11] one particularly convenient way is to prescribe

$$\tilde{\mathbf{W}}^v = 0$$

This will, in general, result in elastic and inelastic deformation gradients which both contain rotations. The rate of viscoplastic flow of network B is constitutively prescribed by

$$\tilde{\mathbf{D}}^v = \dot{\gamma}^v_{dev}\mathbf{N}^v_{dev} + \dot{\gamma}^v_{vol}\mathbf{N}^v_{vol}$$

where the first term gives the deviatoric viscoelastic flow and the second terms gives the volumetric viscoelastic flow. The terms $\mathbf{N}^v_{dev}$ and $\mathbf{N}^v_{vol}$ specify the directions of the driving deviatoric and volumetric stresses of the relaxed configuration converted to the current configuration, and the terms $\dot{\gamma}^v_{dev}$ and $\dot{\gamma}^v_{vol}$ specify the effective deviatoric and volumetric flow rates. Noting that $\mathbf{T}_B$ is computed in the loaded configuration, the driving deviatoric stress on the relaxed configuration convected to the current configuration is given by $\mathbf{T}'_B = \text{dev}[\mathbf{T}_B]$ and, by defining an effective stress by the Frobenius norm

$$\tau_B = \left\| \mathbf{T}'_B \right\|_F = \left[\text{tr}\left(\mathbf{T}'_B \mathbf{T}'_B \right) \right]^{1/2}$$

the direction of the driving deviatoric stress becomes

$$\mathbf{N}^v_{dev} = \mathbf{T}'_B / \tau_B$$

The effective deviatoric flow rate is given by the reptation-inspired equation

Eq. (11.14)

$$\dot{\gamma}^v_{dev} = \dot{\gamma}_0 \left[\overline{\lambda}^v - 1 \right]^c \cdot \left(\frac{\tau_B}{\tau_{base} + \beta p} \right)^m \cdot \left(\frac{\theta}{\theta_{base}} \right)^n$$

where

$$\overline{\lambda}^v = \sqrt{\frac{\text{tr}\left[\mathbf{B}^v \right]}{3}},$$

$p = -(\mathbf{T}_{11} + \mathbf{T}_{22} + \mathbf{T}_{33})/3$ is the hydrostatic pressure, and c, m, τ_{base}, n, β, and θ_{base} are material parameters. For numerical implementations, this equation can be condensed to

Eq. (11.15) $$\dot{\gamma}^v_{dev} = \dot{\gamma}_i \left[\overline{\lambda}^v - 1 \right]^C \cdot \tau_B^m \cdot \theta^n$$

Due to the high bulk modulus of PTFE, the effective volumetric flow rate is small and here represented with a constant viscosity:

$$\eta_{vol} : \dot{\gamma}^v_{vol} = p / \eta_{vol}$$

In summary, the velocity gradient of the viscoelastic flow can be written

Eq. (11.16) $$\mathbf{L}^v = \mathbf{F}^{e-1} \left(\dot{\gamma}^v_{dev} \frac{\text{dev}\left[\mathbf{T}_B \right]}{\tau_B} + \dot{\gamma}^v_{vol} \mathbf{I} \right) \mathbf{F}^e$$

The rate of viscoplastic flow is captured by a simple phenomenological representation:

Eq. (11.17) $$\dot{\gamma}^p = \begin{cases} ab\left(\varepsilon - \varepsilon_0 \right)^{b-1} \dot{\varepsilon}, & \text{if } \tau > \sigma_0 \\ 0, & \text{otherwise} \end{cases}$$

where $a > 0$, $b > 0$ and $\sigma_0 > 0$ are material parameters, τ is the Frobenius norm of the deviatoric portion of the Cauchy stress $\mathbf{T}$, and ε_0 is the effective strain at which τ becomes equal to σ_0. The effective strain used in Eq. (11.04) is obtained from

Eq. (11.18) $$\varepsilon = \left\| \mathbf{E}_{\ln} \right\|_F$$

where $\mathbf{E}_{\ln}$ is the logarithmic strain. The key feature of Eq. (11.04) is that it predicts the rate of viscoplastic flow to be proportionate to the applied strain rate and the magnitude of the current strain. By inserting $\mathbf{F} = \mathbf{F}^{ve}\mathbf{F}^p$ into $\mathbf{L} = \dot{\mathbf{F}}\mathbf{F}^{-1}$, the expression for the velocity gradient can be expanded to $\mathbf{L} = \mathbf{L}^{ve} + \mathbf{F}^{ve}\mathbf{L}^p\mathbf{F}^{ve} = \mathbf{L}^{ve} + \tilde{\mathbf{L}}^p$. By taking $\tilde{\mathbf{W}}^p = 0$, the viscoplastic velocity gradient can be written

$$\tilde{\mathbf{L}}^p = \frac{\dot{\gamma}^p \text{dev}\left[\mathbf{T} \right]}{\tau}$$

giving

Eq. (11.19) $$\mathbf{L}^p = \dot{\gamma}^p \mathbf{F}^{ve-1} \frac{\text{dev}\left[\mathbf{T} \right]}{\tau} \mathbf{F}^{ve}$$

specifying the rate kinematics of the viscoplastic flow.

In the case study presented in Sec. 11.5.2, the DNF model can accurately predict the large strain thermomechanical behavior of fluoropolymers, including time dependence, hysteresis, and deviatoric and volumetric flow. The DNF model is currently not implemented as a built-in feature in any commercial finite element software package, but the authors have implemented it as an external user subroutine that can be used as efficiently as the built-in material models.

Before using the DNF model to represent a fluoropolymer material, it first needs to be calibrated. The calibration is performed on a select set of experimental tests that are typically performed in uniaxial loading. The selection of calibration experiments is somewhat arbitrary, since the objective of the testing is simply to sufficiently probe the material response. For the DNF model, it is recommended that uniaxial loading and unloading experiments be performed at three different strain rates. If predictions at different temperatures are required, then it is necessary to repeat these tests at a few temperatures in the temperature range of interest. Finally, if large hydrostatic pressure variations are going to be applied, then the volumetric response also needs to be determined. The material constants can be determined after the calibration experiments have been performed. The Young's modulus and Poisson's ratio are directly obtained from the experimental data. Initial estimations of the remaining material constants can be obtained from previously published values for fluoropolymers.[5] To obtain actual values for the remaining material constants for a new material, it is often beneficial to use an automatic search algorithm to optimize the initial estimations of the material parameters. The procedure is to use the DNF model to simulate the calibration experiments and then compare the predicted response with the experimental data set. In our work, we use a fully automatic specialized computer program based on the Nelder-Mead simplex minimization algorithm[12] to find the optimum set of material parameters. There are many different methods that can be used to quantitatively evaluate the quality of a predicted response. One particularly appropriate method is to use the coefficient of determination (r^2) as the main predictor.[13]

Representative examples of the predictive capabilities of the DNF model are presented in the case study in Sec. 11.5.2.

11.4 Failure and Deformation Predictions

After a constitutive model has been chosen, calibrated, and validated for a particular fluoropolymer, it becomes as easy to perform multiaxial deformation simulations as it is to simulate uniaxial deformation. If the material model considers time dependence, temperature dependence, or damage evolution, then thermomechanical or fatigue loading can also easily be simulated. Since almost all commercial finite element (FE) software packages allow for nonlinear simulations including considerations of large deformations, the key component of performing accurate finite element simulations lies within the specification and calibration of the constitutive model.

Once the geometry and loading conditions have been specified and an appropriate material model is calibrated to relevant experimental data, then FE simulations can provide valuable information about the deformation and loading behavior of fluoropolymer components. At many occasions, however, this is not enough. It is often desirable to determine at what time in an applied loading history the fluoropolymer component is likely to fail. To predict failure requires that the constitutive model be supplemented with a failure model. The constitutive model by itself only specifies the relation between stress and strain, not when failure will occur. The failure model provides a relationship between the stress and strain histories acting on the component and the probability for failure. Predicting when failure will occur in a fluoropolymer component is a difficult task, and is an active area of research.

Failure of polymer components is an inherently stochastic process. Consequently, repeated failure testing on seemingly identical specimens will always result in failure at different load levels. Failure models can either simply attempt to predict the average failure strength, or attempt to determine the distribution of failure strength values for a given test scenario. There are two ways to develop a failure model that allows for predictions of the strength distribution. One approach is to consider that the initial undeformed material has a given stochastic distribution of material properties. The other way is to consider that the material has a given stochastic distribution in the ultimate failure properties. Which of these approaches is most appropriate for a given material and component is dependent on the microstructure of the material and the specific details of the problem at hand. Stochastic failure modeling is a very young field in polymer science and engineering and is not discussed more in this summary.

Failure of polymeric components can occur in different ways under different circumstances. Examples of failure modes include rupture, fatigue, fracture, wear, and abrasion. The simplest type of failure occurs when a component without any apparent defects is monotonically loaded to failure. Once a good understanding of failure under these conditions is obtained, failure predictions of components with defects and inhomogeneities can be addressed by evaluating the enhanced stress state around the inhomogeneities. A different type of failure mode is fatigue caused by cyclic loading. Under cyclic loading, flaws will nucleate, grow, and ultimately cause final failure. Predictions of fatigue failures can be addressed either by incorporating a damage model into the constitutive model, or by using a phenomenological fatigue lifetime representation. Besides pure mechanical loading, chemical and physical aging can also contribute and complicate the failure predictions. The following subsections summarize a more detailed discussion about the different types of failure modes and how they can be predicted.

11.4.1 Failure under Monotonic Loading

The physics of failure of fluoropolymers on the microscale is caused by thermally activated breakages of secondary and primary bonds in the material. The chain scission leads to crack and void formation and ultimate failure. To model and predict these events typically requires an investigation on a larger length scale where a continuum mechanics approach can be used.

There are four main types of models for predicting failure under monotonic loading. The first type is stress-based failure models. A stress-based failure model, in its most general form, can be written $f(\sigma_{ij}) \geq 0$. Since stress is a tensor quantity, the failure model becomes a function of the six independent stress components. Thanks to the difficulty and the experimental effort needed to determine the six-dimensional failure envelope in stress space, the problem is typically simplified by replacing the stress tensor by an effective stress such as the Mises stress. A second type of failure model is strain-based. These are identical to the stress-based failure models except that the stress is replaced by strain. A third type of failure model that is sometimes proposed is energy-based. This type of failure model does not work for fluoropolymers since these materials do not fail under a triaxial compressive stress state, but the applied energy can be very large under these conditions. A fourth type of failure model is fracture mechanics-based models. These models are often expressed in terms of the stress intensity factor K_I,[14] or in terms of the J-integral.[15] In this context, fracture mechanics models can be considered a subset of the stress-based models since the failure criterion is expressed in terms of the stress state. Due to the ductility of fluoropolymers, the size of the plastic zone in front of propagating cracks is often so large that linear elastic fracture mechanics is not applicable. There have been some efforts to apply the J-integral, which can be used in cases with more extensive plasticity, but there are still problems with this approach since thermoplastics undergo viscoplastic deformation and the flow and crack propagation is therefore time dependent. Due to the lack of a well-developed fracture model for polymers in general, and due to the ductility of most fluoropolymers, fracture-like problems and failure are currently best treated by explicitly modeling the inhomogeneities and their influence on the stress field using an advanced constitutive model coupled with a failure model.

It is currently not well established which failure model is most appropriate for predicting failure of fluoropolymers that are monotonically loaded to failure. Commonly used approaches include the maximum principal stress, the maximum principal strain, the Mises stress, the Tresca stress, the Coulomb stress, the volumetric strain, the hydrostatic stress, and the chain stretch. In the chain stretch model, the failure is taken to occur when the molecular chain stretch, calculated from[9]

Eq. (11.20) $$\lambda_{chain} = \sqrt{\frac{\mathrm{tr}[\mathbf{B}]}{3}}$$

where $\mathbf{B} = \mathbf{F}\mathbf{F}^T$ reaches a critical value.

A direct comparison between these and other failure models has not been performed for fluoropolymers, but a recent study of UHMWPE[16] showed that, for UHMWPE, these models are very different. For example, it was shown that the chain stretch model is the most promising for predicting multiaxial deformation states, and that the hydrostatic stress, and the volumetric strain are not good predictors of failure.

11.4.2 Failure under Cyclic Loading

Predicting failure under cyclic loading is more challenging than predicting failure under monotonic loading. One of the main difficulties in predicting failure under cyclic loading is that the number of cycles-to-failure is not only dependent on the load amplitude, but also on the frequency of the applied load and, to some extent, on the specimen geometry. The reason for the frequency and geometry dependence is that the hysteresis loss under cyclic loading causes the specimen to heat up, and the rate of heat transfer away from the specimen to the load platens greatly influences the steady-state specimen temperature. Different specimen geometries allow for different heat transfer rates and, consequently, different steady-state temperatures. The fatigue behavior obviously depends on the specimen temperature, which complicates the analysis of fatigue experiments.

The lifetime of any material under fatigue loading is controlled by an initiation phase and a propagation phase. The initiation phase constitutes the time it takes to initiate cracks and other defects in the material, and the propagation phase consists of the time it takes for the initial flaws to grow to a critical size where final failure occurs. Often one of these phases dominates and controls the lifetime under cyclic loading. For fluoropolymers, which of these phases is dominating depends on the inherent damage and flaw distribution in the material, which, in turn, is controlled by the processing, and additive and filler packages that are used in the material. Due to the inherent processing difficulty of many fluoropolymers, the material often contains a distribution of microvoids that can act as initiation sites for fatigue cracks. Propagation therefore may dominate.

One way to predict failure under cyclic loading of fluoropolymers is to use traditional S-N fatigue data curves. To predict failure, the material must first be experimentally characterized by performing fatigue tests to failure at different applied load levels. Results from this testing is then graphically represented in an S-N curve, as schematically shown in Fig. 11.7.

The fatigue life of real components can be approximated by determining the maximum stress in the actual component using the finite element method, and then extracting the predicted number of cycles to failure from an experimentally determined S-N curve. Note that this method only provides a crude approximation of the fatigue life of the component. For example, the final failure strength depends on the details of the stress state and the geometry, and how they change during the lifetime of the component. Also, both fatigue life and fracture strength depend on specimen volume. Large specimens often tend to fail at lower stresses than smaller specimens. This volume dependence is caused by the larger probability of finding a large initial defect in a larger volume than in a smaller volume.

Another method to predict fatigue failure is to use a damage-based failure model. As discussed earlier, predicting failure under monotonic loading conditions does not require a damage-based model. Under monotonic loading conditions, the material can be considered to be in the same material state throughout its lifetime. To successfully predict failure under cyclic loading, on the other hand, requires a material model that keeps track of the evolution in damage during the loading. In other words, the material model needs to keep track of the history

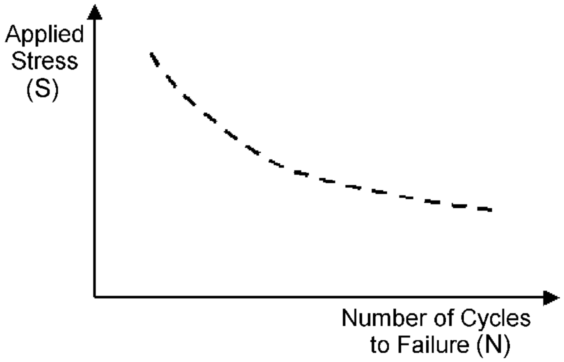


Figure 11.7 Schematic fatigue data for fluoropolymers illustrating the relation between applied stress (S) and the number of cycles to failure (N).

of the material state variables. Damage-based failure models can, in general form, be written as

Eq. (11.21) $$\frac{dD(t)}{dt} = f\left(\sigma_{ij}, \varepsilon_{ij}, t\right)$$

This formulation expresses the rate of change of damage as a function of the current loading state. There currently does not exist any well-tested damage models of this type for predicting the damage evolution and fatigue failure of fluoropolymers. The formulism, however, has been shown to work very well for predicting craze formation in various thermoplastics.[17]

Further discussion of the fatigue and failure behavior of polymers in general is presented in a number of specialized text books.[18]–[21]

11.5 Examples

The following two examples provide first a relatively simple example analysis followed by a second more sophisticated effort that exercises many aspects of advanced fluoropolymer mechanical analysis.

11.5.1 Corrugated PTFE Hose

A PTFE-lined, stainless steel braided hose was used to transport sulphur trioxide at a chemical plant. The hose was attached to an external tank system and was insulated and heated. One day the hose failed and sulphur trioxide leaked and caused serious environmental problems. The failed hose had one long axial crack that had split the hose open, which allowed the liquid to be released. The engineering assignment in this case was to examine the cause of the failure.

An inspection of the failed hose clearly demonstrated that the sulphur trioxide had permeated through the PTFE liner and corroded large portions of the stainless steel liner. As a consequence, the weight of a valve that was attached to the end of the hose was partly supported by the PTFE liner itself. In addition to this axial load, the liner was also exposed to an internal pressure. A schematic representation of the applied loads acting on the liner is shown in Fig. 11.8.

A separate calculation determined that the internal pressure was between 0.15 and 0.60 MPa, and that the weight of the valve at the end of the hose was 280 N.

One further complication in this case was that the temperature of the hose was not known. The ambient temperature was 0°C, but the function of the heating element at the time of the failure was not known. The temperature of the hose could have been as high as 100°C.

The strength of the hose was determined through a set of ten tension-to-failure experiments performed on miniature tension specimens cut from the accident hose. The experiments were performed both at room temperature and at 100°C (Fig. 11.9).

In the figure, the minimum, maximum, and average tensile strengths determined from the incident hose is shown. The figure shows that the tensile strength depends on the temperature and has a large variability between repeated tests.

The finite element method was used to investigate the stress distributions created by the different scenarios presented in Table 11.3.

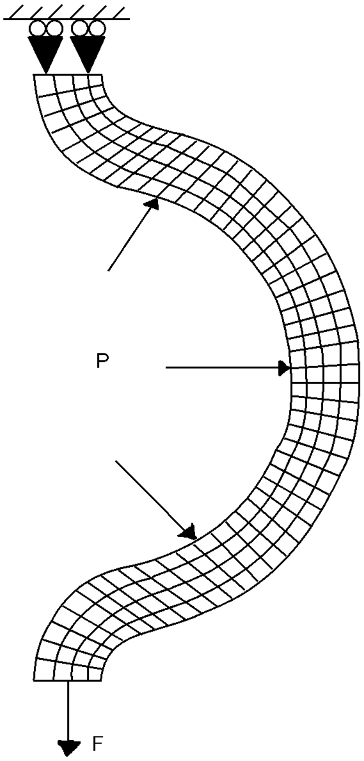


Figure 11.8 Axisymmetric representation of the hose showing the axial load (F) and the internal pressure (P).

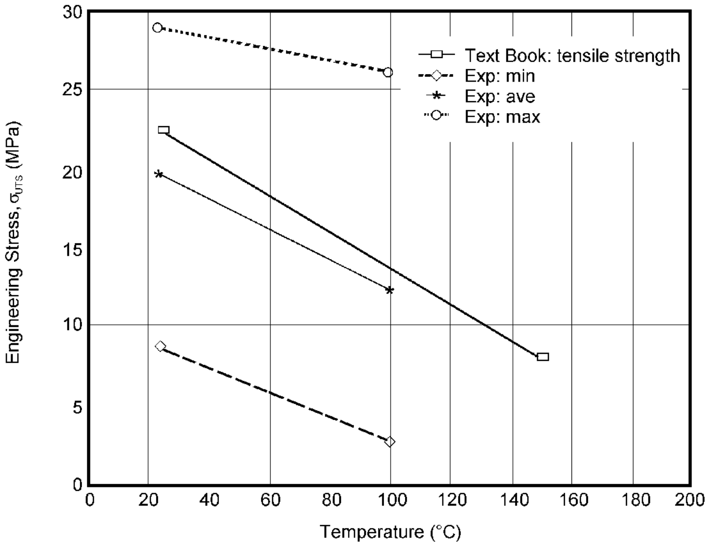


Figure 11.9 Experimentally determined tensile strength as a function of temperature.

Table 11.3. Load Cases Investigated Using the Finite Element Method

Pressure, P (MPa)	Axial Load, F (N)	Temperature (°C)
0.6	0	20
0.6	280	20
0.15	0	100
0.15	280	100

The finite element simulations were performed using the DNF constitutive model presented in Sec. 11.3.4. This model allows for direct simulations of the viscoplastic flow and temperature behavior of the hose in the different loading scenarios. Material parameters for the DNF model were obtained from the literature and the tension tests described above.

One representative figure illustrating the results obtained from the FE simulations is shown in Fig. 11.10.

A comparison of the predicted stresses from the FE analysis with the experimentally determined strength of the PTFE liner showed that the failure of the liner was to be expected. Even if the temperature of the liner was 20°C, the combination of internal pressure and axial load could have caused the axial split in the PTFE liner that was observed.

This analysis was straightforward. The greatest effort was in determining the material parameters for the DNF model, but sufficient literature was available on PTFE to reduce the number of tests to simple tensile and multiple temperatures. The following example provides a more detailed analysis where more material testing was needed to explain the performance of a fluoropolymer gasket.

11.5.2 Threaded Connection Gasket

One common application of fluoropolymers is in gaskets and seals. This section presents a case study of a threaded connection gasket in a high pressure pipeline application. The pipeline was used to transport various gases at temperatures between 20°C and 200°C. Different parts of the pipeline were threaded together, and the primary seal to prevent the gases from leaking out at the threaded connections was established by a metal-to-metal seal (Fig. 11.11). During normal usage, it was discovered that the primary seal was not always reliable. It was decided that a PTFE gasket should be used as a secondary seal. The PTFE gasket was made of a 15 vol% glass-fiber filled PTFE that was inserted into a groove on the exterior portion of the threaded connection (Fig. 11.12).

Since this type of PTFE gasket had not been used before by the manufacturer, it was decided that a finite element study should be performed in order to analyze and optimize the design of the gasket and the threaded connection geometry. The specific aim was to simulate and predict the performance of the gasket for temperatures between 20°C and 200°C. The performance of different designs was to be evaluated by comparing permanent deformation and creep behavior, and by assessing the sealing capability of the secondary seal.

During the assembly process, the seal is exposed to very large deformations, and a large hydrostatic pressure is applied both during assembly and during the final usage. Therefore, it is necessary to use a constitutive model capable of large deformation

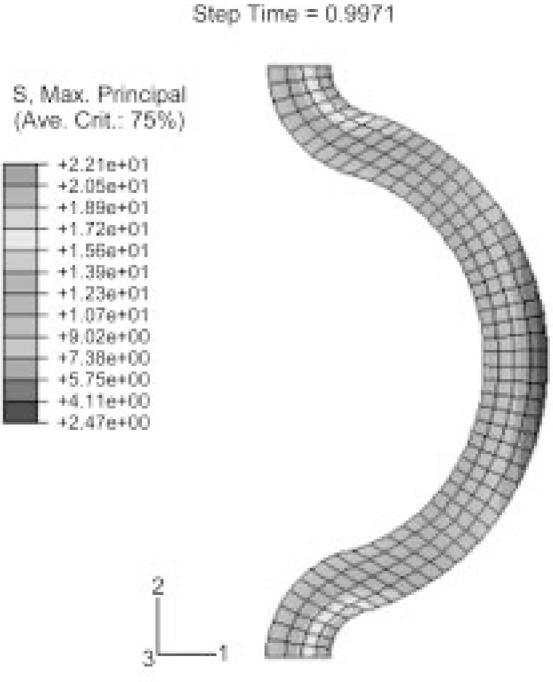


Figure 11.10 Contours of maximum principal stress in the hose at 20°C, P = 0.6 MPa, F = 280 N, after a loading time of 1 min.

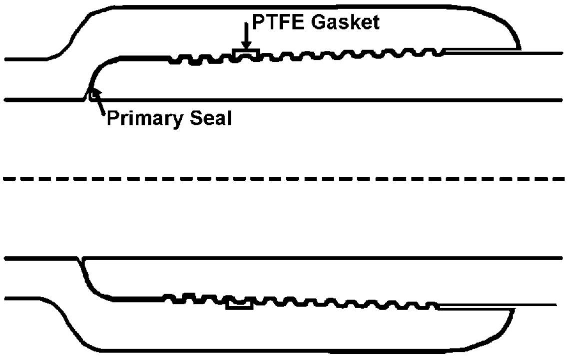


Figure 11.11 Geometry of the threaded connection.

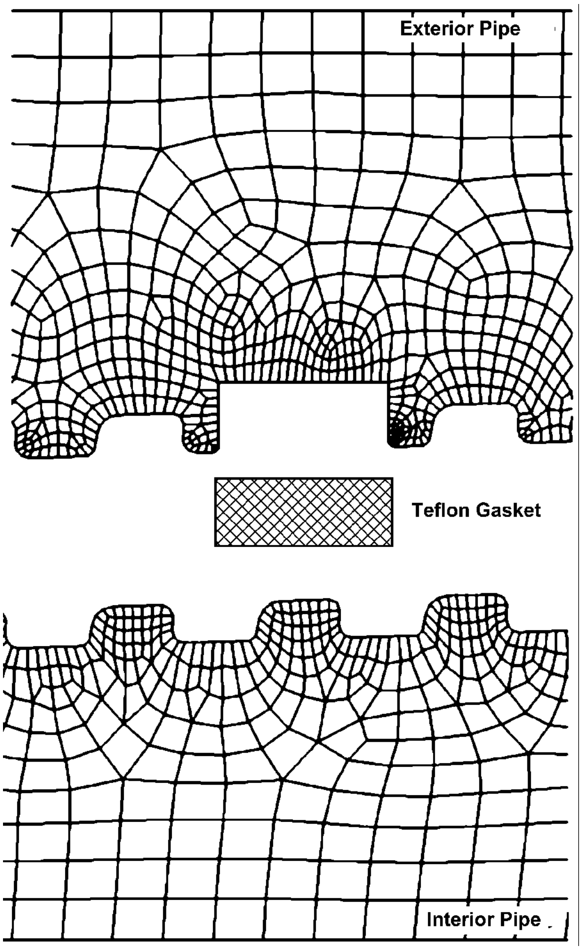


Figure 11.12 FE mesh used to represent the exterior pipe, interior pipe, and PTFE gasket.

analysis to perform accurate simulations of the gasket. The model also needs to be capable of predicting creep behavior and both deviatoric and volumetric flow of the filled PTFE. Furthermore, it is required that the constitutive model be capable of predicting the behavior for a wide range of temperatures. These requirements are very stringent and clearly suggest the use of an advanced constitutive model. In this work, the Bergstrom Dual Network Fluoropolymer (DNF) model was chosen due to its ability to predict the necessary material characteristics.[5] The DNF model is not yet a built-in feature of any commercial finite element code, but it has been implemented as a user subroutine into both ABAQUS and LS-DYNA, and can be used as easily as any of the built-in materials models in these FE packages. In the results presented below, ABAQUS was used as the primary FE solver.

The first step in the project was to perform an extensive set of experimental tests on the actual glass-filled PTFE that was used in the gasket. Specifically, uniaxial tension and compression experiments at different strain rates and different final strain levels were performed. Both the loading and unloading behavior was examined. A few select stress relaxation experiments were also performed to directly probe the stress relaxation behavior of the material. Examples of the experimental data obtained from these tests are shown in Figs. 11.13 to 11.16.

Since the seals were going to be exposed to very large hydrostatic pressures, a set of hydrostatic pressure tests of loading followed by unloading were also performed. The results from these tests indicated that the volumetric response of the material also included volumetric hysteresis during cyclic loading. One example of the volumetric response is shown in Fig. 11.15.

Finally, to examine the multiaxial behavior of the glass-filled PTFE material, a set of small punch experiments[13] were performed. In these tests, a cylindrical specimen with a diameter of 6 mm and a thickness of 0.5 mm was indented by a spherical punch head (Fig. 11.17).

In the small punch tests (Figs. 11.18 and 11.19), the indentation force versus displacement responses of the punch head were recorded. These punch experiments were performed both at 20°C and at 200°C. Figure 11.20 illustrates representative results from these tests.

After the experimental characterization of the material had been completed, the DNF model was calibrated to the uniaxial experimental data. Examples of the calibration simulations are shown in Figs. 11.21 to 11.24. The material parameters used in the simulations are listed in Table 11.4.

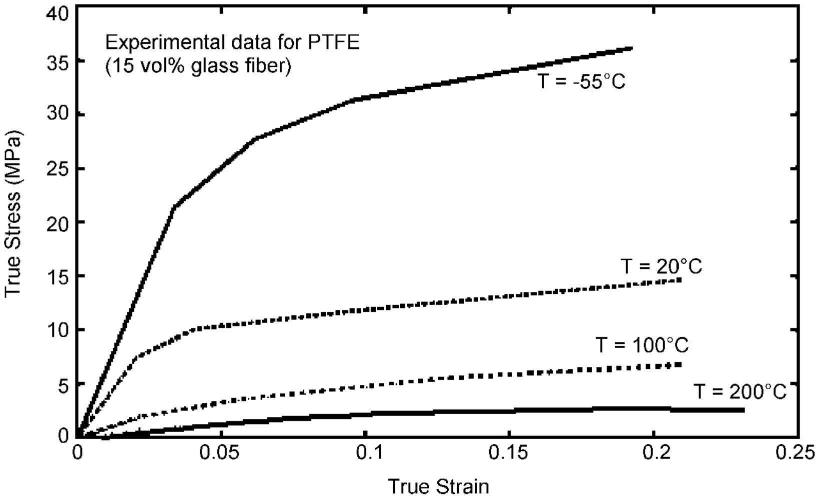


Figure 11.13 Comparison between experimental and predicted data for uniaxial tension at different temperatures.

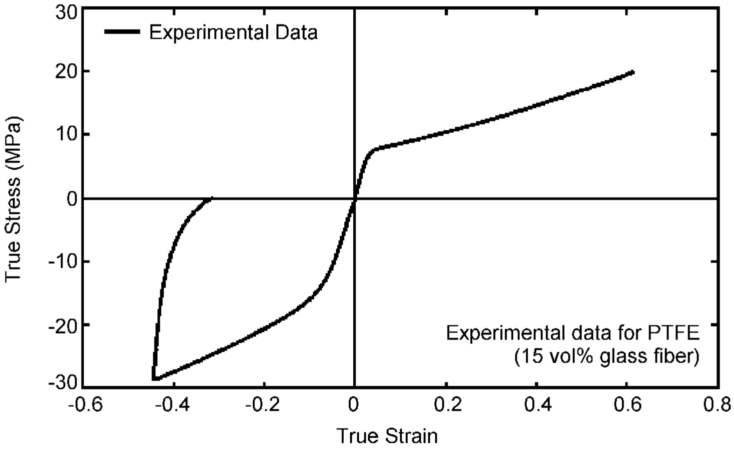


Figure 11.14 Comparison between experimental data and predicted behavior for uniaxial tension at different strain rates.

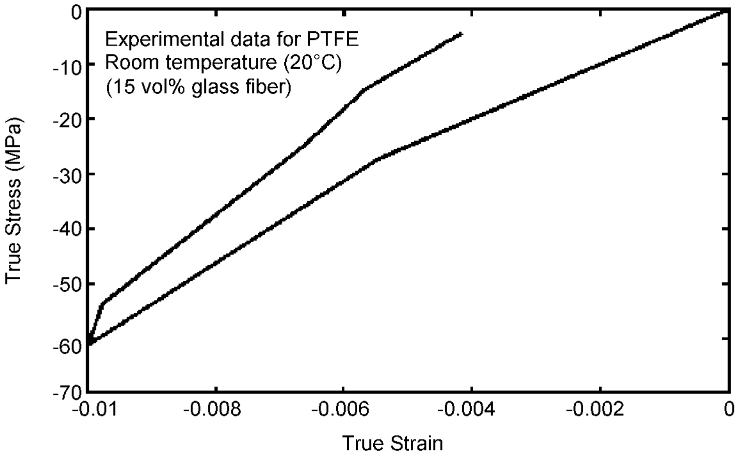


Figure 11.15 Comparison between experimental triaxial compression data and model predictions for filled PTFE.

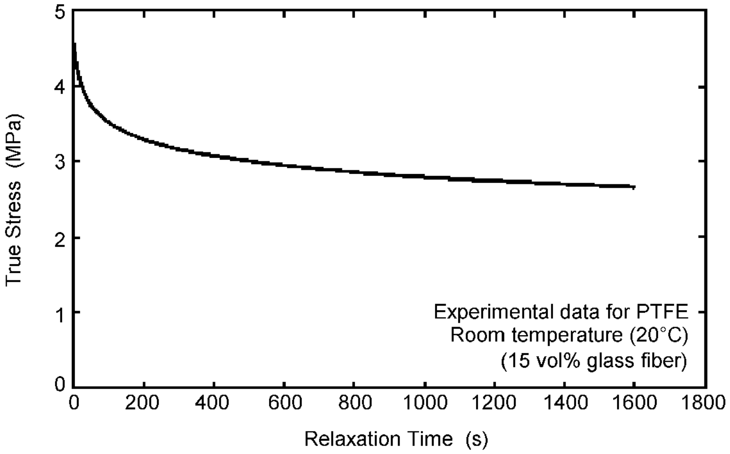


Figure 11.16 Stress relaxation data after a strain jump to 0.01 at time 0.

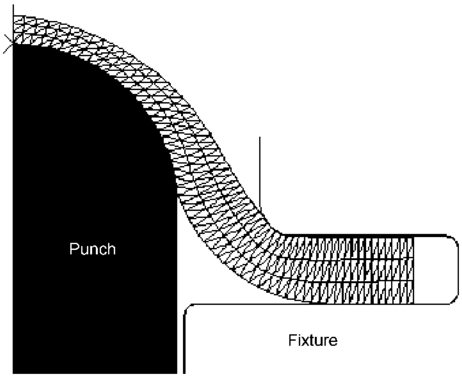


Figure 11.17 Finite element mesh used in the small punch simulations. In the testing, the spherical punch head indented the disc-shaped specimen that was held in place in the fixture by frictional forces. The figure shows the deformed mesh at a punch displacement of 2.0 mm.

Figure 11.18 Micrograph of a deformed and failed specimen used in a small punch test.

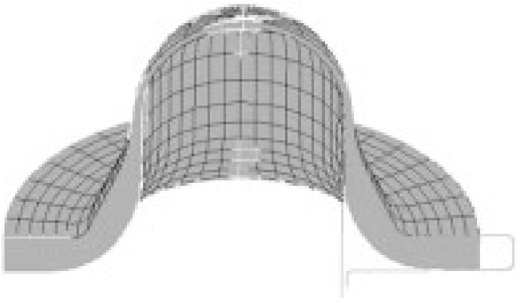


Figure 11.19 Example of deformed mesh used to simulate a small punch experiment.

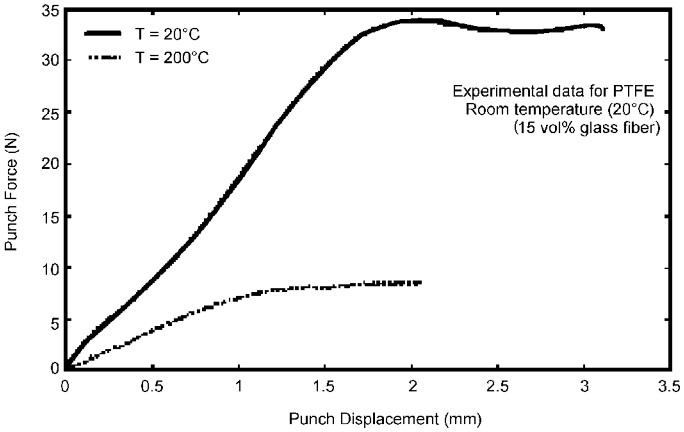


Figure 11.20 Experimental small punch results at 20°C and at 200°C.

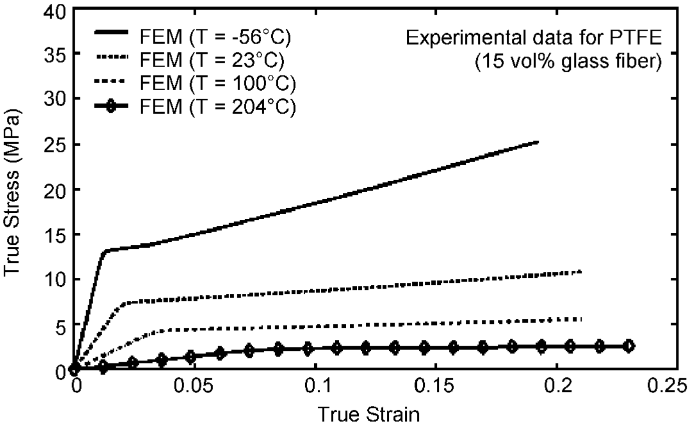
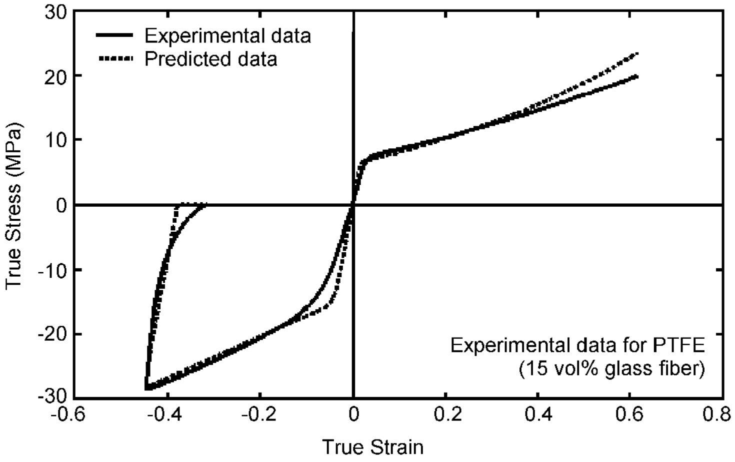


Figure 11.21 FE predictions of uniaxial deformation at different temperatures.

Figure 11.22 Comparison between experimental and predicted data in uniaxial tension and compression.



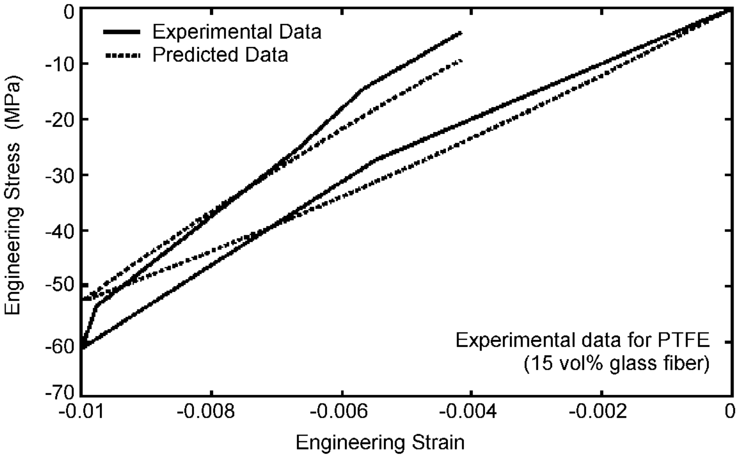


Figure 11.23 Comparison between experimental and predicted data in triaxial compression.

Figure 11.24 Comparison between experimental and predicted stress relaxation response.

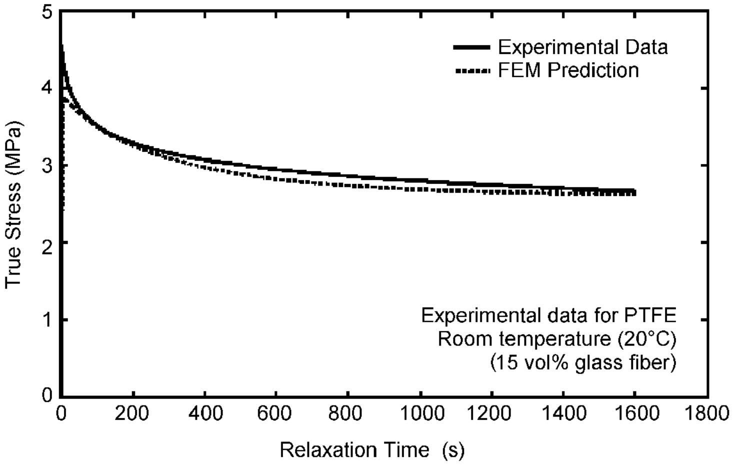


Table 11.4. Material Parameters Used in the DNF Model to Predict the Behavior of 15 vol% Glass-filled PTFE

Network A:

μ_A (MPa)	8.52
θ_{base} (°C)	71.2
λ^{lock}	5.0
κ (MPa)	500

Network B:

S_B	12.97

Viscoelastic Flow:

C	-1
m	9.11
n	28.9
τ_{base} (MPa)	19.0
η_{vol} (GPa)	152

Plastic Flow:

a	0.046
b	1.0
σ_0 (MPa)	19.0

After the DNF model had been calibrated using the uniaxial data, it was validated by simulating the small punch tests. By using the same material parameters that were found in the calibration step (Table 11.4), it was possible to examine the accuracy of the DNF model when applied to a different and more complicated loading configuration. Results from the validation simulations are shown in Fig. 11.25.

After the DNF had been calibrated and validated, it was ready for simulating the behavior of the gaskets in the pipeline application. Figure 11.24 shows one example of the predictions of the gasket after a complete simulation of the assembly and load steps.

A select set of different simulations (Figs. 11.26 and 11.27) were then performed in a parametric study of different seal and connection geometries. The predictions from the finite element simulations were validated further by a few select full-scale experiments on real pipeline parts.

In summary, the simulations of the PTFE gasket in this seal application enabled a more systematic and cost-effective comparison of different designs. It was demonstrated that the use of sophisticated technologies enabled a more efficient evaluation of different designs early on in the new product development cycle. The simulations provided the manufacturer with a new and powerful tool for systematic evaluations and improvements.

11.6 Summary

The use of advanced fluoropolymer modeling provides the opportunity for designers and engineers to advance the sophistication of component designs and understand where problems may arise. Advanced finite element techniques coupled with increased computing speeds have removed many of the previous challenges of modeling components. The challenge that remains to the individual wishing to model fluoropolymer behavior is in selecting the appropriate material model. Simple linear elastic or viscoplastic analyses will provide accurate solutions for problems at small strains, but conditions of large deformations and temperature variations will frequently invalidate those models' analyses.

More sophisticated material models for fluoropolymer behavior are available that provide dramatic improvements in modeling accuracies. These models will increase in power and capability, and the result will be increasingly reliable predictions of fluoropolymer behavior.

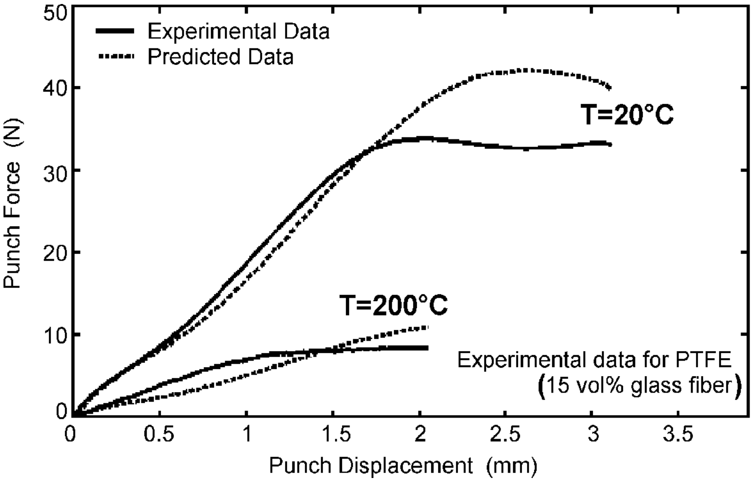


Figure 11.25 Load vs displacement response of a small punch test performed at 20°C.

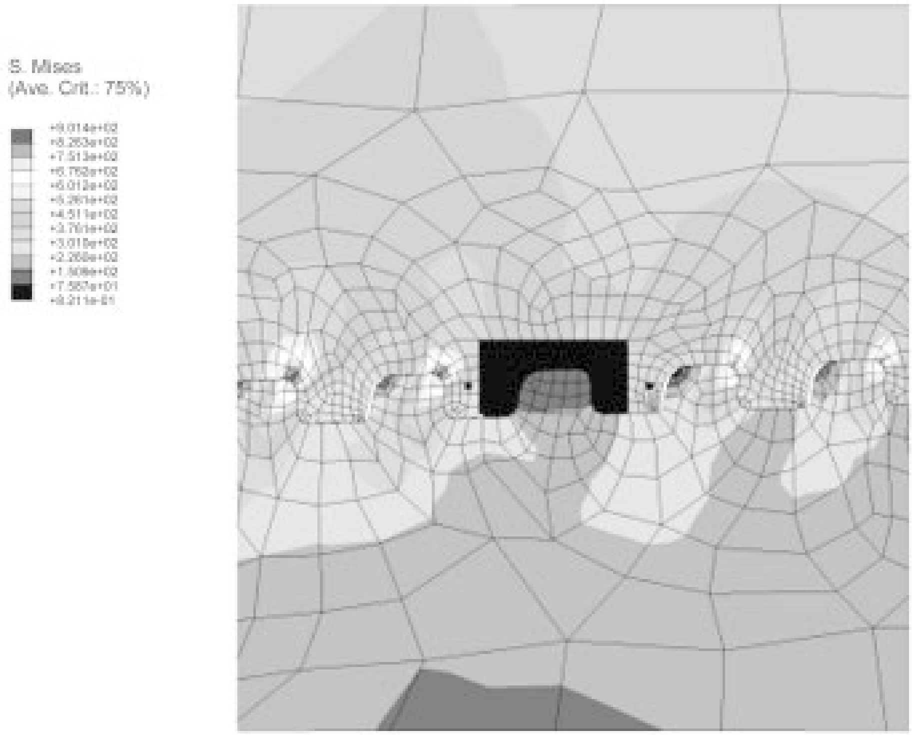


Figure 11.26 Contours of Mises stress of the threaded connection and PTFE gasket.

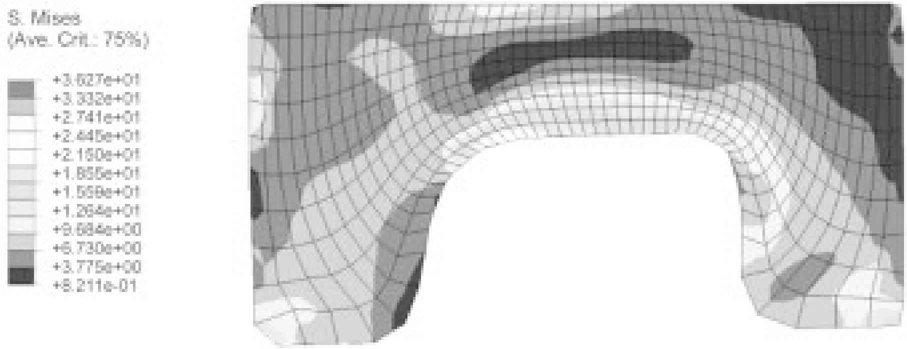


Figure 11.27 Details of Mises stress in the PTFE gasket.

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12 Cost Analysis

12.1 Introduction

Plastic materials are quite effective in controlling corrosion in industrial processing and storage. In a variety of applications, plastics are the only acceptable choice for process surfaces because of their chemical inertness. In each case, plastics must be qualified by testing to insure adequate corrosion protection and compliance with ever more stringent environmental and safety regulations.

Engineering decisions on the selection of materials depend, to a large extent, on the economic data. The technically best-designed equipment is not an obvious choice because it might not meet the economic requirements of the process. Capital budgets and operating costs often limit an equipment designer's choice. This is precisely the reason that equipment suppliers strive to achieve the lowest cost. Nevertheless, unique corrosion-resistant equipment designed for long service could be quite costly, particularly if exotic metals are used in the construction of process surfaces.

12.2 Cost Analysis

Typically, cost analysis should be done on the basis of installed cost plus operating cost considering the useful service life of the equipment. It is also possible to base the selection solely on the initial cost of the equipment which consists of equipment and installation costs. A more accurate basis would consider the cost of the equipment over its useful life. This calculation is based on some discounted cash flow considerations and depreciation of the cost over the life of the equipment. Tables 12.1–12.3 compare the costs of piping, vessels, and lining systems for different material selections. The reader should consult these tables to compare the initial equipment cost.

The overall cost analysis requires an understanding of the overall economics of various options including parts lined with fluoropolymers. A review of this subject is outside the scope of the present book. There are, however, a number of excellent references that could be consulted to learn more about cost analysis and decision making processes.[1]–[3]

Table 12.1. Cost Estimation: Linings of Tanks*[1],*[2]

Type of Lining	Thickness*[3]	Installed Cost ($\$/ft^2$)*[4]	
		Field	**Shop**
Elastomeric: Natural: soft natural semi-hard triflex chlorobutyl	¼ inch (6.35 mm)	15–17	10–12
Synthetic: precured neoprene Hypalon® spray applied neoprene spray applied	 ¼ inch (6.35 mm) 12–20 mils 12–15 mils	 10–12 16–20 16–20	 10–12 16–20 16–20
Vinylester/polyester/fiberglass	60 mils 90 mils	10–12 12–14	10–12 12–14
Epoxy fiberglass	60 mils 90 mils	6–8 6–8	6–8 6–8
Epoxy and phenolic based: chemically cured heat cured	 10–12 mils 6–8 mils	 5–7 8–10	 4–6 6–8
PVDF: unreinforced glass fiber reinforced carbon reinforced	 25 mils 40 mils 40 mils	 NA NA NA	 30–35 46–51 55–60
Rubber backed polypropylene	60 mil	48–54	42–44
Glass backed polyvinylidene fluoride	60 mils	60–64	55–60
Glass backed FEP	60 mils	140–160	125–135
Nucrel® (polyethylene-based copolymer with methacrylic acid)	12–16 mils	6–8	4–6
Glass backed PTFE	60 mils	NA	50–70
PTFE loose lining	90 mils	NA	55–65
Powder coatings– PTFE, FEP	25–40 mils	NA	40–45
Refractory brick (super duty brick backed with 1” mineral wool insulating board)	9 inches 4½ inches	60–80 NA	NA
Acid-resistant brick (with furan-type acid mortar and mastic w/PTFE liner)	3¾ inches	45–60	—

*[1] All prices are intended as general guidelines. Pricing per unit of area will vary significantly depending on size of tanks, complexity of tank, and labor situation on job site (in case of field work).

*[2] Field installation cost will vary significantly depending on number of square feet over which to amortize mobilization and travel costs.

*[3] To convert from mils to mm, multiply by 0.0254.

*[4] To convert to $\$/m^2$, multiply by 10.76.

Table 12.2. Comparison of Costs of Tanks: Steel vs Lined Steel vs FRP vs 304 Stainless Steel

Material for Tank	Estimated Installed Cost ($/ft^2)*^{2}					
	10 Mgal*^{1}	20 Mgal*^{1}	70 Mgal*^{1}	70 Mgal*^{1}	05 Mgal*^{1}	305 Mgal*^{1}
Carbon steel (C/S), ¼ inch or 6.35 mm	17	13	17	14	16	16
C/S + thin chemically cured lining (Plastite® 7155 or Plastite® 7122)	20	16	21	21	18	20
C/S + thin heat-cured lining (Plastite® 3066)	21	17	23	23	20	22
C/S + thick plastic lining (⅛ inch or 3.17 mm Ceilcote Lining 74)	26	23	27	24	26	26
C/S + thick elastomer lining (¼ inch or 6.35 mm natural rubber)	28	24	23	30	32	32
Glass fiber reinforced polyester (std. filament wound)	13	21	—	—	—	—
Type 304 stainless steel	45	33	—	—	—	25

*^{1}To convert from Mgal to Mliters, multiply by 3.78.

*^{2}To convert to $/m^2, multiply by 10.76.

Plastite® is a trademark of Wisconsin Protective Coatings Corp.

Table 12.3. Relative Installed Cost of Piping System

Piping System	2-inch Piping	6-inch Piping
Carbon steel, Schedule 40 welded	1.00	1.00
Polypro, Schedule 80 screwed	1.05	—
PVC, Schedule 80 glued	0.64	0.78
CPVC, Schedule 80 glued	1.09	—
FRP (commodity)	1.53	1.42
FRP (custom)	1.91	1.81
Stainless steel 304, Schedule 10	1.51	1.11
Aluminum, Schedule 40-3003	0.82	0.89
Rubber-lined steel	2.52	1.932
Polypro-lined steel	2.43	2.673
PVDF-lined steel	3.09	4.02
Teflon FEP-lined steel	4.15	5.57
Glass-lined steel	4.43	5.27
Titanium, Schedule 5	5.95	9.31
Hastelloy B or C	7.83	—

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13 Safety, Disposal, and Recycling of Fluoropolymers

13.1 Introduction

Fluoropolymers are among the most versatile plastics thanks to their properties. Thermal stability is a major feature of these polymers spurring their application where high temperature exposures are encountered. Fluoropolymers can produce toxic products if they are overheated. Precautions should be taken to remove any degradation fragments produced during the processing and fabrication of parts from fluoropolymers.

This chapter contains information about safe processing of fluoropolymers and safe handling of parts made from these plastics. The material in this chapter is in no way intended as a replacement for the specific information and data supplied by the manufacturers of fluoropolymer resins and parts. A source of information that is frequently referenced in this chapter is *The Guide to Safe Handling of Fluoropolymers Resins*, published by The Society of Plastics Industry, Inc. Disposal and recycling issues are also reviewed.

13.2 Toxicology of Fluoropolymers

Fluoropolymers are chemically stable and inert or relatively unreactive. Reactivity, generally, decreases as the fluorine content of the polymer increases. Fluorine induces more stability than chlorine. The fluoropolymer family of plastics has low toxicity and almost no toxicological activity. No fluoropolymers have been known to cause skin sensitivity and irritation in humans. Polyvinyl fluoride contains one fluorine atom and three hydrogen atoms per monomer unit and has been shown to cause no skin reaction in human beings.[1] Excessive human exposure to fluoropolymer resin dust resulted in no toxic effects, although urinary fluoride content increased.[2]

Filled or compounded resins contain pigments, surfactants, and other additives to modify the plastic properties. These additives are likely to present risks and hazards in the processing of fluoropolymer compounds. For example, aqueous dispersions of fluoropolymers contain surfactants that may produce adverse physiological symptoms. The hazards of using these additives should be considered by themselves and in conjunction with fluoropolymers. Safety information provided by manufacturers of the additives and the compounds should be consulted.

13.3 Thermal Properties of Fluoropolymers

Thermal decomposition of fluoropolymers is discussed in Ch. 3. The reader should refer to those sections for a review of this topic. Fluoropolymers are heated to high temperatures during processing and degrade to some extent. It is important to remember that the type of degradation products and the extent of decomposition depend on several factors. One must consider the following variables during processing and fabrication:

Temperature

Presence of oxygen

Physical form of the article

Residence time at temperature

Presence of additives

The products of decomposition of fluoropolymers fall in three categories: fluoroalkenes, oxidation products, and particulates of low molecular-weight fluoropolymers. These products must be removed by adequate ventilation from the work environment to prevent human exposure. A major oxidation product of PTFE is carbonyl fluoride, which is highly toxic and hydrolyzes to yield hydrofluoric acid and carbon dioxide. At 450°C in the presence of oxygen, PTFE degrades into carbonyl fluoride and hydrofluoric acid. At 800°C, tetrafluoromethane is formed. It has been suggested that tetrafluoroethylene (TFE) is the only product that is produced when PTFE is heated to melt stage.[3] Some studies have proposed that TFE, trapped in the polymer matrix, is released upon heating.

It is important for service protocols of fluoropolymer parts to follow the recommendations and specifications of the resin and part suppliers. From a thermal exposure standpoint, the maximum continuous-use temperature should comply with the values specified by *The Guide to Safe Handling of Fluoropolymers Resins*, published by The Society of Plastics Industry, Inc. (see Table 13.1).

Table 13.1. Maximum Continuous-Use and Processing Temperatures[3]

Polymer	Maximum Continuous-Use Temperature, °C	Typical Processing Temperature, °C
PTFE	260	380
PFA	260	380
FEP	205	360
ETFE	150	310
ECTFE	150	280
PCTFE	120	265
PVDF	120	230

13.4 Emission During Processing

Fluoropolymers degrade during processing and generate effluents at an accelerating rate as temperature increases. Operation of process equipment at high temperatures may result in the generation of toxic gases and particulate fume. The most common adverse effect associated with human exposure to degradation products of fluoropolymers is *polymer fume fever* (PFF). This exposure presents itself by a temporary (about 24 hours) flu-like condition similar to metal fume fever.[1] Fever, chills, and occasionally coughs are among the observed symptoms.

Other than inhalation of degradation products, fume fever may also be caused by fluoropolymer-contaminated smoking material. It is prudent to ban tobacco products from fluoropolymer work areas. Local exhaust ventilation should be installed to remove the process effluents from the work areas. It has been suggested that no health hazards exist unless the fluoropolymer is heated above 300°C.[4]

Johnston and his coworkers[5] have proposed that heating PTFE gives rise to fumes which contain very fine particulates. The exposure of lung tissues to these particulates can result in a toxic reaction causing pulmonary edema or excessive fluid build up in the lung cells. Severe irritation of the tissues along with the release of blood from small vessels is another reaction to exposure. In controlled experiments, animals were exposed to filtered air from which fumes had been removed, and to the unfiltered air. Unfiltered air produced the expected fume fever response. Animals exposed to the filtered air did not develop any of the symptoms of polymer fume fever.

The products of fluoropolymer decomposition produce certain health effects upon exposure, summarized in Table 13.2. The risks associated with exposure to these effluents have prompted the establishment of a number of exposure limits by various regulatory agencies (Table 13.3). Resin manufacturers can supply available exposure information.

13.5 Safety Measures

A number of measures can be taken to reduce and control exposure to monomers and decomposition products during the processing of fluoropolymers. It is important to monitor processing plants and take measures where necessary according to legal requirements established under the Occupational Safety and Health Act (OSHA). The customary precautionary actions for safe fluoropolymer processing are described in this section. They include ventilation, processing measures, spillage cleanup and equipment cleaning, and maintenance procedures. A number of measures should be taken while handling fluoropolymers including the use of protective clothing, appropriate personal hygiene, fire hazard precautions, and material incompatibility safeguards.

13.5.1 Ventilation

Removal of the decomposition products from the work environment is one of the most important actions taken to reduce and control human exposure. Even at room temperature, small amounts of trapped monomers or other gases can diffuse out of the resin particles. It is a good practice to open the fluoropolymer container in a well-ventilated area. All processing equipment should be ventilated by local exhaust ventilation schemes.

Table 13.2. Health Hazards of Fluoropolymers Decomposition Products[3]

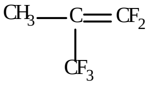
Decomposition Product	Associated Health Effects
Hydrogen Fluoride (HF)	Symptoms: choking, coughing, and sever eye, nose and throat irritation, fever, chills, breathing difficulty, cyanosis and pulmonary edema. HF is corrosive to the eyes, skin, and respiratory tract. May be absorbed through skin in toxic quantities. Sometimes-invisible delayed burns. Overexposure to HF may cause kidney and liver injury.
Carbonyl Fluoride (COF_2)	Overexposure causes skin irritation with rash, eye corrosion or conjunctival ulcer, irritation of upper respiratory passage, and temporary lung irritation with coughs, discomfort, breathing difficulty or shortness of breath.
Tetrafluoro-ethylene (TFE) ($CF_2{=}F_2$)	Causes acute effects when inhaled, including irritation of upper respiratory tract and eyes, mild depression of central nervous system, nausea and vomiting, and dry cough. Massive inhalation produces cardiac arrhythmia, cardiac arrest, and death. A study by National Toxicology Program has reported kidney and liver tumors in rats and mice, which had exposed to lifetime inhalation of TFE. Relationship to human response has not been established. An exposure limit of 5ppm has been established by fluoropolymer producers.
Perfluoro-isobutylene  $CH_3—C{=}CF_2$, CF_3	Animal studies of PFIB inhalation indicate occurrence of severe adverse effects including pulmonary edema as a result of exposure to high concentrations and death. Wheezing, sneezing, difficulty breathing and deep or rapid breathing are among the symptoms. Animals that survived 24 hours after exposure and recovered with no after-effects.

Table 13.3. Exposure Limit Types

Limit	Type	Source
Permissible Exposure Limit (PEL)	Legal occupation exposure limit (OEL)	US Code of Federal Regulations, Title 29, Part 1910 (29 CFR 1910)
Threshold Limit Values (TLV)	Recommended exposure limit (REL)	American Conference of Governmental Industrial Hygienists or National Institute for Occupational Safety and Health (NIOSH)

The most effective method of controlling emissions is to capture them close to the source before they are dispersed in the workspace. A fairly small volume of air has to be removed by local exhaust compared to the substantially larger volume of air that must be removed from an entire building. Correct design and operation of local exhaust systems can minimize human exposure. Examples of hood devices available for ventilation are shown in Figs. 13.1–13.5.

Exhaust air must enter and flow through the hood to carry the contaminants with it and convey them to the exhaust point. At the point contaminants are emitted, the air velocity required to force these contaminants into an exhaust hood is called the *capture velocity* and should be at least 0.5 m/sec. An airflow meter can be used to measure the air velocity. A static pressure gauge can be installed to continuously monitor the air pressure in the hood, thus providing an indirect measurement of the air velocity.

Three publications by The Society of Plastics Industry,[3] American Conference of Governmental Industrial Hygienists,[7] and Canadian Center for Occupational Health and Safety[8] provide detailed information on various aspects of industrial ventilation.

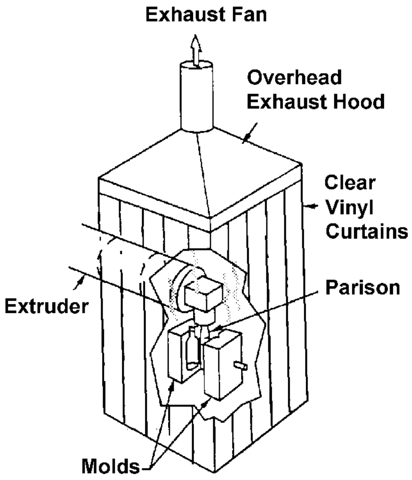


Figure 13.1 Exhaust scheme for blow molding.[6]

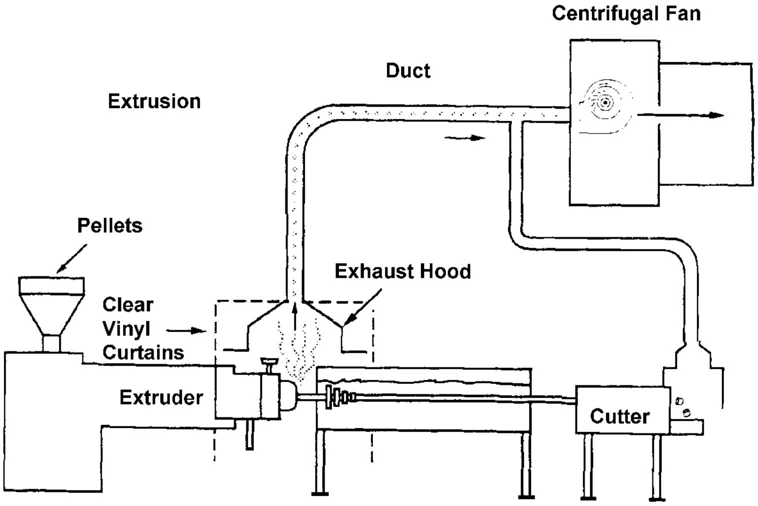


Figure 13.2 Typical setup for exhaust.[6]

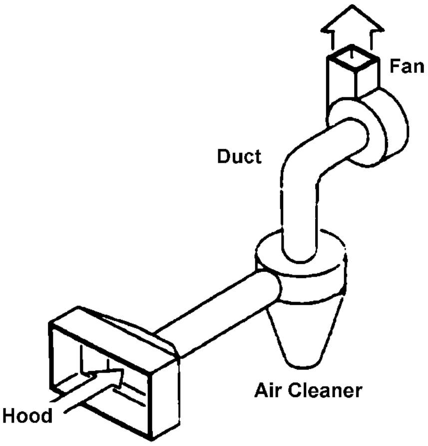


Figure 13.3 Exhaust system.[6]

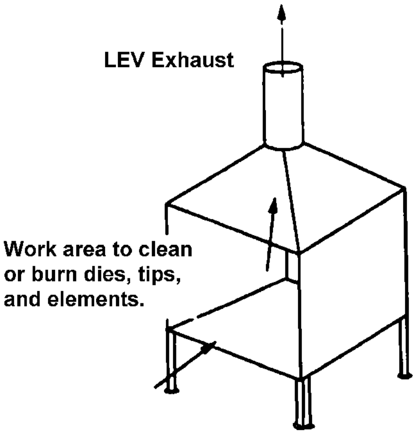


Figure 13.4 Burnout hood.[6]

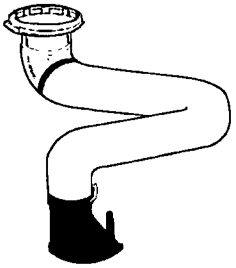


Figure 13.5 Adjustable hood ducting.[6]

13.5.2 Processing and Fabrication

Processing and fabrication of different fluoropolymers may involve one or more of a number of processes. These include sintering, paste extrusion, dispersion coating, melt processing, machining, soldering and melt stripping, welding, and welding and flame cutting of fluoropolymer-lined metals. This section covers each of these processing steps.

13.5.2.1 Sintering

This operation requires heating the polymer in ovens at high temperatures where decomposition products are formed to different extents. Ovens must be equipped with sufficiently strong ventilation to remove the gaseous products and prevent them from entering the work area. It is important that ventilation prevent the entrance of the contaminants into the plant area during the operation of the oven and when the door is open.

Ovens operate at high temperatures, approaching 400°C. Limit switches should be installed to avoid oven runoff (overheating) to prevent the occurrence of high temperatures and accelerated decompositions. It is a good practice to operate the sintering ovens at the lowest possible temperature that is adequate for the completion of the part fabrication. An overheated oven must be cooled before opening the doors. Proper personal protective equipment, including a self-contained breathing apparatus, must be worn prior to opening the oven doors.

Compounds containing fillers are usually more sensitive to thermal decomposition due to the acceleration of thermo-oxidative reactions by a number of additives at elevated temperatures. Fillers could allow sintering compounds at lower temperatures due to an increase in the conductivity of the part. For example, a metal-filled PTFE compound (steel, lead, or bronze) has a significantly higher thermal conductivity than PTFE, which leads to rapid heating of the part.

13.5.2.2 Paste Extrusion

Dispersion-polymerized polytetrafluoroethylene powder is processed by *paste extrusion* in which the polymer is mixed with a hydrocarbon lubricant. These petroleum-based lubricants have low flash points posing potential fire hazards. Lubricants should be stored in electrically conductive containers and the process equipment should be grounded to eliminate static electricity as a source of ignition. Inhalation of vapors and skin contact are the human exposure hazards. Removal of the lubricant from the extrudate takes place in a batch oven or continuously. Action must be taken to minimize the risk of forming explosive mixtures of lubricant and air. In continuous operations, sintering zones immediately follow the drying oven. Incorrect operation may carry flammable vapors into the very high temperature oven zones, resulting in almost certain ignition and fire. Ventilating the ovens by adequate air flow minimizes fire hazards.

13.5.2.3 Dispersion Coating

Aqueous dispersions of fluoropolymers are applied to substrates by coating techniques. Water and surfactant are normally removed in a heating step prior to sintering during which surfactants may decompose. The degradation fragments and the surfactant may be flammable. They may also have adverse health effects. Forced ventilation of the drying oven is necessary to remove the surfactant vapors and minimize buildup of degradation products. Some coating formulations contain organic solvents. Combustion hazards and health effects of these substances should be considered during the handling and processing of the coating.

13.5.2.4 Melt Processing

Melt processing of fluoropolymers exposes them to high temperatures required to reduce viscosity and improve flow. Thermal degradation can take place at these temperatures. Discoloration of the polymer is an indication of thermal degradation. Typical melt processes such as extrusion and injection molding confine the melt in a closed environment. Any decomposition as a result of extended high temperature exposure may produce gases and generate pressure, causing blow-back into the feed section or equipment rupture in the absence of a vent. Rupture disks are installed on melt process equipment to act as emergency pressure relief. Special metal alloys are specified for the construction of contact surfaces due to the corrosive properties of the molten fluoropolymer.

13.5.2.5 Machining

Fabricators of fluoropolymer articles machine, saw, and grind the plastic shapes into their final geometry. Sharp tools can be used in high speed machining of these plastics. Coolants are recommended to increase production rates without overheating. Dust is generated, particularly during the grinding and sawing of shapes. It is recommended that dust particulates be removed from the workspace. An occupational exposure limit of 10 mg/m^3 and a respirable limit of 5 mg/m^3 are recommended.[2] These limits may have to be lowered when machining parts containing fillers which may form hazardous dust. Material safety data sheets (MSDS) provide further information about the additives.

13.5.2.6 Soldering and Melt Stripping

In electronic applications, wires are commonly stripped by heat and soldered for hookup of circuits. Fluoropolymer insulation is subjected to heat and decomposition occurs. It is important to remove the fumes by local ventilation to avoid exposure to gases.

13.5.2.7 Welding Fluoropolymer

Welding fluoropolymer parts to each other should be done carefully due to the generation of large quantities of hydrofluoric acid. Appropriate protective clothing including self-contained breathing apparatus must be worn during welding.

13.5.2.8 Welding and Flame-Cutting Fluoropolymer-Lined Metals

Welding arcs and torches are capable of massive destruction of fluoropolymers due to the excessive heat that they generate. The plastic part should be removed before metal is cut or welded. Local exhaust ventilation should be provided whenever it is not possible to remove the polymer from the area to be welded or cut.

13.5.3 Spillage Cleanup

Fluoropolymers can create a slippery surface if they are rubbed against a hard surface because they are soft and easily abrade and coat the surface. Any spills during handling should be cleaned up immediately. It is helpful to cover the floors of the processing area with anti-slip coatings.

13.5.4 Equipment Cleaning and Maintenance

Dies, screens, molds, screws, mandrels, screen packs, and other components of processing equipment should be periodically cleaned up and polymer residues removed. The cleaning method includes a pyrolysis step which should be conducted under adequate ventilation.

13.5.5 Protective Clothing

Appropriate protective clothing should be worn to avoid burns at the processing temperatures of fluoropolymers. They include safety glasses, gloves and gauntlets (arm protection). Dust masks or respirators should be worn to prevent inhalation of dust and particulates of fluoropolymers during grinding and machining. Additional protection may be required when working with filled compounds. Surfactant and/or solvent content of fluoropolymer dispersions require wearing gloves, overalls, and safety glasses to avoid skin contact while working with these materials. Fluoropolymer coatings must be sprayed in a properly equipped spray booth. Overspray should be captured in a water bath. The spray operator should wear a disposable (Tyvek®) suit, goggles, gloves, and a respirator or self-contained breathing apparatus.

13.5.6 Personal Hygiene

Tobacco products should be banned from the work areas to prevent polymer fume fever. Street clothing should be stored separately from work clothing. Thorough washing after removal of work clothing will remove powder residues from the body.

13.5.7 Fire Hazard

Fluoropolymers do not ignite easily and do not sustain flame. They can decompose in a flame and evolve toxic gases. For example, PFA, FEP, and PTFE will sustain flame in an ambient of >95% oxygen (Limiting Oxygen Index by ASTM D2863). In less oxygen rich environments, burning stops when the flame is removed. Underwriters Laboratory rating of fluoropolymers is 94–V0. Self-ignition temperature of PTFE is 500°C–560°C according to ASTM D1929, far above most other organic materials.[2] PTFE does not form flammable dust clouds under normal conditions as determined by the Godwert Greenwald test at 1000°C. Polytetrafluoroethylene falls in the explosion class ST1.[2]

13.5.8 Material Incompatibility

Small particles of fluoropolymers become highly combustible in the presence of metal fines. Aluminum and magnesium produce fire and/or explosion with PTFE powder when exposed to temperatures above 420°C. Practical situations where a similar reaction is possible include pumps with fluoropolymer packing used to pump aluminum flake dispersions, or grinding or sanding metal parts coated with fluoropolymers.[3]

13.6 Food Contact and Medical Applications

Fluoropolymer resins are covered by Federal Food, Drug and Cosmetic Act, 21 CFR & 177.1380 & 177.1550 in the United States and EC Directive 90/128 in the European Union. The US Food and Drug Administration has approved many fluoropolymers (e.g., PTFE, PFA, and FEP) for food contact. Additives such as pigments, stabilizers, antioxidants, and others must be approved under a food additive regulation if they do not have prior clearance.

Medical applications of fluoropolymers have been a sensitive area for the resin manufacturers and medical device fabricators. Some fluoropolymers have been used in the construction of FDA regulated medical devices. FDA only grants approval for a complete device, not components such as resin. Resin suppliers usually have specific policies regarding the use of their products in medical devices. Thorough review of these policies and regulatory counsel advice would be prudent before initiation of any activity in this area.

13.7 Fluoropolymer Scrap and Recycling

The fluoropolymers described in this book are thermoplastics and can be reused under the right circumstances. There are a few sources of waste fluoropolymers. Various processing steps such as preforming, molding, machining, grinding, and cutting all create debris and scrap. Some of the scrap material is polymer that does not meet specifications and cannot be used in its intended applications. The incentive to recycle fluoroplastic scrap has a strong economic component due to the high value of these plastics. PFA is the most valuable commercial fluoroplastic. Today, a small industry has evolved around recycling fluoropolymers. Polymer manufacturers, part fabricators, and users are the sources of raw material for this industry. The Society of Plastics Industry should be contacted for more information.

Recycling fluoroplastics involves re-extrusion, filtration, and cleaning of these polymers. The recycling operations subject the polymer to temperatures higher than its melting point that cause degradation of the polymer to varying degrees. The main impact of degradation is reduction of the molecular weight resulting in an increase in the melt flow rate. Information about the effect of temperature and time on the melt flow rate of various fluoroplastics should be consulted (see Ch. 6). Lowering molecular weight adversely affects a number of properties of parts made from recycled fluoroplastics.

13.8 Environmental Protection and Disposal Methods

None of fluoropolymers or their decomposition products poses any threats to the ozone layer. None are subject to any restrictive regulations under the Montreal Protocol and the US Clean Air Act. Reacting HF with chloroform produces the main fluorinated ingredient of tetrafluoroethylene synthesis $CHClF_2$. It has a small ozone depleting potential but is excluded from the Montreal Protocol regulation due to its intermediate role and destruction from the environment.

The preferred methods of disposing of fluoropolymers are recycling and landfilling according to the various regulations. In the case of suspensions and dispersions, solids should be removed from the liquid and disposed. Liquid discharge to waste water systems should be according to the permits. None of the polymers should be incinerated unless the incinerator is equipped to scrub out hydrogen fluoride, hydrogen chloride, and other acidic products of combustion.

In the disposal of fluoropolymer scrap containing pigments, additives, or solvents, additional consideration must be given to the regulation for the disposal of the non-fluoropolymer ingredients. Some of the compounds and mixtures may require compliance with Hazardous Material Acts.

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14 Future Trends

14.1 Introduction

No other polymers have surpassed fluoropolymers with respect to chemical resistance, low surface energy, low dielectric constant, and low coefficient of friction. These polymers will most certainly continue to be an indispensable part of world industry for the foreseeable future. The use of fluoropolymers is, however, expected to undergo significant changes in the future as legislations become more stringent with respect to safety and environmental emission standards. Specifically, the bars on fugitive emissions and non-intrusive condition assessment will have to be raised.

In this chapter, industrial and technological future trends and present and future needs are briefly discussed. Fluoropolymers Division of the Society of Plastics Industry is an excellent source of additional information.[1]

14.2 Fluoropolymer Applications

Fluoropolymers hold a unique position among the specialty or engineering thermoplastics. They are unparalleled in terms of their ability to resist chemical attack, and as a group they almost all qualify as high-temperature resins—that is, able to resist long-term thermal excursions above 150°C (300°F). In light of their inherent lubricity and durability, they are the materials of choice in several applications such as chemical handling/processing equipment, plastic bearings, gears, and other vital industrial parts where they replace metals which are vulnerable to chemical attack and corrosion.[2]

Applications of fluoropolymers are still growing, even decades after the discovery of the first plastic (polytetrafluoroethylene) in this family. The increasing use of fluoropolymers in such dynamic industries as wire and cable insulation, automotive, aerospace, oil and gas recovery, and semiconductor manufacture has led to significant material developments and trends in the last few years. New fluoropolymers have been introduced to the market (amorphous fluoroplastics, modified PTFE, low-temperature fluoroelastomers, and amine-resistant fluoroelastomers), expanding the already broad slate of applications.[3]

14.3 Fluoropolymer Resin Manufacturing

World consumption of fluoropolymers reached a record level of 120 million kg (246 million pounds) per year in 2001.[4] They are expected to grow at a rate above the growth rate of the US Gross Domestic Product. In addition to perfluoropolymers, partially fluorinated polymers will continue to impact a wide range of technologies as better control of their unique optical, electronic, processing, and surface properties is achieved. However, the fluoropolymer industry faces new challenges to maintain an environmentally and economically sustainable production. The use of supercritical or dense-phase carbon dioxide by DuPont as the reaction medium aims to eliminate conventional chlorofluorocarbon solvent and reduce waste generation.[5] Conventional chlorofluorocarbon polymerization media are environmentally unfriendly and are restricted due to their high ozone-depletion potential. Processes using aqueous media are energy inefficient and generate a large amount of wastewater. Fluoropolymer production in a carbon dioxide medium is not only environmentally friendly but also requires lower capital investment and reduces the production costs. High-purity grades of fluoropolymer can potentially be produced by this process.

14.4 Growth of Fluoropolymer Industries

These industries include those that produce the polymers all the way through the fabrication and installation steps. The growth of industries is tied to population growth, rise in living standards, and government regulations. Rapidly developing countries, especially China, that are highly populated are the next growth grounds for the fluoropolymer industries. China has a population of over one billion who are engaged in raising their living standards. Invariably, higher standards involve products that require industries that process and handle corrosive chemicals. From food to semiconductor manufacturing factories, process surfaces come in contact with chemicals that either require exotic metals or resistant plastics. The latter has been the value proposition of fluoropolymer industries.

China and most developing countries have encouraged and often required, through passage of laws, local investment as a condition of business. Lower wages, capital cost, and favorable government support offer economic advantages to industries including fluoropolymers to build production facilities in these countries. This trend has brought about a migration of fluoropolymer industries to countries like China beginning with the most competitive segments involving moldable PTFE (granular) mostly used for producing lined pipes and accessories.

14.5 Technological Needs of Chemical Processing Industry

14.5.1 Non-destructive and Non-intrusive Condition Assessment

Currently, only a direct visual examination of the plastics including fluoropolymer offers any real condition assessment. The industry will have to respond through research and development efforts to develop techniques that will compare with those now available for metals. The ultimate aim is the same, that is to enable the user to non-intrusively evaluate the condition of the material. Use of microwaves, thermal imaging analysis, and others are being examined.

The alternative is to build into the material an element of “smartness” using sensors and communicative devices. This will also require a great deal of research and development. The aim is to sense permeation, environmental stress cracking, change in shape or form, and any breach in the material’s integrity due to mechanical forces.

14.5.2 Accelerated Testing for Compatibility

Current evaluation methods are time consuming, and are application specific. A common test protocol that would identify a degradation mechanism in a relatively short time does not exist. This also will require research and development to relate such parameters as temperature to time.

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Appendix I: Permeation Properties of Perfluoroplastics

I.1 Perfluoroalkoxy Resin

I.1.1 Permeability to Gases

DuPont: Teflon® PFA and FEP
Product form: film.

The permeation of gases through thin film (0.08–0.13 mm) is dependant on the molecular size, shape, wettability, and soundness of the fabricated membrane.

Attempts have been made to relate permeation rates through thin films to absorption of thicker films, sheets, tubes, pipe, etc. This has been generally unsuccessful. Thicker films and sheets represent an average set of properties obtainable from many thin films produced under a variety of conditions. To produce a thin film representative of this average is impossible from a practical viewpoint. Since permeation in well-fabricated articles is essentially a molecular transport phenomenon through fluorocarbon chains, it is affected by orientation, degree of crystallinity, and temperature.

However, comparative data on identical tests can be used to predict performance in many thin film and coating applications.

Increased permeability with temperature parallels the decrease in specific gravity with increased temperature in the resin. This corresponds with increased spacing between molecules and increasing molecular activity which allows easier diffusion of the gas through the specimen.[1]

Table I.1. Gas Permeability of Carbon Dioxide, Nitrogen, and Oxygen through DuPont Teflon® PFA Perfluoroalkoxy Film

Material Family	**PERFLUOROALKOXY RESIN**
Material Supplier/Grade	**DUPONT TEFLON® PFA**
Product Form	**FILM**
Reference Number	1

TEST CONDITIONS

Penetrant	carbon dioxide	nitrogen	oxygen
Temperature, °C	25	25	25
Test Method	ASTM D1434	ASTM D1434	ASTM D1434

PERMEABILITY (source document units)

Gas Permeability (cm³ · mil/100 in² · day)	2260	291	881
Gas Permeability (cm³ · mm/m² · day · Pa)	0.00878	0.00113	0.00342

PERMEABILITY (normalized units)

Permeability Coefficient (cm³ · mm/m² · day · atm)	890	115	347

Table I.2. Hydrogen Permeability vs Temperature and Pressure through DuPont Teflon® Fluorinated Ethylene Propylene Copolymer

Material Family	**FLUORINATED ETHYLENE PROPYLENE COPOLYMER**								
Material Supplier/Grade	**DUPONT TEFLON®**								
Reference Number	2								
MATERIAL CHARACTERISTICS									
Sample Thickness, mm	0.05								
TEST CONDITIONS									
Penetrant	hydrogen								
Temperature, °C	-15	25	68	-13	25	67	-16	25	67
Pressure Gradient, kPa	1724			3447			6895		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratory								
PERMEABILITY (source document units)									
Gas Permeability ($cm^3 \cdot mm/cm^2 \cdot kPa \cdot sec$)	9.06×10^{-10}	4.41×10^{-9}	1.87×10^{-8}	9.64×10^{-10}	4.35×10^{-9}	1.77×10^{-8}	8.77×10^{-10}	4.4×10^{-9}	1.8×10^{-8}
PERMEABILITY (normalized units)									
Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	79.3	386	1637	84.4	381	1550	76.8	385	1576

Table I.3. Nitrogen Permeability vs Temperature and Pressure through DuPont Teflon® Fluorinated Ethylene Propylene Copolymer

Material Family	**FLUORINATED ETHYLENE PROPYLENE COPOLYMER**								
Material Supplier/Grade	**DUPONT TEFLON®**								
Reference Number	2								
MATERIAL CHARACTERISTICS									
Sample Thickness, mm	0.05								
TEST CONDITIONS									
Penetrant	nitrogen								
Temperature, °C	-9	25	71	-7	25	66	-5	25	68
Pressure Gradient, kPa	1724			3447			6895		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratory								
PERMEABILITY (source document units)									
Gas Permeability ($cm^3 \cdot mm/cm^2 \cdot kPa \cdot sec$)	5.06×10^{-11}	3.8×10^{-10}	3.79×10^{-9}	5.64×10^{-11}	3.86×10^{-10}	3.85×10^{-9}	6.39×10^{-11}	3.85×10^{-10}	3.8×10^{-9}
PERMEABILITY (normalized units)									
Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	4.4	33.3	332	4.9	33.8	337	5.6	33.7	333

Table I.4. Ammonia and Oxygen Permeability vs Temperature and Pressure through DuPont Teflon® Fluorinated Ethylene Propylene Copolymer

Material Family	**FLUORINATED ETHYLENE PROPYLENE COPOLYMER**
Material Supplier/Grade	**DUPONT TEFLON®**
Reference Number	2

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.05

TEST CONDITIONS

Penetrant	ammonia			oxygen					
Temperature, °C	0	25	66	-16	25	52	-16	25	53
Pressure Gradient, kPa	965			1724			3447		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratory								

PERMEABILITY (source document units)

Gas Permeability (cm^3 · mm/cm^2 · kPa · sec)	3.31×10^{-10}	1.15×10^{-9}	6.3×10^{-9}	1.04×10^{-10}	1.33×10^{-9}	5.16×10^{-9}	1.03×10^{-10}	1.15×10^{-9}	5.31×10^{-9}

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)	29.0	101	552	9.1	116	452	9.0	101	465

Table I.5. Water Vapor, Oxygen, Nitrogen, and Carbon Dioxide Permeability through Fluorinated Ethylene Propylene Copolymer

Material Family	**FLUORINATED ETHYLENE PROPYLENE COPOLYMER**
Reference Number	3

TEST CONDITIONS

Penetrant	water vapor	oxygen	nitrogen	carbon dioxide
Temperature, °C	37.8	25		
Relative Humidity, %	90			
Test Note		STP conditions		

PERMEABILITY (source document units)

Gas Permeability (cm^3 · mil/100 in^2 · day)		750	320	1670
Vapor Transmission Rate (g · mil/100 in^2 · day)	0.4			

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)		295	126	657
Vapor Transmission Rate (g · mm/m^2 · day)	0.16			

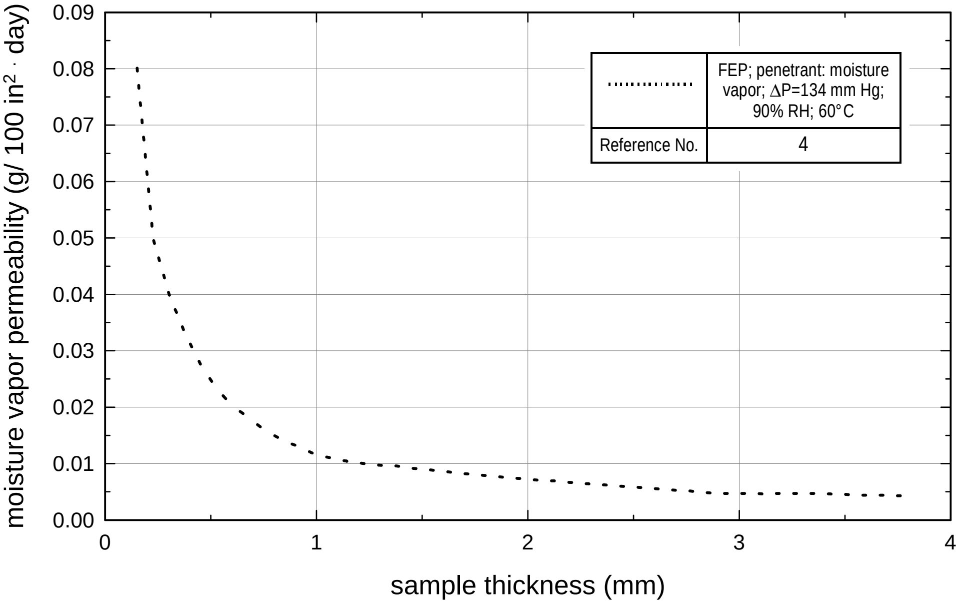


Figure I.1 Moisture vapor permeability rate vs thickness through fluorinated ethylene propylene copolymer.

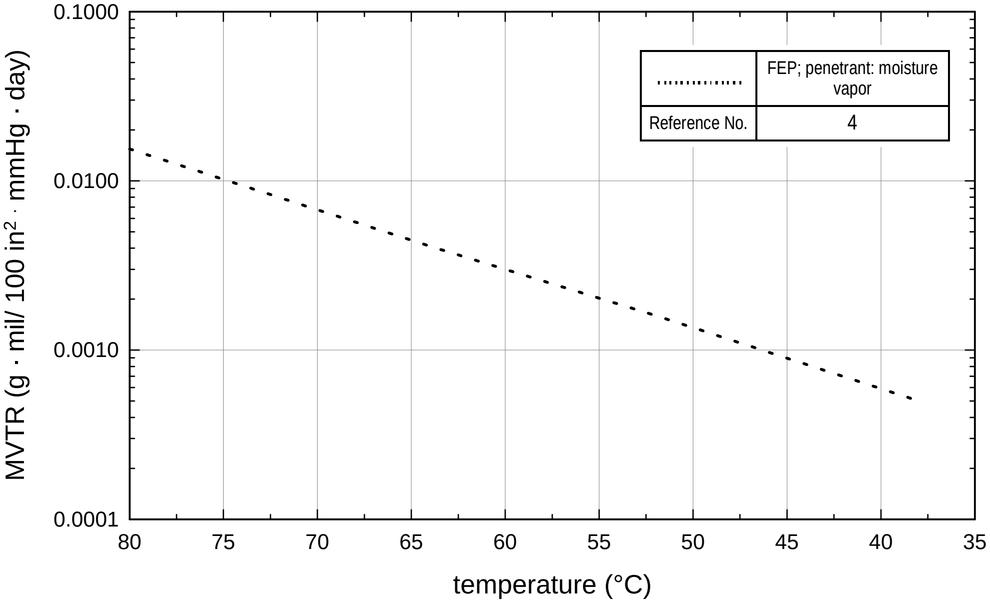


Figure I.2 Moisture vapor permeability rate vs temperature through fluorinated ethylene propylene copolymer.

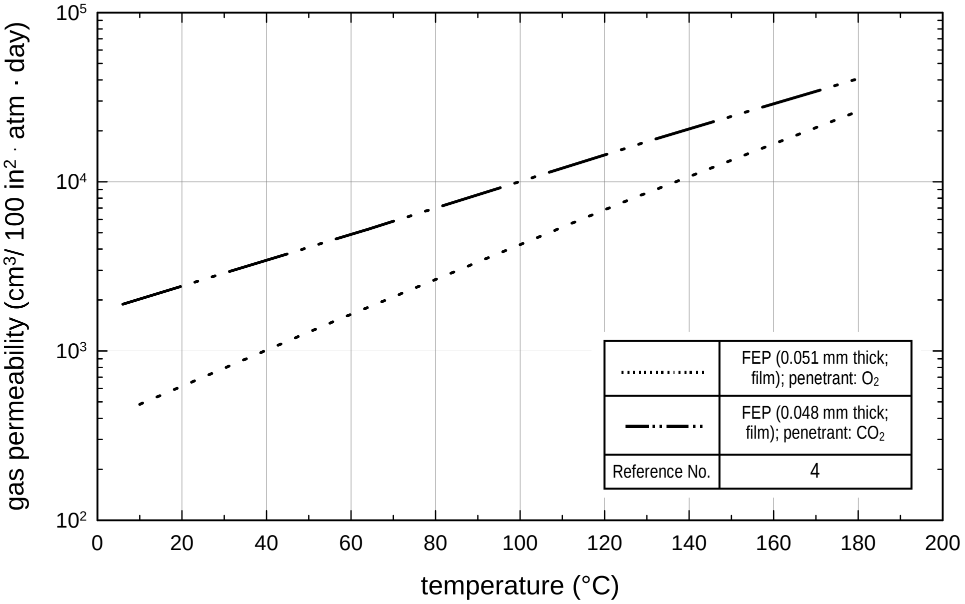


Figure I.3 Oxygen and carbon dioxide permeability vs temperature through fluorinated ethylene propylene copolymer.

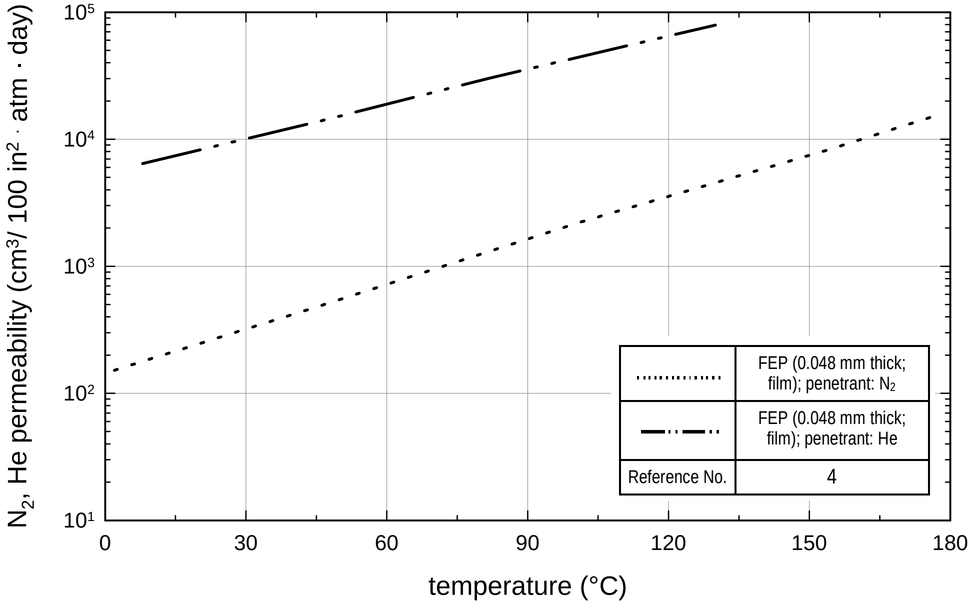


Figure I.4 Nitrogen and helium permeability vs time after retort through fluorinated ethylene propylene copolymer.

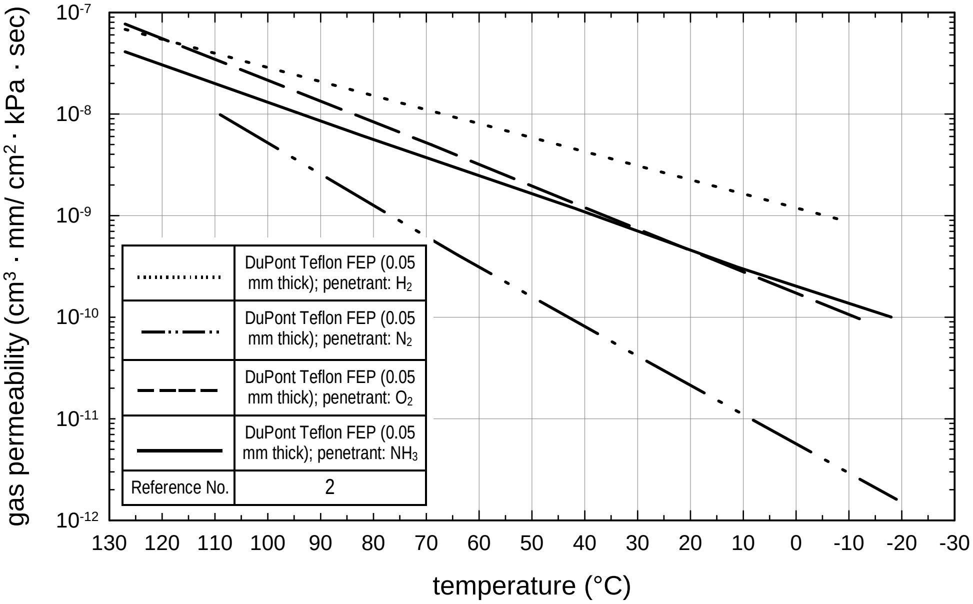


Figure I.5 Gas permeability vs temperature through fluorinated ethylene propylene copolymer.

References

1. *Handbook of Properties for Teflon® PFA*, supplier design guide (E-96679) - DuPont Company (1987)
2. Adam, S. J., and David, C. E., Permeation Measurement of Fluoropolymers Using Mass Spectroscopy and Calibrated Standard Gas Leaks, 23rd International SAMPE Tech. Conf., *Conf. Proceedings - SAMPE* (1991)
3. Aclar® Performance Films, Suppl. Tech Rep. No. SFI-14, Revised 9-89, Allied Signal Eng. Plastics (1989)
4. Chemical Resistance of Halar® Fluoropolymers, Supp. Tech. Rep. AHH, Ausimont.

Appendix II: Permeation Properties of Partially Fluorinated Fluoroplastics

II.1 Polyvinylidene Fluoride

II.1.1 Permeability

Solvay: Solef®

Solef® PVDF has average permeability to small molecules such as carbon dioxide, nitrogen, oxygen, water, and nitrous oxide.[1]

II.1.2 Permeability To Gases

Atochem: Foraflon®

The permeability of a crystalline polymer to gases depends on its crystallinity index and degree of order. These depend on processing conditions, so the preparation conditions and thermal history of the samples to be measured must be clearly stated.[2]

II.1.3 Permeability To Liquids

Atochem: Foraflon®

The impermeability of solid Foraflon® has been verified with respect to several liquid compounds.[2]

Mineral acids: A 20 mm diameter Foraflon tube, 2 mm thick, has not allowed any trace of hydrochloric acid or sulfuric acid to pass through its walls during six months at 100°C. On the other hand, a certain permeability to hydrochloric acid is noted above 70°C.

Liquid bromine: A 1.5 mm flask made by blow injection has not allowed any trace of bromine to pass through its walls during two years at ambient temperature.

Other liquids: Foraflon is not at all or only very slightly permeable to aliphatic and aromatic hydrocarbons, perchloroethylene, and trichloroethylene.

Table II.01. Ammonia, Helium, Chlorine, and Hydrogen Permeability through Solvay Solef® Polyvinylidene Fluoride Film

Material Family	**POLYVINYLIDENE FLUORIDE**			
Material Supplier / Grade	**SOLVAY SOLEF®**			
Product Form	**FILM**			
Manufacturing Method	cast film			
Reference Number	1			
MATERIAL CHARACTERISTICS				
Sample Thickness, mm	0.1			
TEST CONDITIONS				
Penetrant	ammonia	helium	chlorine	hydrogen
Temperature, °C	23			
Test Method	ASTM D1434			
PERMEABILITY (source document units)				
Gas Permeability (cm^3 · N/m^2 · bar · day)	65	850	12	210
PERMEABILITY (normalized units)				
Permeability Coefficient (cm^3 · mm/m^2 · day · atm)	6.6	86	1.2	21.3

Table II.02. Carbon Dioxide, Nitrogen, Oxygen, and Water Vapor Permeability through Solvay Solef® 1008 Polyvinylidene Fluoride Film

Material Family	**POLYVINYLIDENE FLUORIDE**
Material Supplier / Grade	**SOLVAY SOLEF® 1008**
Product Form	**FILM**
Features	translucent
Reference Number	1

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.1

TEST CONDITIONS

Penetrant	carbon dioxide	nitrogen	oxygen	water vapor
Temperature, °C	23			38
Test Method	ASTM D1434			ASTM E96, proc. E

PERMEABILITY (source document units)

Vapor Transmission Rate (g/m^2 · day)				7.5
Gas Permeability (cm^3 · N/m^2 · bar · day)	70	30	21	

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)	7.09	3.04	2.13	
Vapor Transmission Rate (g · mm/m^2 · day)				0.75

Table II.03. Freon, Nitrous Oxide, Hydrogen Sulfide, and Sulfur Dioxide Permeability through Solvay Solef® Polyvinylidene Fluoride Film

Material Family	**POLYVINYLIDENE FLUORIDE**
Material Supplier / Grade	**SOLVAY SOLEF®**
Product Form	**FILM**
Features	cast film
Reference Number	1

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.025

TEST CONDITIONS

Penetrant	freon 12	freon 114	freon 115	freon 318	nitrous oxide	hydrogen sulfide	sulfur dioxide
Temperature, °C	23						
Test Method	ASTM D1434						

PERMEABILITY (source document units)

Gas Permeability ($cm^3 \cdot N/m^2 \cdot bar \cdot day$)	6.3	10	4	7	900	60	60

PERMEABILITY (normalized units)

Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	0.16	0.25	0.1	0.18	22.8	1.52	1.52

Table II.04. Water Vapor, Oxygen, and Carbon Dioxide Permeability through Atochem Foraflon® Polyvinylidene Fluoride Film

Material Family	**POLYVINYLIDENE FLUORIDE**
Material Supplier / Grade	**ATOCHEM FORAFLON®**
Product Form	**EXTRUDED FILM**
Reference Number	2

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.02	0.028	0.04	0.037	0.034

TEST CONDITIONS

Penetrant	Water vapor			oxygen	carbon dioxide
Temperature, °C	38			30	
Test Method	NFH 00044			ISO 2556	

PERMEABILITY (source document units)

Vapor Transmission Rate (g/m^2 · day)	34	22	16		
Gas Permeability (cm^3/m^2 · day)				140	890

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)				5.18	30.26
Vapor Transmission Rate (g · mm/m^2 · day)	0.68	0.62	0.64		

Table II.05. Water Vapor, Oxygen, Nitrogen, and Carbon Dioxide Permeability through Polyvinylidene Fluoride

Material Family	**POLYVINYLIDENE FLUORIDE**
Reference Number	3

TEST CONDITIONS

Penetrant	water vapor	oxygen	nitrogen	carbon dioxide
Temperature, °C	23	25		
Relative Humidity, %	90			
Test Method		STP conditions		

PERMEABILITY (source document units)

Gas Permeability (cm^3 · mm/100 in^2 · day)		1.4	9	5.5
Gas Permeability (cm^3 · mm/m^2 · day · atm)		0.55	3.5	2.2
Vapor Transmission Rate (g · mil/100 in^2 · day)	2.6			
Vapor Transmission Rate (g/day · 100 in^2)	1.0			

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)		0.55	3.5	2.2
Vapor Transmission Rate (g · mm/m^2 · day)	1.0			

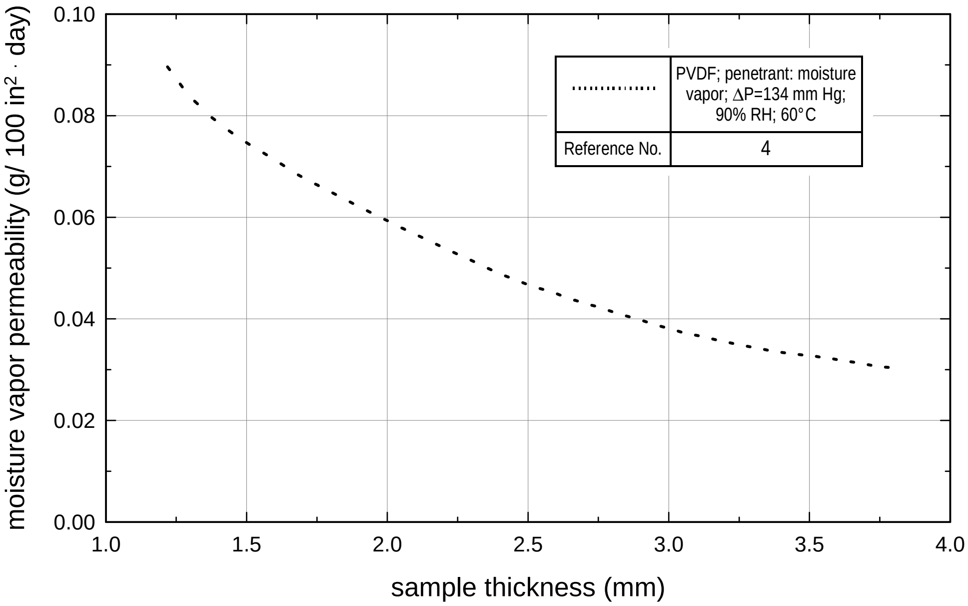


Figure II.01 Moisture vapor permeability rate vs thickness through polyvinylidene fluoride.

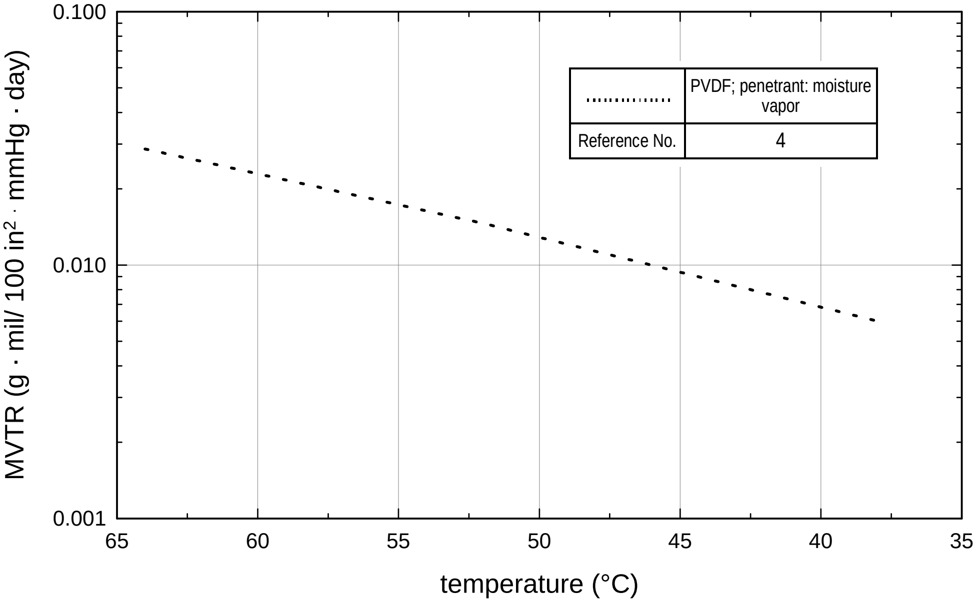


Figure II.02 Moisture vapor permeability rate vs temperature through polyvinylidene fluoride.

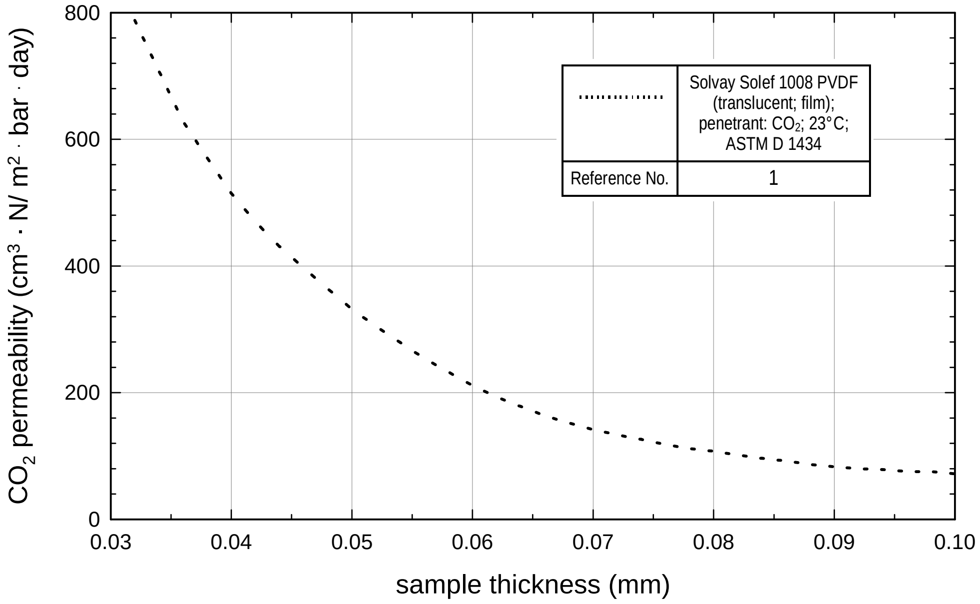


Figure II.03 Carbon dioxide permeability vs thickness through polyvinylidene fluoride.

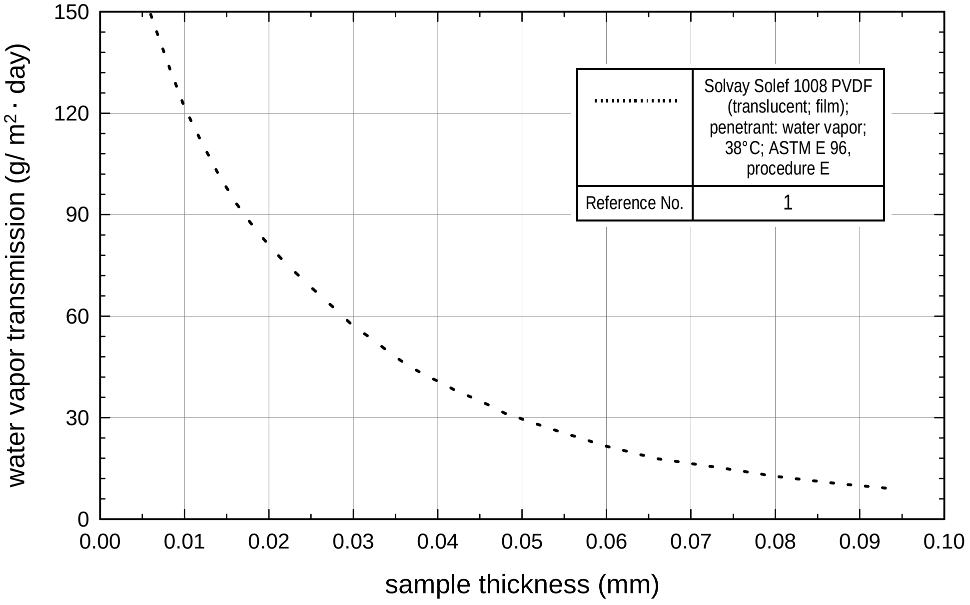


Figure II.04 Water vapor permeability vs thickness through polyvinylidene fluoride.

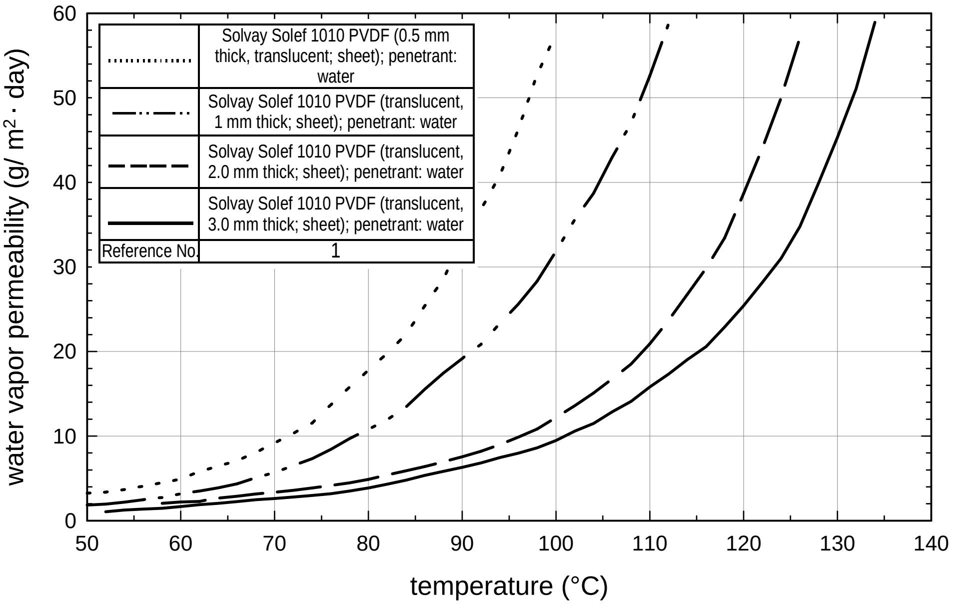


Figure II.05 Water vapor permeability vs temperature through polyvinylidene fluoride.

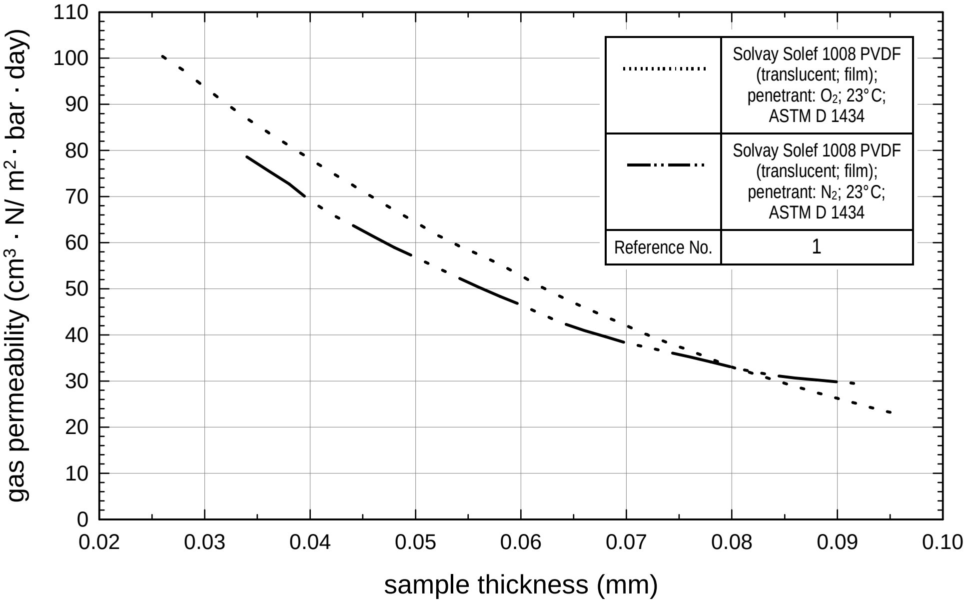


Figure II.06 Nitrogen and oxygen permeability vs thickness through polyvinylidene fluoride.

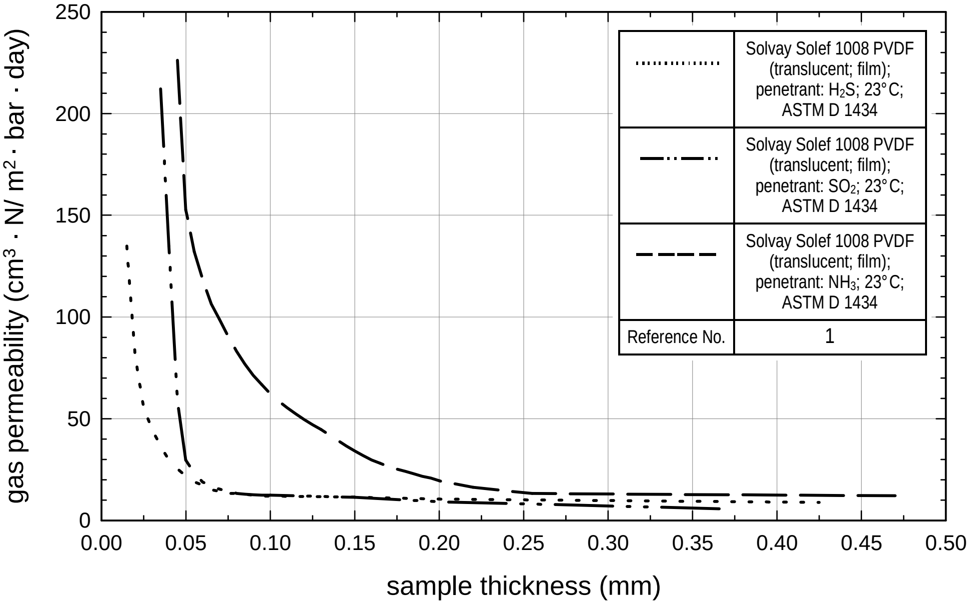


Figure II.07 Gas permeability vs thickness through polyvinylidene fluoride.

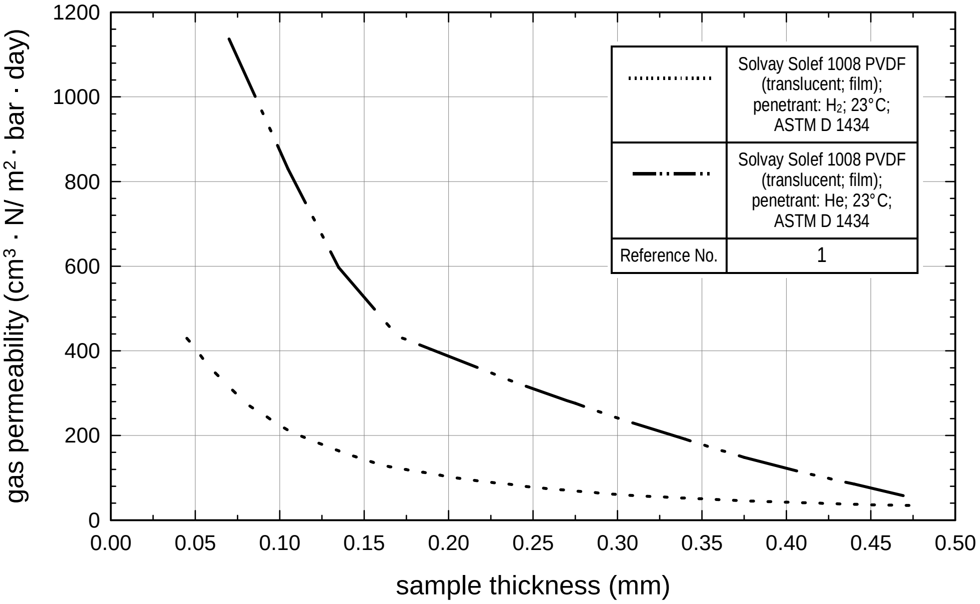


Figure II.08 Helium and hydrogen permeability vs thickness through polyvinylidene fluoride.

II.2 Ethylene Tetrafluoroethylene Copolymer

Table II.06. Carbon Dioxide, Nitrogen, Oxygen, Helium, and Water Vapor Permeability through DuPont Tefzel® Ethylene Tetrafluoroethylene Copolymer

Material Family	**ETHYLENE TETRAFLUOROETHYLENE COPOLYMER**
Material Supplier/Grade	**DUPONT TEFZEL®**
Product Form	**FILM**
Features	—
Reference Number	5

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.102

TEST CONDITIONS

Penetrant	carbon dioxide	nitrogen	oxygen	helium	water vapor
Temperature, °C	25				
Test Method	ASTM D1434				ASTM E96

PERMEABILITY (source document units)

Vapor Transmission Rate (g · mil/100 in^2 · day)					1.65
Gas Permeability (cm^3 · mil/m^2 · day)	250	30	100	900	

PERMEABILITY (normalized units)

Permeability Coefficient (cm^3 · mm/m^2 · day · atm)	98.4	11.8	39.4	354	
Vapor Transmission Rate (g · mm/m^2 · day)					0.65

Table II.07. Oxygen, Nitrogen, Carbon Dioxide, Methane, and Helium Permeability through Ausimont Hyflon® Ethylene Tetrafluoroethylene Copolymer

Material Family	**ETHYLENE TETRAFLUOROETHYLENE COPOLYMER**	
Material Supplier/Grade	**AUSIMONT HYFLON® 700**	**AUSIMONT HYFLON® 800**
Features	high molecular weight	low molecular weight
Reference Number	6	

MATERIAL CHARACTERISTICS

Melt Flow Index	4 grams / 10 minutes	11 grams / 10 minutes

TEST CONDITIONS

Penetrant	oxygen	nitrogen	carbon dioxide	methane	helium	oxygen	nitrogen	carbon dioxide	methane	helium
Temperature, °C	23									
Test Method	ASTM D1434									
Test Note	activation energy = 6-8 kcal/mole									

PERMEABILITY (source document units)

Gas Permeability ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	62.646	21.67	232.46	7.88	591	62.646	21.67	232.46	7.88	591

PERMEABILITY (normalized units)

Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	62.6	21.7	232	7.9	591	62.6	21.7	232	7.9	591

II.3 Ethylene Chlorotrifluoroethylene Copolymer

II.3.1 Permeability to Gases and Water Vapor

Ausimont: Halar®

Halar fluoropolymer has low permeability to water vapor and various other gases. Water vapor permeability measured at 38°C and 90% RH was found to be 0.15 g · mil/100 in^2 · 24 hrs.

At an elevated surface temperature, Halar fluoropolymer has superior moisture vapor impermeability compared to certain other fluoropolymers at the same conditions.[3]

Table II.08. Hydrogen Permeability vs Temperature and Pressure through Ausimont Halar® Ethylene Chlorotrifluoroethylene Copolymer

Material Family	**ETHYLENE CHLOROTRIFLUOROETHYLENE COPOLYMER**								
Material Supplier / Grade	**AUSIMONT HALAR®**								
Reference Number	7								
MATERIAL CHARACTERISTICS									
Sample Thickness, mm	0.02								
TEST CONDITIONS									
Penetrant	hydrogen								
Temperature, °C	-22	25	66	-20	25	67	-21	25	68
Pressure Gradient, kPa	1724			3447			6895		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratories								
PERMEABILITY (source document units)									
Gas Permeability (cm^3 · mm/cm^2 · kPa · sec)	1.19×10^{-10}	1.21×10^{-9}	6.58×10^{-9}	1.18×10^{-10}	1.25×10^{-9}	6.65×10^{-9}	1.18×10^{-10}	1.23×10^{-9}	6.74×10^{-9}
PERMEABILITY (normalized units)									
Permeability Coefficient (cm^3 · mm/m^2 · day · atm)	10.4	106	576	10.3	109	582	10.3	108	590

Table II.09. Nitrogen Permeability vs Temperature and Pressure through Ausimont Halar® Ethylene Chlorotrifluoroethylene Copolymer

Material Family	**ETHYLENE CHLOROTRIFLUOROETHYLENE COPOLYMER**
Material Supplier / Grade	**AUSIMONT HALAR®**
Reference Number	7

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.02

TEST CONDITIONS

Penetrant	nitrogen								
Temperature, °C	11	25	71	10	25	72	10	25	68
Pressure Gradient, kPa	1724			3447			6895		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratories								

PERMEABILITY (source document units)

Gas Permeability ($cm^3 \cdot mm/cm^2 \cdot kPa \cdot sec$)	5.53×10^{-12}	1.29×10^{-11}	2.43×10^{-10}	5.53×10^{-12}	1.49×10^{-11}	4.27×10^{-10}	6.09×10^{-12}	1.43×10^{-11}	2.48×10^{-10}

PERMEABILITY (normalized units)

Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	0.48	1.13	21.3	0.48	1.3	37.4	0.53	1.25	21.7

Table II.10. Oxygen and Ammonia Permeability vs Temperature and Pressure through Ausimont Halar® Ethylene Chlorotrifluoroethylene Copolymer

Material Family	**ETHYLENE CHLOROTRIFLUOROETHYLENE COPOLYMER**								
Material Supplier / Grade	**AUSIMONT HALAR®**								
Reference Number	7								

MATERIAL CHARACTERISTICS

Sample Thickness, mm	0.02

TEST CONDITIONS

Penetrant	ammonia			oxygen					
Temperature, °C	-1	25	65	-18	25	55	-15	25	56
Pressure Gradient, kPa	965			1724			3447		
Test Method	Mass Spectrometry and Calibrated Standard Gas Leaks Developed by McDonnell Douglas Space Systems Company Chemistry Laboratories								

PERMEABILITY (source document units)

Gas Permeability ($cm^3 \cdot mm/cm^2 \cdot kPa \cdot sec$)	3.73×10^{-10}	1.29×10^{-9}	7.05×10^{-9}	5.52×10^{-12}	1.16×10^{-10}	5.16×10^{-10}	5.73×10^{-12}	1.1×10^{-10}	5.26×10^{-10}

PERMEABILITY (normalized units)

Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)	32.6	113	617	0.48	10.2	45.2	0.5	9.6	46.0

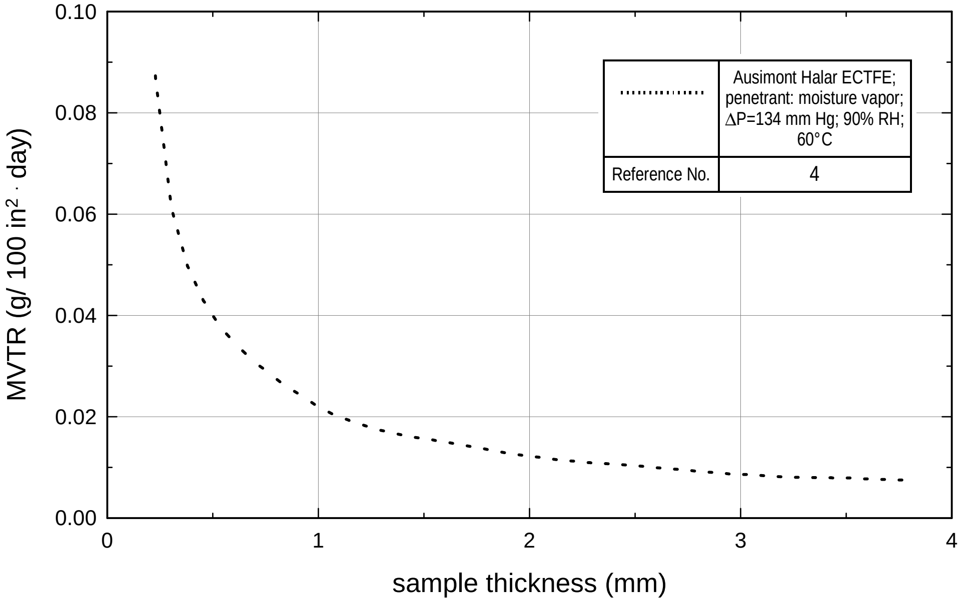


Figure II.09 Moisture vapor permeability rate vs thickness through ethylene chlorotrifluoroethylene copolymer.

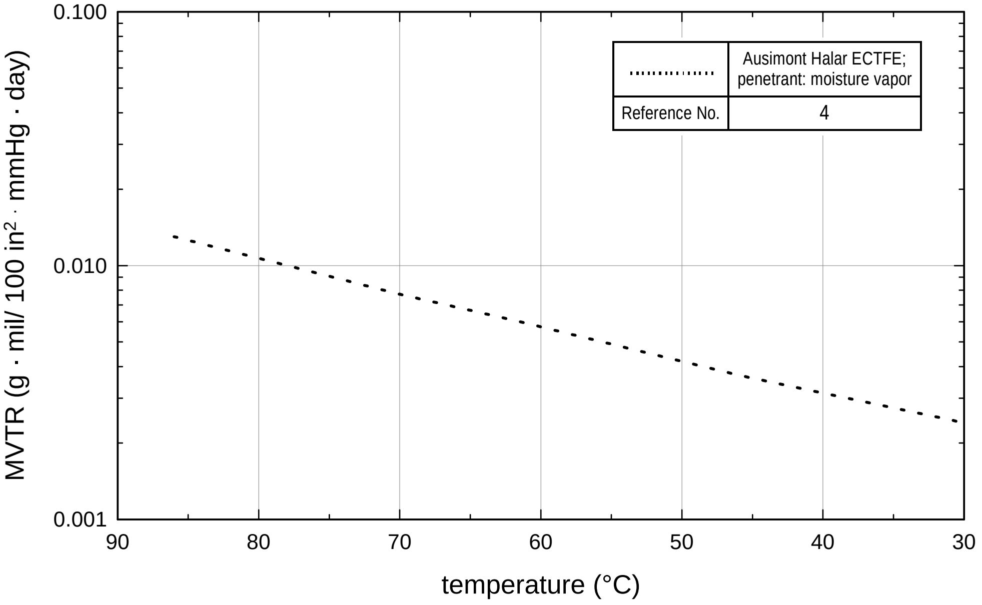


Figure II.10 Moisture vapor permeability rate vs temperature through ethylene chlorotrifluoroethylene copolymer.

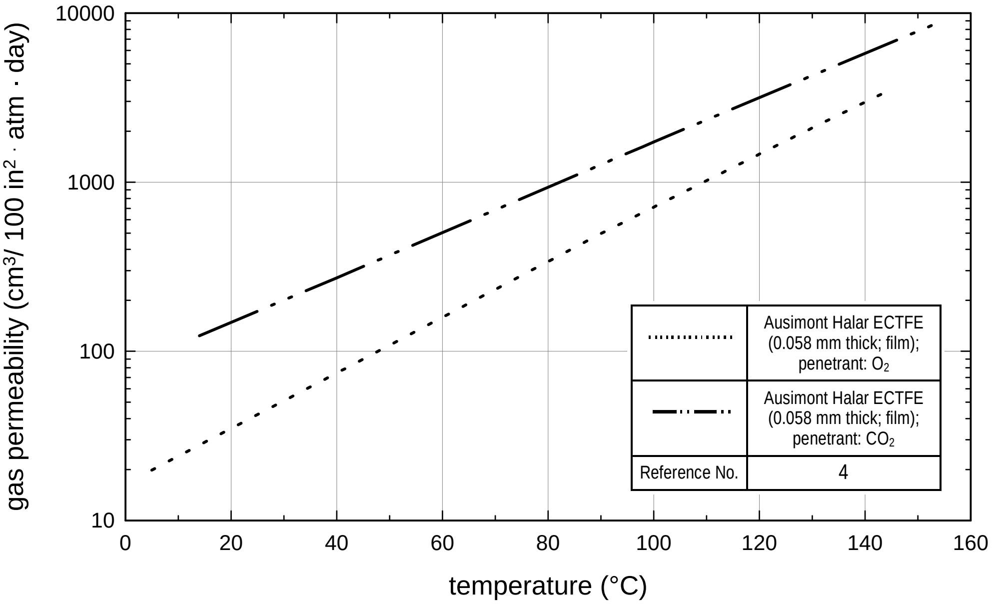


Figure II.11 Carbon dioxide and oxygen permeability vs temperature through ethylene chlorotrifluoroethylene copolymer.

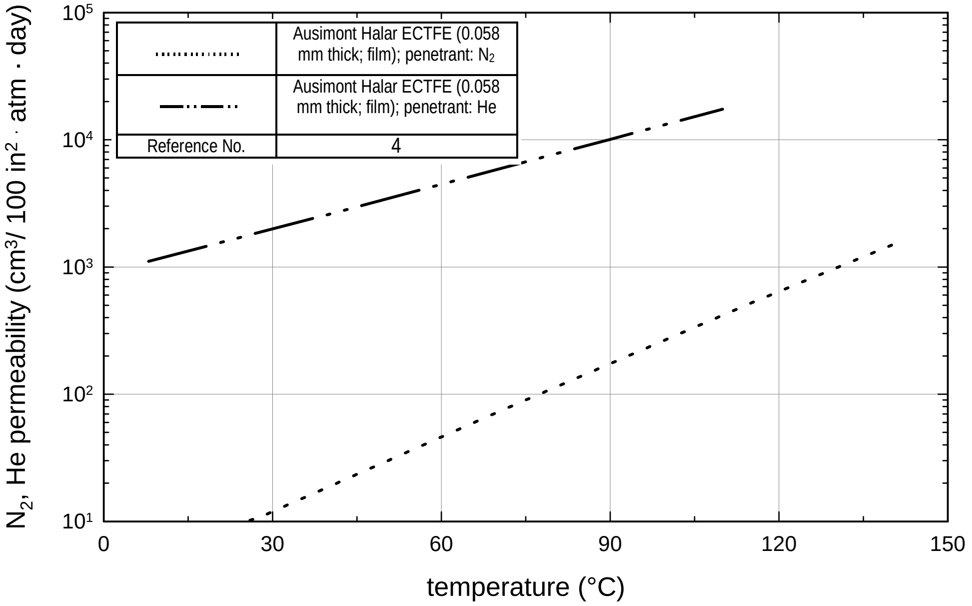


Figure II.12 Nitrogen and helium permeability vs temperature through ethylene chlorotrifluoroethylene copolymer.

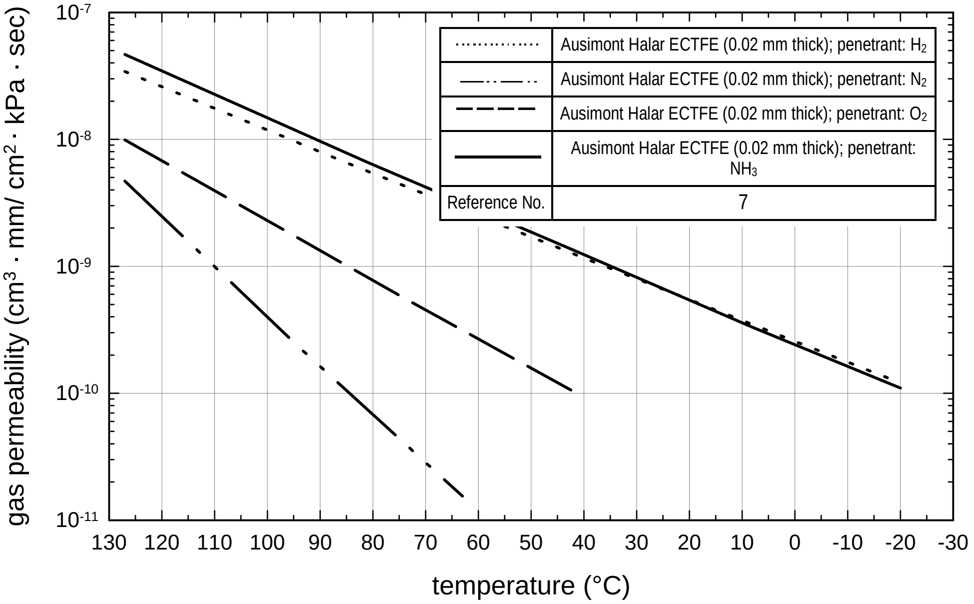


Figure II.13 Gas permeability vs temperature through ethylene chlorotrifluoroethylene copolymer.

II.4 Polyvinyl Fluoride

Table II.11. Water Vapor, Oxygen, Nitrogen, and Carbon Dioxide Permeability through Polyvinyl Fluoride

Material Family	**POLYVINYL FLUORIDE**			
Reference Number	3			
TEST CONDITIONS				
Penetrant	water vapor	oxygen	nitrogen	carbon dioxide
Temperature, °C	37.8	25		
Relative Humidity, %	90			
Test Method		STP conditions		
PERMEABILITY (source document units)				
Gas Permeability ($cm^3 \cdot mil/100\ in^2 \cdot day$)		3.0	0.25	11
Gas Permeability ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)		1.2	0.10	4.3
Vapor Transmission Rate ($g \cdot mil/100\ in^2 \cdot day$)	3.24			
Vapor Transmission Rate ($g/day \cdot 100\ in^2$)	1.3			
PERMEABILITY (normalized units)				
Permeability Coefficient ($cm^3 \cdot mm/m^2 \cdot day \cdot atm$)		1.2	0.1	4.3
Vapor Transmission Rate ($g \cdot mm/m^2 \cdot day$)	1.3			

II.5 Fluorinated Polyethylene

II.5.1 Permeability to Oxygen

FPE:

Features: Barrier properties

Product form: Bottles

Fluorinated bottles do not provide any improvement in oxygen barrier over untreated straight HDPE bottles.[4]

Table II.12. Cyclohexanone, Chlorobenzene, Hexane, Butyl Alcohol, Trichloroethlyene, Methyl Salicylate, and Tetrahydrofuran Permeability through Fluorinated Polyethylene Bottles

Material Family	**FLUORINATED POLYETHYLENE**
Product Form	**BOTTLES**
Features	barrier properties
Reference Number	8

TEST CONDITIONS

Penetrant	cyclohexanone	chlorobenzene	hexane	butyl alcohol	trichloroethene	methyl salicylate	tetrahydrofuran
Temperature, °C	50						23
Exposure Time, days	28						180

PERMEABILITY (source document units)

Penetrant Weight Loss, %	0.17	0.65	0.42	0.1	0.58	0.03	8.89

Table II.13. Ethyl Acetate, Isopropyl Acetate, Acetone, Butyl Acetate, Toluene, Xylene, Methyl Isobutyl Ketone, and Methyl Ethyl Ketone Permeability through Fluorinated Polyethylene Bottles

Material Family	**FLUORINATED POLYETHYLENE**
Product Form	**BOTTLES**
Features	barrier properties
Reference Number	8

TEST CONDITIONS

Penetrant	ethyl acetate	isopropyl acetate	acetone	butyl acetate	toluene	xylene	methyl isobutyl ketone	methyl ethyl ketone
Temperature, °C	50		23	50				
Exposure Time, days	28		180	28				

PERMEABILITY (source document units)

Penetrant Weight Loss, %	2.7	0.62	0.69	1.0	0.6	0.21	0.56	2.7

Table II.14. Kerosene, d-Limonene, 2-Cycle Motor Oil, Pine Oil Cleaner, Diesel Fuel Conditioner, and Brakleen Gas Additive Permeability through Fluorinated Polyethylene Bottles

Material Family	**FLUORINATED POLYETHYLENE**
Product Form	**BOTTLES**
Features	barrier properties
Reference Number	8

TEST CONDITIONS

Penetrant	kerosene	d-limonene	motor oils	pine oil	diesel fuel conditioner	gas additive
Penetrant Note			2 cylce	cleaner		brakleen
Temperature, °C	50					
Exposure Time, days	28					

PERMEABILITY (source document units)

Penetrant Weight Loss, %	0.04	0.11	0.07	0.10	0.08	0.06

Table II.15. Mineral Spirits, Turpentine, STP Gas Treatment, Paint Thinner, Charcoal Starter, and Naphtha Permeability through Fluorinated Polyethylene Bottles

Material Family	**FLUORINATED POLYETHYLENE**
Product Form	**BOTTLES**
Features	barrier properties

TEST CONDITIONS

Penetrant	mineral spirits	turpentine	STP gas treatment	paint thinner	charcoal starter	naphtha
Temperature, °C	50					
Exposure Time, days	28					

PERMEABILITY (source document units)

Penetrant Weight Loss, %	0.02	0.06	0.12	0.08	0.03	0.06

References

1. Solvay Polyvinylidene Fluoride, supplier design guide (B-1292c-B-2.5-0390), Solvay (1992)
2. Foraflon® PVDF, supplier design guide (694.E/07.87/20), Atochem S. A. (1987)
3. Aclar® Performance Films, Suppl. Tech Rep. No. SFI-14, Revised 9-89, Allied Signal Eng. Plastics (1989)
4. Chemical Resistance of Halar® Fluoropolymer, supplier technical report (AHH), Ausimont.
5. Tefzel® *Fluoropolymers Design Handbook*, supplier design guide No. E-31301-1, DuPont Co. (1973)
6. Hyflon® ETFE 700/800 Prop. and Appl. supplier design guide, Ausimount USA, Inc.
7. Adam, S. J., and David, C. E., Permeation Measurement of Fluoropolymers Using Mass Spectroscopy and Calibrated Standard Gas Leaks, 23rd International SAMPE Tech. Conf., *Conf. Proceedings - SAMPE* (1991)
8. Selar® RB Barrier Resins, Resin Blend Technical Information, supplier technical report (H-42016), DuPont Co. (1992)

Appendix III: Permeation of Automotive Fuels Through Fluoroplastics

III.1 Test Method

Modified SAE J-30 (Sec. 6.12) Method, 2000 Hours.

III.1.1 Fuel Types

- *Fuel C:* Reference fuel, 50/50 blend, by volume, of iso-octane and toluene.
- *M20:* 20 vol% methanol in Fuel C.
- *Sour Gas:* 0.08 molar t-butyl hydroperoxide in Fuel C.

The majority of the test was conducted using M20. The resins studied were:

- *Teflon® 62:* Polytetrafluoroethylene (PTFE); fine powder, paste extrusion resin.
- *Teflon® FEP 100:* Fluorinated ethylene propylene copolymer (FEP); general purpose, medium viscosity, melt extrusion resin.
- *Teflon® PFA 340:* Copolymer of tetrafluoroethylene and a perfluoroalkoxy monomer (PFA); general purpose, medium viscosity, melt extrusion resin.
- *Tefzel® 200:* Ethylene tetrafluoroethylene copolymer (ETFE); general purpose, melt extrusion resin.
- *Vestamid® L2121:* Nylon 12 polyamide; 7% plasticizer, melt extrusion resin.
- *Zyth® CFE 3011:* Nylon 12, 12 polyamide; 13% plasticizer, melt extrusion resin.

Table III.01. Permeation Rates (g · mm)/(day · m²)

Hose	M20	Fuel C	Sour Gas
PTFE	0.23	0.15	0.11
PTFE/w overbraid	0.22		
Conductive PTFE	0.18		
PFA (0.76 mm)	0.14		0.16
PFA (0.53 mm)	0.12		
PFA (0.28 mm)	0.13		
Conductive PFA	0.08		
ETFE	0.13	0.09	
FEP	0.18		
Nylon 12	1.35		
Nylon 12, 12	1.32		
Note: Tube diameters 6–10 mm, wall thickness 0.75–0.85 mm except those noted.			

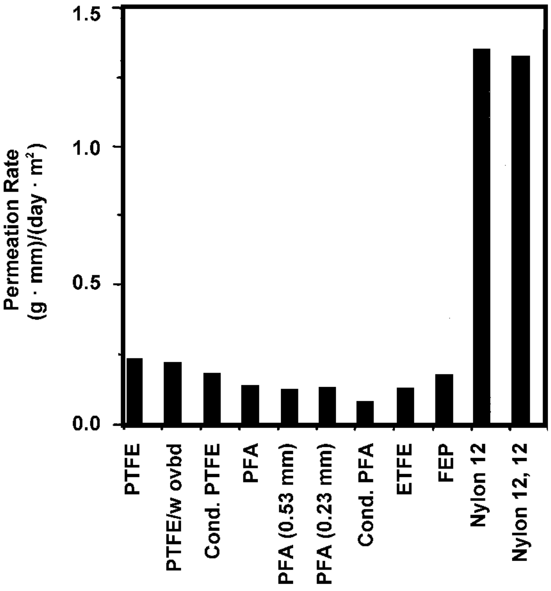


Figure III.01 Permeation of M20 fuel through fluoropolymers and nylons. Note: ovbd = overbraided.

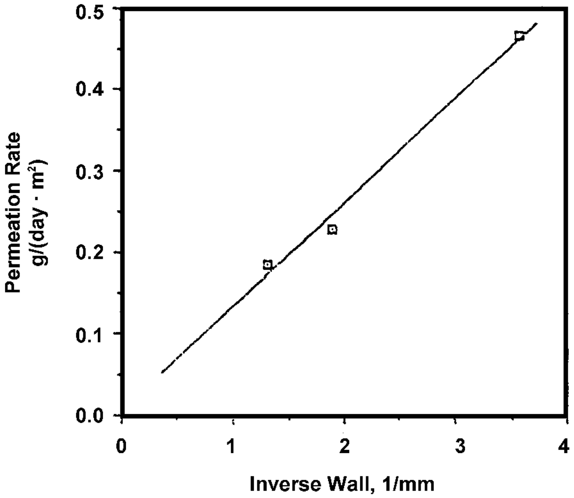


Figure III.02 Permeation of M20 fuel through PFA vs inverse wall thickness.

References

1. Teflon®/Tefzel® Technical Information published by DuPont, No. H34374 (Sep. 1992)
2. Goldberry, D. R., Society of Automotive Paper Series 910104, Part II. Fluoropolymer Resins: Permeation of Automotive Fuels.
3. Chillous, S. E., and Will, R. R., presented at Int. Congress & Exposition, Detroit, MI (Feb. 25–Mar. 1, 1991)

Appendix IV: Permeation of Organic and Inorganic Chemicals Through Fluoroplastic Films

Table IV.01. Permeation Rate of Chlorine Gas Through Fluoroplastic Films

Chlorine		
Polymer	**Thickness, microns**	**Permeation Rate, g/m^2/24 hr @ 25°C**
Granular PTFE	250	1.974
	2,250	0.358
	4,450	0.255
Fine Powder PTFE	250	5.55
	2,250	0.369
	4,450	0.289
FEP	4,450	0.190
PFA	250	1.605
	2,250	0.569
	4,450	0.265
ETFE	250	1.164
	2,250	0.254
	4,450	0.250
ECTFE	4,450	0.199
PVDF	250	1.018
	5,250	0.167

Table IV.02. Permeation Rate of Nitric Acid Through Fluoroplastic Films

20% Nitric Acid			
Polymer	**Thickness, microns**	**Permeation Rate, g/m^2/24 hr**	
		@ 25°C	**@ 45°C**
Granular PTFE	250	—	0.395
FEP	—	—	—
PFA	250	0.397	0.610
ETFE	250	0.469	—
	2,250	0.035	0.107
ECTFE	250	0.072	1.453
	2,250	0.061	0.037
PVDF	250	0.344	3.703
	2,250	—	0.265

Table IV.03. Permeation Rate of Methylene Chloride Through Fluoroplastic Films

Methylene Chloride			
Polymer	Thickness, microns	Permeation Rate, $g/m^2/24$ hr	
		@ 25°C	@ 45°C
Granular PTFE	250	3.85	9.08
Fine Powder PTFE	250	20.6	60.8
FEP	—	—	—
PFA	250	2.34	10.6
ETFE	250	33.1	113.6
ECTFE	250	59.5	634.6
PVDF	250	8.55	36.06
Polypropylene	250	504.2	2,250

Table IV.04. Permeation Rate of Phenol Through Fluoroplastic Films

Phenol				
Polymer	Thickness, microns	Permeation Rate, $g/m^2/24$ hr		
		@ 25°C	@ 45°C	@ 75°C
Granular PTFE	250	0.050	0.247	5.854
Fine Powder PTFE	250	0.084	0.991	—
FEP	—	—	—	—
PFA	250	0.013	0.237	—
ETFE	250	0.158	1.562	15.3
ECTFE	250	0.067	—	—
PVDF	250	0.218	3.394	—
Polypropylene	250	0.027	0.734	—

Table IV.05. Permeation Rate of Benzene Through Fluoroplastic Films

Benzene				
Polymer	Thickness, microns	Permeation Rate, g/m^2/24 hr		
		@ 25°C	@ 45°C	@ 75°C
Granular PTFE	250	2.591	29.4	89.26
	2,250	0.777	—	3.286
	4,450	0.0335	—	—
Fine Powder PTFE	—	—	—	—
FEP	—	—	—	—
PFA	—	—	—	—
ETFE	250	5.326	16.4	94.9
	2,250	0.118	0.011	5.655
	4,450	0.068	—	—
ECTFE	—	—	—	—
PVDF	—	—	—	—

Table IV.06. Permeation Rate of Methyl Ethyl Ketone Through Fluoroplastic Films

Methyl Ethyl Ketone				
Polymer	Thickness, microns	Permeation Rate, g/m^2/24 hr		
		@ 25°C	@ 45°C	@ 75°C
Granular PTFE	250	7.726	20.4	29.1
	2,250	0.316	—	—
	4,450	0.028	—	—
Fine Powder PTFE	—	—	—	—
FEP	—	—	—	—
PFA	—	—	—	—
ETFE	250	6.882	42.3	426.8
	2,250	0.034	—	—
	4,450	0.023	—	—
ECTFE	250	27.6	66.1	519.6
	2,250	0.033	—	—
PVDF	250	482.1	1866.8	8247.0
	2,250	0.168	—	—

Table IV.07. Permeation Rate of Water Through Fluoroplastic Films

Polymer	**Thickness, microns**	**Permeation Rate, g/m^2/24 hr**		
		@ 25°C	**@ 45°C**	**@ 75°C**
Granular PTFE	250	0.295	0.845	5.568
	2,250	0.050	—	—
ETFE	250	0.672	2.513	17.18
	4,450	0.053	—	—
ECTFE	—	—	—	—

References

1. Teflon® Industrial Coatings, The Facts: Permeation, Its Effects on Teflon® ETFE Coatings on Corrosive Fume Exhaust Ducts, DuPont Co. (1999)

Appendix V: Chemical Resistance of Thermoplastics

V.1 Chemical Resistance of Fluoropolymers

This appendix contains extensive chemical resistance data for a number of commercial fluoropolymers. Most of the chemicals are frequently encountered in processing operations. The data for each fluoropolymer are organized alphabetically, using the common name of each chemical. The reader should review the next section (Sec. V.2) to understand the basis for the PDL Rating. Exposure conditions for each chemical have been listed because the same chemical could behave in a different way if the conditions of exposure (such as temperature or concentration) are altered. Where data have been available, the effect of exposure on the physical properties such as weight change and tensile properties have been listed.

V.2 PDL Resistance Rating

The PDL Resistance Rating is determined using a weighted value scale developed by PDL and reviewed by experts. Each of the ratings is calculated from test results provided for a material after exposure to a specific environment. It gives a general indication of a material's resistance to a specific environment. In addition, it allows the users to search for materials most likely to be resistant to a specific exposure medium.

After assigning the weighted value to each field for which information is available, the PDL Resistance Rating is determined by adding together all weighted values and dividing this number by the number of values added together. All numbers to the right of the decimal are truncated to give the final result. If the result is equal to 10, a resistance rating of 9 is assigned. Each reported field is given equal importance in assigning the resistance rating since, depending on the end use, different factors play a role in the suitability for use of material in a specific environment. Statistically, it is necessary to consider all available information in assigning the rating. Supplier resistance ratings are also figured into the calculation of the PDL Resistance Rating. Weighted values assigned depend on the scale used by the supplier.

Table V.1 gives the values and guidelines used in assigning the PDL Resistance Rating. The guidelines—especially in the case of visual observations—are sometimes subject to an educated judgement. An effort is made to maintain consistency and accuracy.

Table V.1. PDL Resistance Rating Guidelines

Weighted Value	Weight Change	Diameter Length Change	Thickness Change	Volume[*1] Change	Mechanical[*2] Property Retained	Visual[*3] Observed Change	BTT (min.)	Permeation Rate ($\mu g/cm^2$/min)	Hardness Change (Units)
10	0–0.25	>0–0.1	0–0.25	0–2.5	≥97	No change	≤1	≤0.9	0–2
9	>.25–0.5	>0.1–0.2	>.25–0.5	>2.5–5.0	94 to <97		>1 to ≤2		>2–4
8	>0.5—0.75	>0.2–0.3	>0.5—0.75	>5.0–10.0	90 to <94		>2 to ≤5	>0.9–9	>4–6
7	>0.75–1.0	>0.3–0.4	>0.75–1.0	>10.0–20.0	85 to <90	Slightly discolored, slightly bleached	>5 to ≤10		>6–9
6	>1.0–1.5	>0.4–0.5	>1.0–1.5	>20.0–30.0	80 to <85	Discolored yellows, slightly flexible	>10 to ≤30	>9–90	>9–12
5	>1.5–2.0	>0.5–0.75	>1.5–2.0	>30.0–40.0	75 to <80	Possible stress crack agent, flexible, possible oxidizing agent, slightly crazed	>30 to ≤120		>12–15
4	>2.0–3.0	>0.75–1.0	>2.0–3.0	>40.0–50.0	70 to <75	Distorted, warped, softened, slight swelling, blistered, known stress crack agent	>120 to ≤240	>90–900	>15–18
3	>3.0–4.0	>1.0–1.5	>3.0–4.0	>50.0–70.0	60 to <70	Cracking, crazing, brittle, plasticizer oxidizer, softened swelling, surface hardness	>240 to ≤480		>18–21
2	>4.0–6.0	>1.5–2.0	>4.0–6.0	>60.9–90.0	50 to <60	Severe distortion, oxidizer and plasticizer deteriorated	>480 to ≤960	>900–9000	>21–25
1	>6.0	>2.0	>6.0	>90.0	>0 to <50	decomposed	>960		>25
					0	solvent dissolved, disintegrated		>9000	

[*1] All values are given as percent change from original.

[*2] Percent mechanical properties retained include tensile strength, elongation, modulus, flexural strength, and impact strength. If the % retention is greater than 100%, a value of 200 minus the %property retained is used in the calculation.

[*3] Due to the variety of information of this type reported, this table can be used only as a guideline.

Chemical Resistance Tables

The tables on the following pages have been reproduced in their entirety from *Chemical Resistance, Vol. 1: Thermoplastics*, ISBN: 1-884207-12-X, a *PDL Series Databook* from William Andrew, Inc.

Chemical Resistance - Cellulosic Plastics

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change		Resistance Note	Material Note
						Weight	Thickness		
Sachet Powder			50	30	9			appearance unchanged	Eastman Tenite Propionate; dry (CP)
Shaving Cream	Mennen		23	2	9			«	Eastman Tenite Acetate; dry (CA)
Shoe Polish	Kusan		23	3	8	0.15		stained	«
Silicone Oils	Dow Corning # 200		23	90	8	0.77	0.16	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
Silver Nitrate		2.5	23	2	7	1.46		appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
		3	23	2	6	1.97	0.61	slightly softened	Eastman Tenite Acetate; dry (CA)
Skydrol	hydraulic fluid		23		0			unsatisf.; dissolved	Eastman Tenite Butyrate; dry (CAB)
	«		23	365	8	-1.07	-0.24	appearance unchanged	Eastman Tenite Acetate; dry (CA)
Skydrol 500	Monsanto; hydraulic fluid		23		0			unsatisf.; dissolved	Eastman Tenite Butyrate; dry (CAB)
	«		23	365	7	1.15	0.42	surface dulled	Eastman Tenite Acetate; dry (CA)
Soap		10	88	1	2		4.13		«
	solution; USP		23	365	9			appearance unchanged	Eastman Tenite Propionate; dry (CP)
Sodium Acetate		3	38	3	7	1.3		«	Eastman Tenite Butyrate; dry (CAB)
Sodium Aluminum Sulfate	solid		23	7	7	1.64	0.44	«	«
Sodium Bicarbonate		2.5	23	2	7	1.68	0.53	«	«
	solid		23	2	6	2.96	1.6	«	Eastman Tenite Acetate; dry (CA)
Sodium Bisulfate		1	38	3	7	1.25		«	Eastman Tenite Butyrate; dry (CAB)
	solid		38	7	9	0.1		«	«
Sodium Bisulfite		20	23	7	6	2.14	0.8	«	«
		20	23	7	5	4.03	2.37	«	Eastman Tenite Acetate; dry (CA)
Sodium Borate		2.5	23	2	6	2.88	1.56	«	«
		2.5	23	2	7	1.53	0.52	«	Eastman Tenite Butyrate; dry (CAB)
Sodium Carbonate		2.5	23	365	7	1.28	0.93	«	«
		2.5	23	365	3	-8.74	-2.25	slightly softened	Eastman Tenite Acetate; dry (CA)
		2.5	23	365	9			appearance unchanged	Eastman Tenite Propionate; dry (CP)
		6	38	3	7	1.18		«	Eastman Tenite Butyrate; dry (CAB)
		10	23	365	9			«	«
	solid		23	4	9	-0.1	-0.08	«	Eastman Tenite Acetate; dry (CA)
	«		38	7	6	3.9		«	Eastman Tenite Butyrate; dry (CAB)
Sodium Chloride		2.5	23	365	9			«	«
		10	23	365	7	1.33	0.54	«	«
		10	23	365	6	2.52	1.53	«	Eastman Tenite Acetate; dry (CA)
		10	23	365	9			«	Eastman Tenite Propionate; dry (CP)
	saturated		23	60	7	1.26	0.54	«	Eastman Tenite Acetate; dry (CA)
	«		23	60	8	0.79	0.31	«	Eastman Tenite Butyrate; dry (CAB)
	«		60	60	7	0.89	0.89	«	«
	«		60	60	7	1.03	-0.52	«	Eastman Tenite Acetate; dry (CA)
Sodium Chromate	«		23	7	9	0.57	0.2	«	Eastman Tenite Butyrate; dry (CAB)
Sodium Cyanide		10	23	60	8	1.02	0.28	«	«
		10	23	60	2	-4.2	-5.6	unsatisf., soft, discolor.	Eastman Tenite Acetate; dry (CA)
	saturated		23	60	4	-0.84	-2.59	«	«
	«		23	60	9	-0.18	-0.44	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
Sodium Ferrocyanide	dry crystals		23	7	9	0.37		«	Eastman Tenite Acetate; dry (CA)
	«		23	7	8	0.84		«	Eastman Tenite Butyrate; dry (CAB)
	«		23	7	7	0.8	0.96	«	Eastman Tenite Propionate; dry (CP)
Sodium Fluoride		4	23	30	6	2.45		«	Eastman Tenite Butyrate; dry (CAB)
		4	23	30	6	3.6		«	Eastman Tenite Acetate; dry (CA)

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change		Resistance Note	Material Note
						Weight	Thickness		
Sodium Hydroxide		1	23	30	5	-1.94	-0.12	unsatisf.; soft, warp	Eastman Tenite Acetate; dry (CA)
		1	23	365	8	0.95	0.61	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
		1	23	365	9			"	Eastman Tenite Propionate; dry (CP)
		10	23	7	0			unsatisf.; decomposed	Eastman Tenite Acetate; dry (CA)
		10	23	240	3	3.19	2.2	unsatisf.; brittle	Eastman Tenite Butyrate; dry (CAB)
		10	23	365	0			unsatisf.; disintegrates	Eastman Tenite Propionate; dry (CP)
Sodium Hypochlorite		5	23	2	5	0.85	0.35	unsatisf.; soft., surf. attack	Eastman Tenite Acetate; dry (CA)
		30	23	13	6	1.11	-2.09	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
Sodium Nitrate		10	23	365	8	1.23	0.42	"	"
		10	23	365	6	2.58	1.45	"	Eastman Tenite Acetate; dry (CA)
	saturated		23	60	7	1.48	0.85	"	"
	solid		23	60	9	-0.26	-0.23	"	"
	saturated		23	60	8	0.92	0.39	"	Eastman Tenite Butyrate; dry (CAB)
	solid		23	60	9	0.08	0.12	"	"
Sodium Nitrite	saturated		23	60	8	0.78	0.27	"	Eastman Tenite Acetate; dry (CA)
	solid		23	60	9	-0.42	-0.38	"	"
Sodium Silicate	saturated		23	60	4	-0.34	-2.6	unsatisf., soft.	"
	solid		23	60	6	0.57	0.19	unsatisf.; etched	"
	saturated		23	60	8	1.18	0.13	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
	solid		23	60	9	0.3	0.2	"	"
Sodium Sulfite		10	23	7	6	2.08	0.88	"	"
Sodium Thiosulfate		20	23	13	7	1.1		"	"
		24	38	3	7	1.22		"	"
Spearmint	spearmint oil		23		0			unsatisf.; dissolved	"
	"		23	7	9			appearance unchanged	Eastman Tenite Acetate; dry (CA)
Sperm Oil			90	7	3	-4.03		slightly warped	"
			90	7	9	-0.48		appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
Stearic Acid			23	7	9			"	"
			23	7	9			"	Eastman Tenite Acetate; dry (CA)
Stoddard Solvents	white spirits		23	3	9	-0.05		"	"
	"		23	3	9	0.48		"	Eastman Tenite Butyrate; dry (CAB)
Styrene	monomer		23		0			unsatisf.; dissolved	"
Sulfur	solid		23	7	9			appearance unchanged	"
Sulfur Dioxide	dry		23	60	1	19.4	8.6	unsatisf.; swell., warp	"
	moist		23	60	1	31.9	10.2	"	"
	saturated		23	60	1	23.2	18.1	"	"
	dry		23	60	1	17.3	11.6	"	Eastman Tenite Acetate; dry (CA)
	moist		23	60	1	13.5	9.71	"	"
	saturated		23	60	1	10.6	13.5	"	"
Sulfuric Acid		3	23	30	3	3.04	2.19	unsatisf., soft.	"
		3	23	365	6	1.6	0.97	slight discoloring	Eastman Tenite Butyrate; dry (CAB)
		3	23	365	9			appearance unchanged	Eastman Tenite Propionate; dry (CP)
		10	23	365	7	1.5	0.74	slight discoloring	Eastman Tenite Butyrate; dry (CAB)
		10	23	365	0			unsatisf., decomposed	Eastman Tenite Acetate; dry (CA)
		20	23	240	0			"	"
		20	23	365	5	0.91	0.31	unsatisf.; soft., surf. attack	Eastman Tenite Butyrate; dry (CAB)
		30		365	6	-0.42	-0.29	unsatisf.; surf. attack	"
		30	23	365	5			unsatisf.; sl. warp	Eastman Tenite Propionate; dry (CP)
		94	23		0			unsatisf.; disintegrates	Eastman Tenite Butyrate; dry (CAB)
Talcum Powder			23	3	5	2.93	2.36	appearance unchanged	"

Chemical Resistance - Cellulosic Plastics

Chemical Resistance - Cellulosic Plastics

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change		Resistance Note	Material Note
						Weight	Thickness		
Tannic Acid		10	38	120	6	2.75	1.2	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
		10	60	120	3	7.62	1.83	unsatisf., soft.	Eastman Tenite Acetate; dry (CA)
Tartaric Acid			23	2	6	2.93	1.6	appearance unchanged	"
Tea	iced		23	7	6	1.98	1.04	"	"
	"		23	7	7	1.5	1.05	"	Eastman Tenite Butyrate; dry (CAB)
Terpineol			23	2	8	0.56		appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
			23	2	9	0.06	0.09	"	Eastman Tenite Acetate; dry (CA)
Tetra(2-Ethylbutyl) Silicate			50	30	6	-2.39	-0.83	"	"
			50	30	9	-0.74	-0.1	"	Eastman Tenite Butyrate; dry (CAB)
Tetrabromoethane (sec-)			23	3	2			unsatisf.; swell., soft.	"
			23	3	3	5.36	3.45	unsatisf., sl. swell.	Eastman Tenite Acetate; dry (CA)
Tetrachloroethane			23		0			unsatisf.; dissolved	"
			23		0			"	Eastman Tenite Acetate; dry (CA)
Tetrachloroethylene			23	12	2			unsatisf.; swell.	Eastman Tenite Butyrate; dry (CAB)
			23	14	9			appearance unchanged	Eastman Tenite Acetate; dry (CA)
Tetrahydrofurfuryl			23		0			unsatisf.; dissolved	Eastman Tenite Butyrate; dry (CAB)
			23	3	4			soft, swollen	Eastman Tenite Acetate; dry (CA)
Thyme Oil			23		0			unsatisf.; dissolved	Eastman Tenite Butyrate; dry (CAB)
	white		23	2	9	0.37	0.05	appearance unchanged	Eastman Tenite Acetate; dry (CA)
Titanium Tetrachloride			23	3	2			unsatisf.; brittle	"
			23	3	2			"	Eastman Tenite Butyrate; dry (CAB)
TNT	water slurry		23	28	6			stained	"
Toluene			23	2	2	39.3	54.9	unsatisf., soft.	"
			23	365	2			unsatisf.; soft, swell.	Eastman Tenite Propionate; dry (CP)
			23	365	2	-1.72	8.92	unsatisf.; swell., soft	Eastman Tenite Acetate; dry (CA)
Tomato Juice			23	7	6	2.06	1.52	appearance unchanged	"
	Campbell's		23	7	6	1.77	1.36	"	Eastman Tenite Butyrate; dry (CAB)
Toothpaste	Lever		38	4	7	0.97	1.24	"	Eastman Tenite Acetate; dry (CA)
Transformer Oils	GE#10-C		82	7	7	-2.94	0.56	"	"
	"		82	7	8	-0.9	0.22	"	Eastman Tenite Butyrate; dry (CAB)
	Pyranol		90	7	8	-0.74		"	"
	"		90	7	6	-3.58		"	Eastman Tenite Acetate; dry (CA)
Trichloroacetic Acid		1	23	30	7	3.28	0.5	"	Eastman Tenite Butyrate; dry (CAB)
		5	23	30	2	9.25	3.07	unsatisf., soft.	"
			23	30	0			unsatisf.; decomposed	Eastman Tenite Acetate; dry (CA)
Trichloroethylene			23	0.67	2	32.2		unsatisf.; surf. attack	"
			23	1	2			unsatisf.; swell.	Eastman Tenite Butyrate; dry (CAB)
Triethanolamine		10		7	4	-5.16	0.69	unsatisf.; soft., surf. attack	Eastman Tenite Acetate; dry (CA)
			23	7	2	11.72	24.9	unsatisf., soft.	"
Triethylene Glycol			23	60	2	8.61	6.7	"	Eastman Tenite Butyrate; dry (CAB)
			23	120	1	25.4	22.89	unsatisfact.; warp, swell.	Eastman Tenite Acetate; dry (CA)
Trimethylbenzylammonium Chloride		5	23	17	6	0.59	3.2	appearance unchanged	"
		5	23	17	8	1.13	0.06	"	Eastman Tenite Butyrate; dry (CAB)
Trimethylbenzylammonium Hydroxide		5	23	17	7	1.13		"	"
		5	23	17	2	-4.87	5.85	unsatisf., swell., checked	Eastman Tenite Acetate; dry (CA)
Turpentine			23	365	8	-0.85	0.16	appearance unchanged	"
			23	365	1	99.2	62.62	unsatisfact.; soft, swell.	Eastman Tenite Butyrate; dry (CAB)
			23	365	9			appearance unchanged	Eastman Tenite Propionate; dry (CP)

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change		Resistance Note	Material Note
						Weight	Thickness		
Urine			23	7	8	1.5	0.4	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
Vanilla	imitation		23	2	3	11.8	9.7	unsatisf.; visual chg.	"
Varsol 2	solvent		23	7	7	1.14	0.94	appearance unchanged	"
	"		23	7	7	-1.6	-0.28	"	Eastman Tenite Acetate; dry (CA)
Vicks	decongestant		50	2	2			unsatisf., stain, swollen	Eastman Tenite Butyrate; dry (CAB)
	"		50	2	3			unsatisf.; stained, soft	Eastman Tenite Propionate; dry (CP)
Water	distilled		23	365	7	1.66	0.74	appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
			23	365	9			"	Eastman Tenite Propionate; dry (CP)
			23	365	5	3.09	1.96	"	Eastman Tenite Acetate; dry (CA)
Waxes	Pride		23	7	4	3.01	2.25	slightly softened	Eastman Tenite Butyrate; dry (CAB)
Weed Killer	Weed-B-Gon		23	30	1	13.43	6.58	unsatisfactory	"
	"		23	30	5	1.9	1.74	unsatisf.; visual chg.	Eastman Tenite Acetate; dry (CA)
	End-O-Weed		23	60	5	2.8	-0.45	unsatisf.; sl. soft.	"
	"		23	120	1	19.5	8.19	unsatisf.; soft, swell., discolor.	Eastman Tenite Butyrate; dry (CAB)
Wines	12% ethyl alcohol		23	60	4	7.88	5.17	appearance unchanged	"
Wintergreen Oil			23		0			unsatisf.; dissolved	"
			23	2	4	2.74	1.58	slight surface attack	Eastman Tenite Acetate; dry (CA)
Xylene			23	7	2	41.52	33.17	unsatisf., soft.	Eastman Tenite Butyrate; dry (CAB)
			23	365	2			unsatisf.; soft, swell.	Eastman Tenite Propionate; dry (CP)
			23	365	5	-5.64	2.12	appearance unchanged	Eastman Tenite Acetate; dry (CA)
Zinc Chloride	hydrous salt		23	7	8	0.88		"	"
	saturated solution		23	7	0			unsatisf.; dissolved	"
	hydrous salt		23	7	8	0.53		appearance unchanged	Eastman Tenite Butyrate; dry (CAB)
	saturated solution		23	7	6	1.37	0.78	slightly etched	"
Zinc Oxide	solid		23	7	9			appearance unchanged	"

Chemical Resistance - Ethylene Vinyl Alcohol Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Acetic Acid	glacial	5			6	2.5		no change in appearance	Nippon Goh. Soarnol
	"				4			slight swelling	"
Acetone					9	<0.01		no change in appearance	"
			20	365	4	2.3			Eval E-Series
			20	365	9	0			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	"
			150		5			partially soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Ammonia	aqueous solution	10			6	2.5		no change in appearance	Nippon Goh. Soarnol
Aniline					9	<0.01		"	"
Benzaldehyde			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0			Eval E-Series
			20	365	9	0			Eval F-Series
Benzene					9	<0.01		no change in appearance	Nippon Goh. Soarnol
			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.3			Eval E-Series
			20	365	9	0.04			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Benzyl Alcohol			30		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			30		1			soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 0, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40 mol% VA content
			100		5			partially soluble in reagent	Eval; 62.9 mol% VA content
			150		9			insoluble in reagent	Eval; 0, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 40 mol% VA content
			150		5			partially soluble in reagent	Eval; 62.9 mol% VA content
Benzylic Alcohol			20	30	9	0.4			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	7	1			Eval E-Series
			20	365	9	0.05			Eval F-Series
Butyl Acetate	n-butyl acetate		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
	"		100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
	"		150		1			soluble in reagent	Eval; 0 mol% VA content
	"		150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Butyl Alcohol	n-butanol		30		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		30		5			partially soluble in reagent	Eval; 40 mol% VA content
	"		100		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40 mol% VA content
	"		150		9				Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		150		1			soluble in reagent	Eval; 40 mol% VA content

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Butyl Alcohol (sec-)	sec-butanol		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40 mol% VA content
	"		150		5			"	Eval; 0 mol% VA content
	"		150		1			soluble in reagent	Eval; 40 mol% VA content
	"		150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Butyl Alcohol (tert-)			30		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			30		5			partially soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 40 mol% VA content
Carbolic Acid		5			3	5		becomes transparent	Nippon Goh. Soarnol
Carbon Tetrachloride					9	<0.01		no change in appearance	Nippon Goh. Soarnol
			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	1	21.1			Eval E-Series
			20	365	3	3.5			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Caustic Soda		1			6	2.8		no change in appearance	Nippon Goh. Soarnol
		10			6	2.2		"	"
		40			7	2		"	"
Chlorobenzene			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Chloroform			30		9			"	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Citric Acid		10			6	3.4		no change in appearance	Nippon Goh. Soarnol
Cresol (m-)			30		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			30		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
			100		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
			150		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
Cyclohexane			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents

Chemical Resistance - Ethylene Vinyl Alcohol Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Cyclohexanone			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0			Eval E-Series
			20	365	9	0			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		5			partially soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Cyclohexyl Alcohol			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0			Eval E-Series
			20	365	9	0			Eval F-Series
	cyclohexanol		30		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
Cyclohexyl Alcohol	cyclohexanol		30		5			partially soluble in reagent	Eval; 40 mol% VA content
	“		100		5			“	Eval; 0, 40, 62.9 mol% VA contents
	“		100		9			insoluble in reagent	Eval; 73.4, 100 mol% VA contents
	“		150		5			partially soluble in reagent	Eval; 0, 62.9 mol% VA contents
	“		150		1			soluble in reagent	Eval; 40 mol% VA content
	“		150		9			insoluble in reagent	Eval; 73.4, 100 mol% VA contents
Dichlorobenzene			30		9			“	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		5			partially soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		5			partially soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Dichlorobenzene (o-)			20	30	9	0.01			Eval E-Series
			20	30	9	0.02			Eval F-Series
			20	365	9	0.5			Eval E-Series
			20	365	9	0.3			Eval F-Series
Diethyl Ether			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.4			Eval E-Series
			20	365	9	0			Eval F-Series
Dimethyl Sulfoxide			30		9			insoluble in reagent	Eval; 0 mol% VA content
			30		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			100		9			insoluble in reagent	Eval; 0 mol% VA content
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		9			insoluble in reagent	Eval; 0 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Dimethylformamide			20	30	2	5			Eval E-Series
			20	30	7	0.8			Eval F-Series
			20	365	1	10.4			Eval E-Series
			20	365	8	0.7			Eval F-Series

						% Change	% Retained		
Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	Weight	Tensile Strength	Resistance Note	Material Note
Dimethylformamide			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
			150		9			insoluble in reagent	Eval; 0 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Dioxane			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Ethane Dichloride					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Ethyl Acetate					9	<0.01		"	"
			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.2			Eval E-Series
			20	365	9	0			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Ethyl Acetate			150		5			partially soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Ethyl Alcohol					8	0.88		no change in appearance	Nippon Goh. Soarnol
			20	30	3	3.4			Eval E-Series
			20	30	6	1.5			Eval F-Series
			20	365	1	6.6			Eval E-Series
			20	365	4	2.3			Eval F-Series
	ethanol		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		9			"	Eval; 0, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40.0, 62.9 mol% VA contents
	"		150		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
	"		150		5			partially soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
Ethyl Ether					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Ethylene Chlorohydrin			30		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			30		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
			100		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
			150		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents
Ethylene Glycol			20	30	6	1.2			Eval E-Series
			20	30	7	0.8			Eval F-Series
			20	365	4	2.5			Eval E-Series
			20	365	6	1.5			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0 mol% VA content
			100		5			partially soluble in reagent	Eval; 40, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 62.9 mol% VA content
			150		9			insoluble in reagent	Eval; 0 mol% VA content
Ethylene Glycol			150		5			partially soluble in reagent	Eval; 100 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4 mol% VA contents

Chemical Resistance - Ethylene Vinyl Alcohol Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Formamide			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0, 40 mol% VA contents
			100		1			soluble in reagent	Eval; 62.9 mol% VA content
			100		5			partially soluble in reagent	Eval; 73.4, 100 mol% VA contents
			150		9			insoluble in reagent	Eval; 0, 40 mol% VA contents
			150		1			soluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Formic Acid			30		9			insoluble in reagent	Eval; 0 mol% VA content
			30		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			100		9			insoluble in reagent	Eval; 0 mol% VA content
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		9			insoluble in reagent	Eval; 0 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Freon 12	liquid				9	0.11		no change in appearance	Nippon Goh. Soarnol
Freon 22	"				9	0.11		"	"
Gasoline					9	<0.01		"	"
	LPG				9	<0.01		"	"
Glycerin					9	0.05		"	"
Glycerol			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0, 40 mol% VA contents
			100		5			partially soluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Glycerol			150		9			insoluble in reagent	Eval; 0, 40 mol% VA contents
			150		5			partially soluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Greases					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Hexane	n-hexane		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		1			soluble in reagent	Eval; 0 mol% VA content
	"		100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
	"		150		1			soluble in reagent	Eval; 0 mol% VA content
	"		150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Hydrochloric Acid		10			4	2.5		becomes transparent	Nippon Goh. Soarnol
Hydrogen Peroxide		3			6	2.6		no change in appearance	"
Isoamyl Acetate			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.3			Eval E-Series
			20	365	9	0.04			Eval F-Series
Isobutyl Alcohol	iso-butanol		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40 mol% VA content
	"		150		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		150		5			partially soluble in reagent	Eval; 40 mol% VA content
Isobutyl Aldehyde					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Isopropyl Alcohol	isopropanol				9	<0.01		"	"
	iso-propanol		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40 mol% VA content
Isopropyl Alcohol	iso-propanol		150		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		150		1			soluble in reagent	Eval; 40 mol% VA content
Kerosine					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Lamp Oils					9	<0.01		"	"
Lubricating Oils	heavy				9	<0.01		"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Machining Oils					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Methyl Acetate			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Methyl Alcohol					6	3.2		no change in appearance	Nippon Goh. Soarnol
			20	30	1	13.3			Eval E-Series
			20	30	2	5.7			Eval F-Series
			20	365	1	16.7			Eval E-Series
			20	365	1	12.2			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 40 mol% VA content
Methyl Ethyl Ketone					9	<0.01		no change in appearance	Nippon Goh. Soarnol
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		1			"	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			"	Eval; 0 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Methyl Isobutyl Ketone			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 0, 40 mol% VA contents
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Methylene Chloride			30		9			"	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Methylnaphthalene (α-)			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.05			Eval E-Series
			20	365	9	0			Eval F-Series
Nitric Acid		10			4	2.5		slight swelling	Nippon Goh. Soarnol
	concentrated				5			carbonization	"
Nitromethane			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	"
			150		5			partially soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Pentane	n-pentane				9	<0.01		no change in appearance	Nippon Goh. Soarnol
Perchloroethylene					9	<0.01		"	"
Petroleum Benzene					9	<0.01		"	"
Petroleum Ether			20	30	9	0			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.3			Eval E-Series
			20	365	9	0			Eval F-Series

Chemical Resistance - Ethylene Vinyl Alcohol Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Phenol			30		9			insoluble in reagent	Eval; 0 mol% VA content
			30		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			100		9			insoluble in reagent	Eval; 0 mol% VA content
			100		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 0 mol% VA content
			150		1			soluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Propyl Alcohol	n-propanol		30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
	"		100		9			"	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		100		5			partially soluble in reagent	Eval; 40 mol% VA content
	"		150		9			insoluble in reagent	Eval; 0, 62.9, 73.4, 100 mol% VA contents
	"		150		1			soluble in reagent	Eval; 40 mol% VA content
Propylene Glycol			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		9			"	Eval; 0, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 40 mol% VA content
			100		5			partially soluble in reagent	Eval; 62.9, 73.4 mol% VA contents
			150		9			insoluble in reagent	Eval; 0, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 40 mol% VA content
			150		5			partially soluble in reagent	Eval; 62.9, 73.4 mol% VA contents
Pyridine			20	30	4	2.8			Eval E-Series
			20	30	9	0.5			Eval F-Series
			20	365	1	10			Eval E-Series
			20	365	9	0.5			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 73.4, 100 mol% VA contents
			30		1			soluble in reagent	Eval; 40 mol% VA content
			30		5			partially soluble in reagent	Eval; 62.9 mol% VA content
			100		5			"	Eval; 0, 62.9 mol% VA contents
			100		1			soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 73.4, 100 mol% VA contents
			150		5			partially soluble in reagent	Eval; 0, 62.9 mol% VA contents
			150		1			soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 73.4, 100 mol% VA contents
Salad Oil			20	30	9	0.03			Eval E-Series
			20	30	9	0			Eval F-Series
			20	365	9	0.07			Eval E-Series
			20	365	9	0.1			Eval F-Series
Sea Water		10			6	2.8		no change in appearance	Nippon Goh. Soarnol
Silicone Oils					9	<0.01		"	"
Sodium Carbonate		2			6	3.3		"	"
Sodium Hydroxide		10	20	7	8	0.62	92		Eval E-Series; 44 mol% ethylene
		10	20	7	5	2.48	81		Eval F-Series; 32 mol% ethylene
		10	20	7	7	1.18	92		Eval H-Series; 38 mol% ethylene
Spring Oil					9	<0.02		no change in appearance	Nippon Goh. Soarnol
Sulfuric Acid		3			7	1.6		"	"
		30			4	2.7		slight swelling	"
		30	20	7	8	0.58			Eval E-Series; 44 mol% ethylene
		30	20	7	4	2.91	79		Eval F-Series; 32 mol% ethylene
		30	20	7	7	1.58	95		Eval H-Series; 38 mol% ethylene
	concentrated	98			5			carbonization	Nippon Goh. Soarnol
Tetrachloroethane			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained	Resistance Note	Material Note
						Weight	Tensile Strength		
Tetrachloroethane			100		5			partially soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		5			partially soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Tetrahydrofuran			20	30	9	0.4			Eval E-Series
			20	30	9	0.3			Eval F-Series
			20	365	3			swelled	Eval E-Series, Eval F Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		5			partially soluble in reagent	Eval; 40 mol% VA content
			100		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		5			partially soluble in reagent	Eval; 40 mol% VA content
			150		9			insoluble in reagent	Eval; 62.9, 73.4, 100 mol% VA contents
Thinners					9	<0.01		no change in appearance	Nippon Goh. Soarnol
Toluene					9	0.03		“	“
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Trichloroethylene					9	0.01		no change in appearance	Nippon Goh. Soarnol
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
Vinyl Chloride	gas				9	<0.01		no change in appearance	Nippon Goh. Soarnol
Water	distilled				6	3.1		“	“
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4 mol% VA contents
			30		1			soluble in reagent	Eval; 100 mol% VA content
			37	182	1	14.2			Nippon Goh. Soarnol D,DT; 29 mol% ethylene
			37	182	1	12.7			Nippon Goh. Soarnol DC; 32 mol% ethylene
			37	182	1	10			Nippon Goh. Soarnol E,ET; 38 mol% ethylene
			37	182	1	7.7			Nippon Goh. Soarnol A; 44 mol% ethylene
			100		9			insoluble in reagent	Eval; 0, 40 mol% VA contents
			100		1			soluble in reagent	Eval; 100 mol% VA content
			100		5			partially soluble in reagent	Eval; 62.9, 73.4 mol% VA contents
			150		9			insoluble in reagent	Eval; 0, 40 mol% VA contents
			150		1			soluble in reagent	Eval; 100 mol% VA content
			150		5			partially soluble in reagent	Eval; 62.9, 73.4 mol% VA contents
Xylene			20	30	9	0			Eval E-Series,Eval F-Series
			20	365	7	0.8			Eval E-Series
			20	365	9	0			Eval F-Series
			30		9			insoluble in reagent	Eval; 0, 40, 62.9, 73.4, 100 mol% VA contents
			100		1			soluble in reagent	Eval; 0 mol% VA content
			100		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents
			150		1			soluble in reagent	Eval; 0 mol% VA content
			150		9			insoluble in reagent	Eval; 40, 62.9, 73.4, 100 mol% VA contents

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Acetic Acid		10	23			8					recommended for use	Ausimont Halar
		10	23	7	0.25%	2		52.7				LNP; 20% carb.fib.
		10	23	7	0.25%	4		71.3				LNP; 20% gl.fib.
		10	23	7		7		89.2				LNP; 20% carb.fib.
		10	23	7		8		90.8				LNP; 20% gl.fib.
		10	82	3	0.25%	1		41.9				LNP; 20% carb.fib.
		10	82	3	0.25%	3		64.4				LNP; 20% gl.fib.
		10	82	3		5		75.3				LNP; 20% carb.fib.
		10	82	3		4		70.1				LNP; 20% gl.fib.
		10	121			8					recommended for use	Ausimont Halar
		10	149	1	0.25%	1		40.9				LNP; 20% carb.fib.
		10	149	1	0.25%	3		62.1				LNP; 20% gl.fib.
		10	149	1		3		69				"
		10	149	1		4		73.1				LNP; 20% carb.fib.
		20	23			8					recommended for use	Ausimont Halar
		20	121			8					"	"
		50	23			8					"	"
		50	121			8					"	"
		80	23			8					"	"
		80	66			8					"	"
	glacial		23			8					"	"
	"		23	11		8	0.2		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	"		66			8					recommended for use	Ausimont Halar
	"		230	11		4	3.5		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Acetic Anhydride			23			8					recommended for use	Ausimont Halar
Acetone			23			8					"	"
			23	11		8	0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			121			2					not recommended for use	"
			125	11		4	4		25-50	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Acetyl Chloride			23			8					recommended for use	Ausimont Halar
			66			8					"	"
Acetyl Nitrile			23			8					"	"
			66			8					"	"
Acetylene			23			8					"	"
			66			8					"	"
Acrylonitrile			23			8					"	"
Adipic Acid			23			8					"	"
			66			8					"	"
Allyl Chloride			23			8					"	"
			149			8					"	"
Alum			23			8					"	"
			149			8					"	"
Aluminum Chloride			23			8					"	"
			149			8					"	"
Aluminum Fluoride			23			8					"	"
			149			8					"	"
Aluminum Hydroxide			23			8					"	"
			149			8					"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Aluminum Nitrate			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Aluminum Oxychloride			23			8					"	"
			66			8					"	"
Aluminum Sulfate			23			8					"	"
			149			8					"	"
Ammonia	aqueous solution	10	23			8					"	"
	"	10	121			8					"	"
	gas		23			8					"	"
	"		149			8					"	"
Ammonium Acetate			23			8					"	"
			66			8					"	"
Ammonium Alum			23			8					"	"
			149			8					"	"
Ammonium Bifluoride			23			8					"	"
			149			8					"	"
Ammonium Bisulfide			23			8					"	"
			149			8					"	"
Ammonium Carbonate			23			8					"	"
			149			8					"	"
Ammonium Chloride			23			8					"	"
			149			8					"	"
Ammonium Dichromate			23			8					"	"
Ammonium Fluoride		10	23			8					"	"
		10	149			8					"	"
		25	23			8					"	"
		25	149			8					"	"
Ammonium Hydroxide		28	23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		28	66	11		8	0.2		80-100	80-100	"	"
			23			8					recommended for use	Ausimont Halar
			23	7	0.25%	2		59.1				LNP; 20% carb.fib.
			23	7	0.25%	7		89.7				LNP; 20% gl.fib.
			23	7		6		81.7				LNP; 20% carb.fib.
			23	7		9		94.3				LNP; 20% gl.fib.
			82	3	0.25%	2		53.8				LNP; 20% carb.fib.
			82	3	0.25%	7		85.1				LNP; 20% gl.fib.
			82	3		5		79.6				LNP; 20% carb.fib.
			82	3		8		92				LNP; 20% gl.fib.
			149			8					recommended for use	Ausimont Halar
			149	1	0.25%	1		44.1				LNP; 20% carb.fib.
			149	1	0.25%	6		82.8				LNP; 20% gl.fib.
			149	1		5		78.5				LNP; 20% carb.fib.
			149	1		8		90.8				LNP; 20% gl.fib.
Ammonium Metaphosphate			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Ammonium Nitrate			23			8					"	"
			149			8					"	"
Ammonium Persulfate			23			8					"	"
			66			8					"	"

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Ammonium Phosphate			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Ammonium Sulfate			23			8					"	"
			149			8					"	"
Ammonium Sulfide			23			8					"	"
			149			8					"	"
Amyl Acetate			23			8					"	"
			66			8					"	"
			121			2					not recommended for use	"
Amyl Alcohol			23			8					recommended for use	"
			149			8					"	"
Amyl Chloride			23			8					"	"
			149			8					"	"
Aniline			23			8					"	"
			23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			2					not recommended for use	Ausimont Halar
			121	11		1					attacked	Ausimont Halar; 2.3 mm thick
Animal Oils	lard oil		23			8					recommended for use	Ausimont Halar
	"		149			8					"	"
Anthraquinone			23			8					"	"
			66			8					"	"
Anthraquinonesulfonic Acid			23			8					"	"
			66			8					"	"
Antimony Trichloride			23			8					"	"
Aqua Regia			23			8					"	"
			23	11		8	0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
			75-105	11		7	0.5		80-100	80-100	"	"
			121			8					recommended for use	Ausimont Halar
Arsenic Acid			23			8					"	"
			149			8					"	"
Barium Carbonate			23			8					"	"
			149			8					"	"
Barium Chloride			23			8					"	"
			149			8					"	"
Barium Hydroxide			23			8					"	"
			149			8					"	"
Barium Nitrate			23			8					"	"
Barium Sulfate			23			8					"	"
			149			8					"	"
Barium Sulfide			23			8					"	"
			149			8					"	"
Beer			23			8					"	"
			66			8					"	"
Beet Sugar Liquors			23			8					"	"
			66			8					"	"
Benzaldehyde		10	23			8					"	"
		10	66			8					"	"
		10	121			2					not recommended for use	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Benzaldehyde		>10	23			8					recommended for use	Ausimont Halar
		>10	66			2					not recommended for use	"
			23	11		8	0.2		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121	11		3	10.5		<25	80-100	"	"
Benzene	benzole		23			8					recommended for use	Ausimont Halar
			23	11		8	0.6		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	benzole		66			8					recommended for use	Ausimont Halar
			74	11		3	7		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	benzole		121			2					not recommended for use	Ausimont Halar
Benzenesulfonic Acid		10	23			8					recommended for use	"
		10	66			8					"	"
		10	121			2					not recommended for use	"
Benzoic Acid			23			8					recommended for use	"
			121			8					"	"
Benzyl Alcohol			23			8					"	"
			149			8					"	"
Bismuth Carbonate			23			8					"	"
Black Liquor			23			8					"	"
			149			8					"	"
Bleach	12.5% chlorine		23			8					"	"
	5.5 % chlorine		23			8					"	"
	12.5% chlorine		149			8					"	"
	5.5 % chlorine		149			8					"	"
Borax			23			8					"	"
			149			8					"	"
Boric Acid			23			8					"	"
			149			8					"	"
Brines	brine acid		23			8					"	"
	"		121			8					"	"
Bromine	bromine vapor	25	23			8					"	"
	"	25	66			8					"	"
	"	25	121			2					not recommended for use	"
	bromine liquid		23			8					recommended for use	"
	bromine water		23			8					"	"
			23	11		7	1.4		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			23	180		4	10.4	86	79	75	"	Ausimont Halar; 3.2 mm thick
	bromine liquid		66			8					recommended for use	Ausimont Halar
	bromine water		121			8					"	"
Bromobenzene			23			8					"	"
			66			2					not recommended for use	"
Bromotoluene			23			8					recommended for use	"
			66			8					"	"
			121			2					not recommended for use	"
Butadiene			23			8					recommended for use	"
			121			8					"	"
Butane			23			8					"	"
			121			8					"	"
Butyl Acetate			23			8					"	"
			23	11		8	0.7		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Butyl Acetate			66			8					recommended for use	Ausimont Halar
			121			2					not recommended for use	“
			121	11		3	10.5		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Butyl Alcohol	butanol		23			8					recommended for use	Ausimont Halar
	butanol; primary		23			8					“	“
	butanol; secondary		23			8					“	“
	butanol		23	11		8	<-0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	“		118	11		5	2		50-75	80-100	“	“
	“		149			8					recommended for use	Ausimont Halar
	butanol; primary		149			8					“	“
	butanol; secondary		149			8					“	“
Butyl Alcohol (sec-)			23			8					“	“
			149			8					“	“
Butyl Cellosolve			23			8					“	“
Butyl Phenol			23			8					“	“
			121			8					“	“
Butyl Stearate			23			8					“	“
Butylene			23			8					“	“
			149			8					“	“
Butyric Acid			23			8					“	“
			121			8					“	“
Cadmium Cyanide			23			8					“	“
			66			8					“	“
Calcium Bisulfide			23			8					“	“
			149			8					“	“
Calcium Bisulfite			23			8					“	“
			149			8					“	“
Calcium Carbonate			23			8					“	“
			149			8					“	“
Calcium Chlorate			23			8					“	“
			149			8					“	“
Calcium Chloride			23			8					“	“
			149			8					“	“
Calcium Hydroxide			23			8					“	“
			149			8					“	“
Calcium Hypochlorite			23			8					“	“
			149			8					“	“
Calcium Nitrate			23			8					“	“
			149			8					“	“
Calcium Oxide			23			8					“	“
			149			8					“	“
Calcium Sulfate			23			8					“	“
			149			8					“	“
Cane Sugar	can sugar liquors		23			8					“	“
	“		66			8					“	“
Caprylic Acid			23			8					“	“
			66			8					“	“
Carbon Dioxide	dry		23			8					“	“
	wet		23			8					“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Carbon Dioxide	dry		149			8					recommended for use	Ausimont Halar
	wet		149			8					"	"
Carbon Disulfide			23			8					"	"
Carbon Monoxide			23			8					"	"
			66			8					"	"
Carbon Tetrachloride			23			8					"	"
			149			8					"	"
Carbonic Acid			23			8					"	"
			149			8					"	"
Castor Oil			23			8					"	"
			149			8					"	"
Caustic Potash			23			8					"	"
			149			8					"	"
Cellosolve	2-ethoxyethanol		23			8					"	"
	"		149			8					"	"
Cellosolve Acetate			23			8					"	"
Chloral Hydrate			23			8					"	"
			66			8					"	"
Chloramines			23			8					"	"
Chlorine	chlorine water		23			8					"	"
	dry gas		23			8					"	"
	liquid		23			8					"	"
	moist gas		23			8					"	"
	dry gas		66			8					"	"
	chlorine water		121			8					"	"
	dry gas		121			2					not recommended for use	"
	liquid		121			8					recommended for use	"
	moist gas		121			8					"	"
Chloroacetic Acid			23			8					"	"
			121			8					"	"
Chlorobenzene			23			8					"	"
			23	11		6	0.9		50-75	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			121			2					not recommended for use	"
			121	11		3	19.5		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Chlorobenzyl Chloride			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	"
Chloroform			23			8					recommended for use	"
			23	11		4	4.5		50-75	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121			8					recommended for use	Ausimont Halar
Chlorosulfonic Acid		60	23	11		8	0.1		80-100	80-100	no stress cracks; may darken @ long expos	Ausimont Halar; 2.3 mm thick
			23			8					recommended for use	Ausimont Halar
Chrome Alum			23			8					"	"
			149			8					"	"
Chromic Acid		10	23			8					"	"
		10	121			8					"	"
		30	23			8					"	"
		30	121			8					"	"
		40	23			8					"	"

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Chromic Acid		40	121			8					recommended for use	Ausimont Halar
		50	23			8					“	“
		50	23	11		8	<0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
		50	111	11		7	0.4		80-100	80-100	“	“
		50	121			8					recommended for use	Ausimont Halar
Citric Acid			23			8					“	“
			149			8					“	“
Coconut Oil			23			8					“	“
			149			8					“	“
Coke Oven Gas			23			8					“	“
			121			8					“	“
Copper Carbonate			23			8					“	“
			66			8					“	“
Copper Chloride			23			8					“	“
			121			8					“	“
Copper Cyanide			23			8					“	“
			121			8					“	“
Copper Fluoride			23			8					“	“
			121			8					“	“
Copper Nitrate			23			8					“	“
			121			8					“	“
Copper Sulfate			23			8					“	“
			121			8					“	“
Corn Syrup			23			8					“	“
			121			8					“	“
Cottonseed Oil			23			8					“	“
			121			8					“	“
Cresol			23			8					“	“
			66			8					“	“
			121			2					not recommended for use	“
Cresylic Acid		50	23			8					recommended for use	“
		50	66			8					“	“
		50	121			2					not recommended for use	“
Crotonaldehyde			23			8					recommended for use	“
			66			2					not recommended for use	“
Crude Oils			23			8					recommended for use	“
	sour crude		23			8					“	“
			149			8					“	“
	sour crude		149			8					“	“
Cupric Chloride		25	23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		25	103	11		8	<0.1		80-100	80-100	“	“
Cupric Fluoride			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Cupric Sulfate			23			8					“	“
			149			8					“	“
Cuprous Chloride			23			8					“	“
			121			8					“	“
Cutting Fluids	thread cutting oils		23			8					“	“
	“		149			8					“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Cyclohexane			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Cyclohexanone			23			8					"	"
			66			2					not recommended for use	"
Cyclohexyl Alcohol			23			8					recommended for use	"
			66			8					"	"
			121			2					not recommended for use	"
Detergents			23			8					recommended for use	"
	heavy duty solution		23			8					"	"
			149			8					"	"
	heavy duty solution		149			8					"	"
Dextrin			23			8					"	"
			121			8					"	"
Dextrose			23			8					"	"
			121			8					"	"
Diacetone Alcohol			23			8					"	"
			66			8					"	"
			121			2					not recommended for use	"
Dichlorobenzene			23			8					recommended for use	"
			66			2					not recommended for use	"
Dichloroethylene			23			8					recommended for use	"
			66			2					not recommended for use	"
Diesel Fuels			23			8					recommended for use	"
			149			8					"	"
Diethyl Cellosolve			23			8					"	"
			149			8					"	"
Diethyl Ether			23			8					"	"
Diethylamine			23			8					"	"
			66			2					not recommended for use	"
Diglycolic Acid			23			8					recommended for use	"
Dimethyl Phthalate			23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121	11		4	3.5		50-75	80-100	"	"
Dimethyl Sulfoxide			23	11		8	0.1		80-100	80-100	"	"
			121	11		6	3		80-100	80-100	"	"
Dimethylamine			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	"
Dimethylformamide			23	11		5	2		50-75	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121	11		3	7.5		<25	80-100	"	"
Dimethylhydrazine			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	"
Dioctyl Phthalate			23			8					recommended for use	"
			66			2					not recommended for use	"
Dioxane			23			8					recommended for use	"
			23	11		7	0.9		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			102	11		5	16		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121			2					not recommended for use	Ausimont Halar

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Dioxane (1,4-)			23			8					recommended for use	Ausimont Halar
			66			8					“	“
			121			2					not recommended for use	“
Disodium Phosphate			23			8					recommended for use	“
			149			8					“	“
Divinylbenzene			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	“
Epsom Salts			23			8					recommended for use	“
			149			8					“	“
Ethyl Acetate			23			8					“	“
			23	11		7	1.5		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			71	11		3	6.5		25-50	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Ethyl Acetoacetate			23			8					recommended for use	Ausimont Halar
Ethyl Acrylate			23			8					“	“
			66			8					“	“
			121			2					not recommended for use	“
Ethyl Alcohol			23			8					recommended for use	“
			149			8					“	“
Ethyl Chloride			23			8					“	“
			149			8					“	“
Ethyl Chloroacetate			23			8					“	“
Ethyl Ether			23			8					“	“
			23	11		7	0.9		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
Ethylene Bromide			23			8					“	“
			149			8					“	“
Ethylene Chloride			23			8					“	“
			149			8					“	“
Ethylene Chlorohydrin			23			8					“	“
			66			2					not recommended for use	“
Ethylene Dichloride			23			8					recommended for use	“
			23	11		7	1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			2					not recommended for use	Ausimont Halar
			85	11		5	9.5		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Ethylene Glycol			23			8					recommended for use	Ausimont Halar
			23	7	0.25%	1		34.4				LNP; 20% carb.fib.
			23	7	0.25%	9		96.6				LNP; 20% gl.fib.
			23	7		9		95.7				LNP; 20% carb.fib.
			23	7		9		100				LNP; 20% gl.fib.
			82	3	0.25%	1		32.3				LNP; 20% carb.fib.
			82	3	0.25%	8		92				LNP; 20% gl.fib.
			82	3		7		86				LNP; 20% carb.fib.
			82	3		9		96.6				LNP; 20% gl.fib.
			149			8					recommended for use	Ausimont Halar
			149	1	0.25%	1		29				LNP; 20% carb.fib.
			149	1	0.25%	8		90.8				LNP; 20% gl.fib.
			149	1		5		77.4				LNP; 20% carb.fib.
			149	1		8		92				LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Ethylene Oxide			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Ethylenediamine			23			8					“	“
			23	11		8	0.2		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			2					not recommended for use	Ausimont Halar
			118	11		1					attacked	Ausimont Halar; 2.3 mm thick
Fatty Acids			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Ferric Chloride		25	23	11		8	0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		25	103	11		8	0.1		80-100	80-100	“	“
			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Ferric Nitrate			23			8					“	“
			149			8					“	“
Ferric Sulfate			23			8					“	“
			149			8					“	“
Ferrous Chloride			23			8					“	“
			149			8					“	“
Ferrous Nitrate			23			8					“	“
			149			8					“	“
Ferrous Sulfate			23			8					“	“
			149			8					“	“
Fluoboric Acid			23			8					“	“
Fluorine	wet gas		23			8					“	“
Fluosilicic Acid			23			8					“	“
			149			8					“	“
Formaldehyde		35	23			8					“	“
		35	66			8					“	“
		37	23			8					“	“
		37	66			8					“	“
		50	23			8					“	“
Formic Acid			23			8					“	“
	anhydrous		23			8					“	“
			121			8					“	“
	anhydrous		121			8					“	“
Freon 11			23			8					“	“
			66			8					“	“
Freon 113			23			8					“	“
			66			8					“	“
Freon 114			23			8					“	“
			66			8					“	“
Freon 12			23			8					“	“
			66			8					“	“
Freon 21			23			8					“	“
			66			8					“	“
Freon 22			23			8					“	“
			66			8					“	“
Fruit Juices	and pulp		23			8					“	“
	“		66			8					“	“

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Gallic Acid			23			8					recommended for use	Ausimont Halar
			66			8					"	"
Gasoline	leaded		23			8					"	"
	natural		23			8					"	"
	sour		23			8					"	"
	unleaded		23			8					"	"
	leaded		149			8					"	"
	natural		149			8					"	"
	sour		149			8					"	"
	unleaded		149			8					"	"
Gelatins			23			8					"	"
			121			8					"	"
Genetron 113	chlorinated solvent		23	11		8	0.4		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	"		49	11		4	2		<25	80-100	"	"
Gin			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Glucose			23			8					"	"
			149			8					"	"
Glycerin	Glycerol		23			8					"	"
	glycerin		23			8					"	"
	Glycerol		149			8					"	"
	glycerin		149			8					"	"
Glycolic Acid			23			8					"	"
			66			8					"	"
Glycols			23			8					"	"
			149			8					"	"
Heptane			23			8					"	"
			149			8					"	"
Hexane			23			8					"	"
			23	11		8	0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			54	11		5	1.4		50-75	80-100	"	"
			149			8					recommended for use	Ausimont Halar
Hexyl Alcohol			23			8					"	"
			149			8					"	"
Hydrobromic Acid		20	23			8					"	"
		20	149			8					"	"
		50	23			8					"	"
		50	149			8					"	"
Hydrochloric Acid		10	23	7	0.25%	2		57				LNP; 20% carb.fib.
		10	23	7	0.25%	6		80.5				LNP; 20% gl.fib.
		10	23	7		6		81.7				LNP; 20% carb.fib.
		10	23	7		7		86.2				LNP; 20% gl.fib.
		10	82	3	0.25%	2		57				LNP; 20% carb.fib.
		10	82	3	0.25%	5		79.3				LNP; 20% gl.fib.
		10	82	3		5		77.4				LNP; 20% carb.fib.
		10	82	3		6		81.6				LNP; 20% gl.fib.
		10	149	1	0.25%	2		54.8				LNP; 20% carb.fib.
		10	149	1	0.25%	5		78.2				LNP; 20% gl.fib.
		10	149	1		5		77.4				LNP; 20% carb.fib.
		10	149	1		6		80.5				LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Hydrochloric Acid		37	23			8					recommended for use	Ausimont Halar
		37	23	11		8	<0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
		37	75-105	11		8	0.1		80-100	80-100	“	“
		37	149			8					recommended for use	Ausimont Halar
		60	23	11		8	<0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
Hydrocyanic Acid		10	23			8					recommended for use	Ausimont Halar
		10	149			8					“	“
			23			8					“	“
			149			8					“	“
Hydrofluoric Acid		30	23			8					“	“
		30	121			8					“	“
		40	23			8					“	“
		40	121			8					“	“
		50	23			8					“	“
		50	121			8					“	“
	dilute		23			8					“	“
	“		149			8					“	“
Hydrofluosilicic Acid			23			8					“	“
			149			8					“	“
Hydrogen			23			8					“	“
			149			8					“	“
Hydrogen Cyanide			23			8					“	“
			149			8					“	“
Hydrogen Peroxide		50	23			8					“	“
		50	66			8					“	“
		90	23			8					“	“
		90	66			8					“	“
			23			8					“	“
Hydrogen Phosphide			23			8					“	“
			66			8					“	“
Hydrogen Sulfide	aqueous solution		23			8					“	“
	dry		23			8					“	“
	aqueous solution		66			8					“	“
	dry		149			8					“	“
Hydroquinone			23			8					“	“
			121			8					“	“
Hypochlorous Acid			23			8					“	“
			149			8					“	“
Iodine	solution	10	23			8					“	“
	“	10	121			8					“	“
			23			8					“	“
			121			8					“	“
Isooctane			23			8					“	“
			23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			115	11		4	3.3		50-75	80-100	“	“
Isopropyl Alcohol	isopropanol		23			8					recommended for use	Ausimont Halar
	“		149			8					“	“
Isopropyl Ether			23			8					“	“

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Jet Aircraft Fuels	JP 4		23			8					recommended for use	Ausimont Halar
	JP 5		23			8					“	“
	JP 4		149			8					“	“
	JP 5		149			8					“	“
Kerosine			23			8					“	“
			149			8					“	“
Lactic Acid		25	23			8					“	“
		25	66			8					“	“
		80	23			8					“	“
Lauric Acid			23			8					“	“
			121			8					“	“
Lauryl Chloride			23			8					“	“
			121			8					“	“
Lead Acetate			23			8					“	“
			149			8					“	“
Lead Chloride			23			8					“	“
			149			8					“	“
Lead Nitrate			23			8					“	“
			149			8					“	“
Lead Sulfate			23			8					“	“
			149			8					“	“
Lemon Oil			23			8					“	“
			121			8					“	“
Lime Sulfur			23			8					“	“
			66			8					“	“
Linoleic Acid			23			8					“	“
			121			8					“	“
Linoleic Oil			23			8					“	“
			121			8					“	“
Linseed Oil			23			8					“	“
	blue		23			8					“	“
			121			8					“	“
	blue		121			8					“	“
Lithium Bromide			23			8					“	“
			66			8					“	“
Lubricating Oils	ASTM Oil No. 1		23			8					“	“
	ASTM Oil No. 2		23			8					“	“
	ASTM Oil No. 3		23			8					“	“
	ASTM Oil No. 1		149			8					“	“
	ASTM Oil No. 2		149			8					“	“
	ASTM Oil No. 3		149			8					“	“
Magnesium Carbonate			23			8					“	“
			149			8					“	“
Magnesium Chloride			23			8					“	“
			149			8					“	“
Magnesium Hydroxide			23			8					“	“
			149			8					“	“
Magnesium Nitrate			23			8					“	“
			149			8					“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Magnesium Sulfate			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Maleic Acid			23			8					"	"
			121			8					"	"
Malic Acid			23			8					"	"
			121			8					"	"
Menthanol			23	11		8	0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			60	11		6	0.4		50-75	80-100	"	"
Mercuric Chloride			23			8					recommended for use	Ausimont Halar
			121			8					"	"
Mercuric Cyanide			23			8					"	"
			121			8					"	"
Mercuric Sulfate			23			8					"	"
			121			8					"	"
Mercurous Nitrate			23			8					"	"
			121			8					"	"
Mercury			23			8					"	"
			149			8					"	"
Methane			23			8					"	"
			121			8					"	"
Methoxyethyl Oleate			23			8					"	"
Methyl Alcohol			23			8					"	"
			149			8					"	"
Methyl Bromide			23			8					"	"
			149			8					"	"
Methyl Cellosolve			23			8					"	"
			149			8					"	"
Methyl Chloride			23			8					"	"
			149			8					"	"
Methyl Ethyl Ketone			23			8					"	"
			23	11		7	1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			79	11		3	6		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121			2					not recommended for use	Ausimont Halar
Methyl Isobutyl Ketone			23			8					recommended for use	"
			66			8					"	"
			121			2					not recommended for use	"
Methyl Isopropyl Ketone			23	11		6	0.5		50-75	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			116	11		3	9		<25	80-100	"	"
Methyl Methacrylate			23			8					recommended for use	Ausimont Halar
Methyl Sulfate			23			8					"	"
			149			8					"	"
Methyl Sulfuric Acid			23			8					"	"
			66			8					"	"
Methylamine			23			8					"	"
			66			2					not recommended for use	"
Methylene Bromide			23			8					recommended for use	"
			66			2					not recommended for use	"

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Methylene Chloride			23			8					recommended for use	Ausimont Halar
			23	11		3	8		25-50	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			41	11		3	9		<25	80-100	“	“
			66			2					not recommended for use	Ausimont Halar
Methylene Iodine			23			8					recommended for use	“
			66			2					not recommended for use	“
Milk			23			8					recommended for use	“
			121			8					“	“
Mineral Oils			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Molasses			23			8					“	“
			66			8					“	“
Motor Oils			23			8					“	“
			23	7	0.25%	2		59.1				LNP; 20% carb.fib.
			23	7	0.25%	9		97.7				LNP; 20% gl.fib.
			23	7		5		75.3				LNP; 20% carb.fib.
			23	7		9		100				LNP; 20% gl.fib.
			82	3	0.25%	2		59.1				LNP; 20% carb.fib.
			82	3	0.25%	9		97.7				LNP; 20% gl.fib.
			82	3		5		75.3				LNP; 20% carb.fib.
			82	3		9		100				LNP; 20% gl.fib.
			149			8					recommended for use	Ausimont Halar
			149	1	0.25%	2		53.8				LNP; 20% carb.fib.
			149	1	0.25%	9		96.6				LNP; 20% gl.fib.
			149	1		2		55.9				LNP; 20% carb.fib.
			149	1		9		98.9				LNP; 20% gl.fib.
Naphtha			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Naphthalene			23			8					“	“
			66			8					“	“
Natural Gas			23			8					“	“
			66			8					“	“
Nickel Acetate			23			8					“	“
Nickel Chloride			23			8					“	“
			149			8					“	“
Nickel Nitrate			23			8					“	“
			149			8					“	“
Nickel Sulfate			23			8					“	“
			149			8					“	“
Nicotine			23			8					“	“
			66			8					“	“
Nicotinic Acid			23			8					“	“
			121			8					“	“
Nitric Acid		10	23			8					“	“
		10	23	7	0.25%	5		76.3				LNP; 20% carb.fib.
		10	23	7	0.25%	6		81.6				LNP; 20% gl.fib.
		10	23	7		6		84.9				LNP; 20% carb.fib.
		10	23	7		7		85.1				LNP; 20% gl.fib.
		10	82	3	0.25%	3		69.9				LNP; 20% carb.fib.
		10	82	3	0.25%	5		78.2				LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Nitric Acid		10	82	3		5		76.3				LNP; 20% carb.fib.
		10	82	3		6		80.5				LNP; 20% gl.fib.
		10	149			8					recommended for use	Ausimont Halar
		10	149	1	0.25%	3		69.9				LNP; 20% carb.fib.
		10	149	1	0.25%	5		75.9				LNP; 20% gl.fib.
		10	149	1		5		75.3				LNP; 20% carb.fib.
		10	149	1		5		79.3				LNP; 20% gl.fib.
		30	23			8					recommended for use	Ausimont Halar
		30	121			8					"	"
Nitric Acid		40	23			8					recommended for use	Ausimont Halar
		40	121			8					"	"
		50	23			8					"	"
		50	66			8					"	"
		50	121			2					not recommended for use	"
		70	23			8					recommended for use	"
		70	23	11		8	<0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
		70	66			8					recommended for use	Ausimont Halar
		70	100	11		7	0.5		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
		70	121			2					not recommended for use	Ausimont Halar
		70	121	11		4	0.8		50-75	<25	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
		90	23	180		8	0.7	98.6	97	112	"	Ausimont Halar; 3.2 mm thick
		100	121			2					not recommended for use	Ausimont Halar
			23			8					recommended for use	"
	red fuming		23	180		7	1.8	92	87	106	no stress cracks; may darken @ long expos.	Ausimont Halar; 3.2 mm thick
			66			8					recommended for use	Ausimont Halar
Nitrobenzene			23			8					"	"
			23	11		8	0.2		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			66			8					recommended for use	Ausimont Halar
			121			2					not recommended for use	"
			121	11		3	11.5		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Nitrous Acid		10	23			8					recommended for use	Ausimont Halar
		10	121			8					"	"
Nitrous Oxide			23			8					"	"
Oleic Acid			23			8					"	"
			121			8					"	"
Oleum		30	23	180		8	0.3	92.9	100	81.2	no stress cracking observed	Ausimont Halar; 3.2 mm thick
			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	"
Oxalic Acid		50	23			8					recommended for use	"
		50	121			2					not recommended for use	"
			23			8					recommended for use	"
			66			8					"	"
Oxygen	gas		23			8					"	"
	"		149			8					"	"
Ozone			23			8					"	"
			149			8					"	"

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Palmitic Acid		10	23			8					recommended for use	Ausimont Halar
		10	121			8					“	“
			23			8					“	“
			121			8					“	“
Paraffin			23			8					“	“
			66			8					“	“
Perchloric Acid		10	23			8					“	“
		10	66			8					“	“
		70	23			8					“	“
		70	66			8					“	“
Perchloroethylene			23	11		7	1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			121	11		3	29		<25	80-100	“	“
Perphosphate			23			8					recommended for use	Ausimont Halar
Petroleum Oils	refined		23			8					“	“
	sour		23			8					“	“
	refined		66			8					“	“
	sour		66			8					“	“
Phenol			23			8					“	“
			66			8					“	“
			121			2					not recommended for use	“
Phenylhydrazine			23			8					recommended for use	“
Phosphoric Acid		10	23			8					“	“
		10	149			8					“	“
		50	23			8					“	“
		50	121			8					“	“
		85	23			8					“	“
		85	121			8					“	“
Phosphorous	yellow		23			8					“	“
Phosphorous Pentoxide			23			8					“	“
			121			8					“	“
Phosphorous Trichloride			23			8					“	“
			121			8					“	“
Photographic Solutions			23			8					“	“
			66			8					“	“
Picric Acid			23			8					“	“
Plating Solutions	brass		23			8					“	“
	cadmium		23			8					“	“
	chrome		23			8					“	“
	copper		23			8					“	“
	gold		23			8					“	“
	lead		23			8					“	“
	nickel		23			8					“	“
	rhodium		23			8					“	“
	silver		23			8					“	“
	tin		23			8					“	“
	zinc		23			8					“	“
	brass		66			8					“	“
	cadmium		66			8					“	“
	chrome		66			8					“	“
	copper		66			8					“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Plating Solutions	gold		66			8					recommended for use	Ausimont Halar
	lead		66			8					"	"
	nickel		66			8					"	"
	rhodium		66			8					"	"
	silver		66			8					"	"
	tin		66			8					"	"
	zinc		66			8					"	"
Potash			23			8					"	"
			149			8					"	"
Potassium Alum			23			8						
			66			8					"	"
			121			8					"	"
			149			8					"	"
Potassium Aluminum Sulfate			23			8					"	"
			149			8					"	"
Potassium Bichromate			23			8					"	"
			121			8					"	"
Potassium Bisulfate			23			8					"	"
			121			8					"	"
Potassium Borate			23			8					"	"
			66			8					"	"
Potassium Bromide			23			8					"	"
			149			8					"	"
Potassium Carbonate			23			8					"	"
			149			8					"	"
Potassium Chlorate			23			8					"	"
	aqueous		23			8					"	"
			149			8					"	"
	aqueous		149			8					"	"
Potassium Chloride			23			8					"	"
			149			8					"	"
Potassium Chromate			23			8					"	"
			149			8					"	"
Potassium Cyanide			23			8					"	"
			149			8					"	"
Potassium Dichromate			23			8					"	"
			149			8					"	"
Potassium Ferricyanide			23			8					"	"
			149			8					"	"
Potassium Ferrocyanide			23			8					"	"
			149			8					"	"
Potassium Hydroxide			23			8					"	"
			66			8					"	"
Potassium Iodide			23			8					"	"
			121			8					"	"
Potassium Nitrate			23			8					"	"
			149			8					"	"
Potassium Perchlorate			23			8					"	"

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Potassium Permanganate		10	23			8					recommended for use	Ausimont Halar
		10	149			8					“	“
		25	23			8					“	“
		25	149			8					“	“
Potassium Persulfate			23			8					“	“
			121			8					“	“
Potassium Sulfate			23			8					“	“
			149			8					“	“
Propane			23			8					“	“
			149			8					“	“
Propyl Alcohol	1-propanol		23			8					“	“
	“		149			8					“	“
Propylene Oxide			23			2					not recommended for use	“
			23	11		3	6		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
Pyridine			23			2					not recommended for use	Ausimont Halar
Pyrogallic Acid			23			8					recommended for use	“
			66			8					“	“
Salicylaldehyde			23			8					“	“
			66			2					not recommended for use	“
Salicylic Acid			23			8					recommended for use	“
			66			8					“	“
Sea Water			23			8					“	“
			149			8					“	“
Sewage	sewage water		23			8					“	“
	“		149			8					“	“
Silicic Acid			23			8					“	“
Silicone Oils			23			8					“	“
Silver Cyanide			23			8					“	“
			149			8					“	“
Silver Nitrate			23			8					“	“
			149			8					“	“
Silver Sulfate			23			8					“	“
			149			8					“	“
Soap			23			8					“	“
			66			8					“	“
Sodium Acetate			23			8					“	“
			149			8					“	“
Sodium Alum			23			8					“	“
			149			8					“	“
Sodium Benzoate			23			8					“	“
			149			8					“	“
Sodium Bicarbonate			23			8					“	“
			149			8					“	“
Sodium Bichromate			23			8					“	“
			66			8					“	“
Sodium Bisulfate			23			8					“	“
			149			8					“	“
Sodium Bisulfite			23			8					“	“
			149			8					“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Sodium Bromide			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Sodium Carbonate			23			8					“	“
			149			8					“	“
Sodium Chlorate			23			8					“	“
			149			8					“	“
Sodium Chloride			23			8					“	“
			149			8					“	“
Sodium Cyanide			23			8					“	“
			149			8					“	“
Sodium Dichromate			23			8					“	“
			66			8					“	“
Sodium Fluoride			23			8					“	“
			149			8					“	“
Sodium Hydroxide		15	23			8					“	“
		15	149			8					“	“
		30	23			8					“	“
		30	121			8					“	“
		50	23			8					“	“
		50	23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		50	121			8					recommended for use	Ausimont Halar
		50	121	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		70	23			8					recommended for use	Ausimont Halar
		70	66			8					“	“
Sodium Hypochlorite			23			8					“	“
			149			8					“	“
Sodium Iodide			23			8					“	“
			149			8					“	“
Sodium Metaphosphate			23			8					“	“
			149			8					“	“
Sodium Nitrate			23			8					“	“
			149			8					“	“
Sodium Nitrite			23			8					“	“
			149			8					“	“
Sodium Perchlorate			23			8					“	“
Sodium Peroxide			23			8					“	“
			149			8					“	“
Sodium Phosphate	acid		23			8					“	“
	alkaline		23			8					“	“
	acid		149			8					“	“
	alkaline		149			8					“	“
Sodium Silicate			23			8					“	“
			149			8					“	“
Sodium Sulfate			23			8					“	“
			149			8					“	“
Sodium Sulfide			23			8					“	“
			149			8					“	“
Sodium Sulfite			23			8					“	“
			149			8					“	“

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Sodium Thiosulfate			23			8					recommended for use	Ausimont Halar
			149			8					"	"
Stannic Chloride			23			8					"	"
			149			8					"	"
Stannous Chloride			23			8					"	"
			149			8					"	"
Starch			23			8					"	"
			66			8					"	"
Stearic Acid			23			8					"	"
			66			8					"	"
Stoddard Solvents	white spirits		23			8					"	"
	"		149			8					"	"
Succinic Acid			23			8					"	"
			121			8					"	"
Sulfates	sulfate liquors		23			8					"	"
Sulfite Liquors			23			8					"	"
Sulfur			23			8					"	"
			121			8					"	"
Sulfur Chloride			23			8					"	"
Sulfur Dioxide	dry		23			8					"	"
	moist		23			8					"	"
	"		66			8					"	"
	dry		121			8					"	"
Sulfuric Acid		10	23			8					"	"
		10	23	7	0.25%	3		65.6				LNP; 20% carb.fib.
		10	23	7	0.25%	4		74.7				LNP; 20% gl.fib.
		10	23	7		6		84.9				LNP; 20% carb.fib.
		10	23	7		6		80.5				LNP; 20% gl.fib.
		10	82	3	0.25%	2		50.5				LNP; 20% carb.fib.
		10	82	3	0.25%	3		60.9				LNP; 20% gl.fib.
		10	82	3		6		80.6				LNP; 20% carb.fib.
		10	82	3		4		71.3				LNP; 20% gl.fib.
		10	121			8					recommended for use	Ausimont Halar
		10	149	1	0.25%	1		49.5				LNP; 20% carb.fib.
		10	149	1	0.25%	1		27.6				LNP; 20% gl.fib.
		10	149	1		2		53.8				LNP; 20% carb.fib.
		10	149	1		1		33.3				LNP; 20% gl.fib.
		30	23			8					recommended for use	Ausimont Halar
		30	121			8					"	"
		50	23			8					"	"
		50	121			8					"	"
		60	23			8					"	"
		60	121			8					"	"
		70	23			8					"	"
		70	121			8					"	"
	60 deg. Be	78	23	11		8	<0.1		80-100	80-100	no stress cracks; may darken @ long expos.	Ausimont Halar; 2.3 mm thick
	"	78	121	11		8	<0.1		80-100	80-100	"	"
		80	23			8					recommended for use	Ausimont Halar
		80	121			8					"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Sulfuric Acid		90	23			8					recommended for use	Ausimont Halar
		90	66			8					"	"
		93	23			8					"	"
		93	66			8					"	"
		94	23			8					"	"
		94	66			8					"	"
		95	23			8					"	"
		95	66			8					"	"
		96	23			8					"	"
		96	66			8					"	"
		98	23			8					"	"
		98	66			8					"	"
		100	23			8					"	"
Sulfurous Acid			23			8					"	"
			121			8					"	"
Tall Oil			23			8					"	"
			149			8					"	"
Tannic Acid			23			8					"	"
			121			8					"	"
Tanning Solutions	tanning liquors		23			8					"	"
	"		121			8					"	"
Tar			23			8					"	"
			149			8					"	"
Tartaric Acid			23			8					"	"
			121			8					"	"
Tetraethyllead			23			8					"	"
			149			8					"	"
Tetrahydrofuran			23			2					not recommended for use	"
			23	11		3	4.5		25-50	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			63	11		3	11		<25	80-100	"	"
Thionyl Chloride			23			8					recommended for use	Ausimont Halar
			66			8					"	"
Toluene	toluol		23			8					"	"
			23	11		8	0.6		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	toluol		66			8					recommended for use	Ausimont Halar
			110	11		3	8.5		<25	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
	toluol		121			2					not recommended for use	Ausimont Halar
Tomato Juice			23			8					recommended for use	"
			121			8					"	"
Transformer Oils			23			8					"	"
	DTE/30		23			8					"	"
	"		66			8					"	"
			121			8					"	"
Transmission Fluid			23	7	0.25%	1		47.3				LNP; 20% carb.fib.
			23	7	0.25%	9		98.9				LNP; 20% gl.fib.
			23	7		9		100				LNP; 20% carb.fib.
			23	7		9		100				LNP; 20% gl.fib.
			82	3	0.25%	1		44.1				LNP; 20% carb.fib.
			82	3	0.25%	9		95.4				LNP; 20% gl.fib.
			82	3		9		97.8				LNP; 20% carb.fib.

Chemical Resistance - Ethylene Chlorotrifluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Transmission Fluid			82	3		9		97.7				LNP; 20% gl.fib.
			149	1	0.25%	1		29				LNP; 20% carb.fib.
			149	1	0.25%	2		51.7				LNP; 20% gl.fib.
			149	1		9		96.8				LNP; 20% carb.fib.
			149	1		8		90.8				LNP; 20% gl.fib.
Tributyl Phosphate			23			8					recommended for use	Ausimont Halar
			66			2					not recommended for use	"
Trichloroacetic Acid			23			8					recommended for use	"
			66			8					"	"
			121			2					not recommended for use	"
Trichloroethane	methyl chloroform		23			8					recommended for use	Ausimont Halar
	"		66			8					"	"
	"		121			2					not recommended for use	"
Trichloroethylene			23			8					recommended for use	"
			23	11		3	9		25-50	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
			85	11		3	16.5		<25	80-100	"	"
			149			8					recommended for use	Ausimont Halar
Triethanolamine			23			8					"	"
			66			2					not recommended for use	"
Triethylamine			23			8					recommended for use	"
			66			8					"	"
			121			2					not recommended for use	"
Trisodium Phosphate			23			8					recommended for use	"
			149			8					"	"
Turpentine			23			8					"	"
			149			8					"	"
Urea			23			8					"	"
			121			8					"	"
Urine			23			8					"	"
			66			8					"	"
Vaseline			23			8					"	"
			66			8					"	"
Vegetable Oils			23			8					"	"
			149			8					"	"
Vinegar			23			8					"	"
	white		23			8					"	"
	"		121			8					"	"
Vinyl Acetate			23			8					"	"
			121			8					"	"
Water			23			8					"	"
	acid mine water		23			8					"	"
	demineralized		23			8					"	"
	distilled or fresh		23			8					"	"
	salt water		23			8					"	"
	sewage water		23			8					"	"
			23	7	0.25%	3		66.7				LNP; 20% carb.fib.
			23	7	0.25%	8		92				LNP; 20% gl.fib.
			23	7		8		91.4				LNP; 20% carb.fib.
			23	7		9		95.4				LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained			Resistance Note	Material Note
							Weight	Tensile Strength	Modulus	Elongation		
Water			82	3	0.25%	1		48.4				LNP; 20% carb.fib.
			82	3	0.25%	6		81.6				LNP; 20% gl.fib.
			82	3		7		86				LNP; 20% carb.fib.
			82	3		8		90.8				LNP; 20% gl.fib.
			149			8					recommended for use	Ausimont Halar
	acid mine water		149			8					“	“
	demineralized		149			8					“	“
	distilled or fresh		149			8					“	“
	salt water		149			8					“	“
	sewage water		149			8					“	“
			149	1	0.25%	3		66.7				LNP; 20% carb.fib.
Water			149	1	0.25%	5		79.3				LNP; 20% gl.fib.
			149	1		6		84.9				LNP; 20% carb.fib.
			149	1		7		89.7				LNP; 20% gl.fib.
Whiskey			23			8					recommended for use	Ausimont Halar
			149			8					“	“
White Liquor			23			8					“	“
			121			8					“	“
Wines			23			8					“	“
			121			8					“	“
Xylene	xylol		23			8					“	“
	“		23			8					“	“
	“		66			8					“	“
	“		66			8					“	“
Zinc Chloride		25	23	11		8	<0.1		80-100	80-100	no stress cracking observed	Ausimont Halar; 2.3 mm thick
		25	104	11		8	<0.1		80-100	80-100	“	“
			23			8					recommended for use	Ausimont Halar
			149			8					“	“
Zinc Nitrate			23			8					“	“
			149			8					“	“
Zinc Sulfate			23			8					“	“
			149			8					“	“

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

							% Change	% Retained			
Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	Weight	Tensile Strength	Elongation	Resistance Note	Material Note
Acetaldehyde			95			8				exp. temp. is max. recom.	DuPont Tefzel
Acetamide			120			8				“	“
Acetic Acid		10	23	7	0.25%	4		72.6			LNP; 20% carb.fib.
		10	23	7	0.25%	9		99.1			LNP; 20% gl.fib.
		10	23	7		9		98.4			LNP; 20% carb.fib.
		10	23	7		9		99.1			LNP; 20% gl.fib.
		10	82	3	0.25%	2		51.6			LNP; 20% carb.fib.
		10	82	3	0.25%	8		92.1			LNP; 20% gl.fib.
		10	82	3		4		71			LNP; 20% carb.fib.
		10	82	3		8		93			LNP; 20% gl.fib.
		10	149	1	0.25%	1		48.4			LNP; 20% carb.fib.
		10	149	1	0.25%	7		87.7			LNP; 20% gl.fib.
		10	149	1		3		64.5			LNP; 20% carb.fib.
		10	149	1		7		88.6			LNP; 20% gl.fib.
		50	120			8				exp. temp. is max. recom.	DuPont Tefzel
	glacial		110			8				“	“
	“		118	7		5	3.4	82	80		“
Acetic Anhydride			139	7		9	0	100	100		“
			150			8				exp. temp. is max. recom.	“
Acetone		50	65			8				“	“
			56	7		4	4.1	80	83		“
			65			8				exp. temp. is max. recom.	“
Acetonitrile			65			8				“	“
Acetophenone			150			8				“	“
			180	7		6	1.5	80	80		“
Acetyl Chloride			65			8				exp. temp. is max. recom.	“
Acetylene			120			8				“	“
Acetylene Tetrabromide			150			8				“	“
Acetylene Tetrachloride			150			8				“	“
Acrylonitrile			65			8				“	“
Adipic Acid			135			8				“	“
Aerosafe			149	7		6	3.9	92	93		“
Air			150			8				exp. temp. is max. recom.	“
Allyl Alcohol			100			8				“	“
Allyl Chloride			100			8				“	“
Aluminum Ammonium Sulfate			150			8				“	“
Aluminum Chloride			150			8				“	“
Aluminum Fluoride			150			8				“	“
Aluminum Hydroxide			150			8				“	“
Aluminum Nitrate			150			8				“	“
Aluminum Oxychloride			150			8				“	“
Aluminum Potassium Sulfate			150			8				“	“
Amino Acids			100			8				“	“
Ammonia		30	110			8				“	“
	anhydrous		150			8				“	“
Ammonium Bifluoride			150			8				“	“
Ammonium Bromide		50	135			8				“	“
Ammonium Carbonate			150			8				“	“
Ammonium Chloride			150			8				“	“
Ammonium Dichromate			135			8				“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Ammonium Fluoride			150			8				exp. temp. is max. recom.	DuPont Tefzel
Ammonium Hydroxide			23	7	0.25%	9		96.8			LNP; 20% carb.fib.
			23	7	0.25%	9		99.1			LNP; 20% gl.fib.
			23	7		9		98.4			LNP; 20% carb.fib.
			23	7		9		99.1			LNP; 20% gl.fib.
			66	7		9	0	97	97		DuPont Tefzel
			82	3	0.25%	9		95.2			LNP; 20% carb.fib.
			82	3	0.25%	9		99.1			LNP; 20% gl.fib.
			82	3		9		98.4			LNP; 20% carb.fib.
			82	3		9		99.1			LNP; 20% gl.fib.
			149	1	0.25%	6		82.3			LNP; 20% carb.fib.
			149	1	0.25%	8		91.2			LNP; 20% gl.fib.
			149	1		9		96.8			LNP; 20% carb.fib.
			149	1		7		89.5			LNP; 20% gl.fib.
			150			8				exp. temp. is max. recom.	DuPont Tefzel
Ammonium Nitrate	concentrated		110			8				"	"
Ammonium Perchlorate			135			8				"	"
Ammonium Persulfate			150			8				"	"
Ammonium Phosphate			150			8				"	"
Ammonium Sulfate			150			8				"	"
Ammonium Sulfide			150			8				"	"
Ammonium Thiocyanate			150			8				"	"
Amyl Acetate			120			8				"	"
Amyl Alcohol			150			8				"	"
Amyl Chloride			150			8				"	"
Aniline			110			8				"	"
			120	7		6	2.7	81	99		DuPont Tefzel
			120	30		7		93	82		"
			180	7		8		95	90		"
Aniline Hydrochloride		10	65			8				exp. temp. is max. recom.	"
Animal Oils	lard oil		150			8				"	"
Anthraquinone			135			8				"	"
Anthraquinonesulfonic Acid			135			8				"	"
Antimony Trichloride			100			8				"	"
Aqua Regia			90	0.25		8	0.2	93	89		"
			100			8				exp. temp. is max. recom.	"
Arsenic Acid			150			8				"	"
Barium Carbonate			150			8				"	"
Barium Chloride			150			8				"	"
Barium Hydroxide			150			8				"	"
Barium Sulfate			150			8				"	"
Barium Sulfide			150			8				"	"
Battery Acid			120			8				"	"
Benzaldehyde			100			8				"	"
Benzene			80	7		9	0	100	100		"
			100			8				exp. temp. is max. recom.	"
Benzenesulfonic Acid			100			8				"	"
Benzoic Acid			135			8				"	"

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Benzoyl Chloride			65			8				exp. temp. is max. recom.	DuPont Tefzel
			120	7		9		94	95		
			120	30		9		100	100		“
Benzyl Alcohol			120	7		9		97	90		“
			150			8				exp. temp. is max. recom.	“
Benzyl Chloride			150			8				“	“
Bismuth Carbonate			150			8				“	“
Black Liquor			150			8				“	“
Bleach	12.5% chlorine		100			8				“	“
	5.5% chlorine; Clorox		100			8				“	“
Borax			150			8				“	“
Boric Acid			150			8				“	“
Brines	chlorinated		120			8				“	“
			150			8				“	“
Bromic Acid			120			8				“	“
Bromine	bromine water	10	110			8				“	“
	anhydrous		23	7		7	1.2	90	90		“
	“		57	7		9		99	100		“
	“		57	30		6	3.4	94	93		“
	dry		65			8				exp. temp. is max. recom.	“
Bromobenzene			100			8				“	“
Bromoform			100			8				“	“
Butadiene			120			8				“	“
Butane			150			8				“	“
Butanediol			135			8				“	“
Butyl Acetate			110			8				“	“
	n-butyl acetate		127	7		6	0	80	60		“
Butyl Acrylate			110			8				exp. temp. is max. recom.	“
Butyl Alcohol	n-butanol		150			8				“	“
Butyl Alcohol (sec-)			150			8				“	“
Butyl Alcohol (tert-)			150			8				exp. temp. is max. recom.	“
Butylamine (tert-)			50			8				“	“
Butyl Bromide			150			8				“	“
Butyl Chloride			150			8				“	“
Butyl Mercaptan	n-butyl mercaptan		150			8				“	“
Butyl Phenol			110			8				“	“
Butyl Phthalate			65			8				“	“
Butylamine	n-butylamine		50			8				“	“
	“		78	7		3	4.4	71	73		“
Butylamine (sec-)			50			8				“	“
Butylene			150			8				exp. temp. is max. recom.	“
Butyraldehyde			100			8				“	“
Butyric Acid			120			8				“	“
Calcium Bisulfate			150			8				“	“
Calcium Bisulfide			150			8				“	“
Calcium Carbonate			150			8				“	“
Calcium Chlorate			150			8				“	“
Calcium Chloride			150			8				“	“
Calcium Hydroxide			150			8				“	“
Calcium Hypochlorite			150			8				“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Calcium Nitrate			150			8				exp. temp. is max. recom.	DuPont Tefzel
Calcium Oxide			135			8				"	"
Calcium Sulfate			150			8				"	"
Calcium Sulfide			120			8				"	"
Caprylic Acid			100			8				"	"
Carbon Dioxide	dry		150			8				"	"
	wet		150			8				"	"
Carbon Disulfide			65			8				"	"
Carbon Monoxide			150			8				"	"
Carbon Tetrachloride			78	7		5	4.5	90	80		"
			135			8				exp. temp. is max. recom.	"
Carbonic Acid			150			8				"	"
Castor Oil			150			8				"	"
Caustic Potash		50	100			8				"	"
Caustic Soda		50	100			8				"	"
Cellosolve	2-ethoxyethanol		150			8				"	"
Chloral Hydrate			100			8				"	"
Chlorine	dry		100			8				"	"
	wet		120			8				"	"
	anhydrous		120	7		4	7	85	84		"
Chlorine Dioxide			120			8				exp. temp. is max. recom.	"
Chloroacetic Acid		50	110			8				"	"
Chlorobenzene			100			8				"	"
			110			8				"	"
Chlorobenzyl Chloride			65			8				"	"
Chloroform			61	7		6	4	85	100		"
			100			8				exp. temp. is max. recom.	"
Chlorohydrin	liquid		65			8				"	"
Chlorosulfonic Acid			25			8				"	"
Chromic Acid		50	65			8				"	"
			125	7		2		66	25		"
Chromic Chloride			100			8				exp. temp. is max. recom.	"
Chromyl Chloride			100			8				"	"
Clorox	5.5% chlorine		100			8				"	"
Coal Gas			100			8				"	"
Copper Chloride			150			8				"	"
Copper Cyanide			150			8				"	"
Copper Fluoride			150			8				"	"
Copper Nitrate			150			8				"	"
Copper Sulfate			150			8				"	"
Cresol			135			8				"	"
Cresol (o-)			180	7		9	0	100	100		"
Cresylic Acid			135			8				exp. temp. is max. recom.	"
Crotonaldehyde			100			8				"	"
Crude Oils			150			8				"	"
	sour crude		150			8				"	"
Cyclohexane			150			8				"	"
Cyclohexanone			150			8				"	"
			156	7		8	0	90	85		"

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Cyclohexyl Alcohol			120			8				exp. temp. is max. recom.	DuPont Tefzel
DDT			100			8				"	"
Decalin			120			8				"	"
			120	7		8		89	95		"
Decane			150			8				exp. temp. is max. recom.	"
Dextrin			150			8				"	"
Diacetone Alcohol			100			8				"	"
Dibromopropane (1,2-)			95			8				"	"
Dibutyl Phthalate			65			8				"	"
Dibutylamine			110			8				"	"
			120	7		7		81	96		"
			120	30		9		100	100		"
			160	7		3		55	75		"
Dichloroacetic Acid			65			8				exp. temp. is max. recom.	"
Dichlorobenzene (o-)			65			8				"	"
Dichloroethylene			32	7		7	2.8	95	100		"
			65			8				exp. temp. is max. recom.	"
Dichloropropionic Acid			65			8				"	"
Diesel Fuels			150			8				"	"
Diethyl Benzene			135			8				"	"
Diethyl Cellosolve			150			8				"	"
Diethyl Ether			100			8				"	"
Diethylamine			110			8				"	"
Diethylenetriamine	DETA		100			8				"	"
Diglycolic Acid			100			8				"	"
Diisobutyl Ketone			100			8				"	"
Diisobutylene			135			8				"	"
Dimethyl Phthalate			100			8				"	"
Dimethyl Sulfate			65			8				"	"
Dimethyl Sulfoxide			90	7		7	1.5	95	90		"
			100			8				exp. temp. is max. recom.	"
Dimethylamine			50			8				"	"
Dimethylaniline			135			8				"	"
Dimethylaniline (N,N-)			120	7		8		82	97		"
Dimethylformamide			90	7		8	1.5	100	100		"
			120			8				exp. temp. is max. recom.	"
			120	7		5	5.5	76	92		"
Dioctyl Phthalate			65			8				exp. temp. is max. recom.	"
Dioxane (p-)			65			8				"	"
Diphenyl Oxide			80			8				"	"
Divinylbenzene			80			8				"	"
Epichlorohydrin			65			8				"	"
Esters			65			8				"	"
Ethers			100			8				"	"
Ethyl Acetate			65			8				"	"
			77	7		6	0	85	60		"
Ethyl Acetoacetate			65			8				exp. temp. is max. recom.	"
Ethyl Acrylate			100			8				"	"
Ethyl Alcohol			65			8				"	"
			150			8				"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Ethyl Chloride			150			8				exp. temp. is max. recom.	DuPont Tefzel
Ethyl Chloroacetate			100			8				"	"
Ethyl Cyanoacetate			100			8				"	"
Ethylamine			40			8				"	"
Ethylene Bromide			150			8				"	"
Ethylene Chloride			150			8				"	"
Ethylene Chlorohydrin			65			8				"	"
Ethylene Glycol			23	7	0.25%	9		100			LNP; 20% carb.fib.
			23	7	0.25%	9		100			LNP; 20% gl.fib.
			23	7		9		100			LNP; 20% carb.fib.
			23	7		9		100			LNP; 20% gl.fib.
			82	3	0.25%	7		88.7			LNP; 20% carb.fib.
			82	3	0.25%	9		96.5			LNP; 20% gl.fib.
			82	3		9		98.4			LNP; 20% carb.fib.
			82	3		9		96.5			LNP; 20% gl.fib.
			149	1	0.25%	6		80.6			LNP; 20% carb.fib.
			149	1	0.25%	8		92.1			LNP; 20% gl.fib.
			149	1		9		98.4			LNP; 20% carb.fib.
			149	1		9		96.5			LNP; 20% gl.fib.
			150			8				exp. temp. is max. recom.	DuPont Tefzel
Ethylene Oxide			110			8				"	"
Ethylenediamine			50			8				"	"
Fatty Acids			150			8				"	"
Ferric Chloride		25	100	7		9	0	95	95		"
		50	150			8				exp. temp. is max. recom.	"
Ferric Hydroxide			150			8				"	"
Ferric Nitrate			150			8				"	"
Ferric Sulfate			150			8				"	"
Ferrous Chloride			150			8				"	"
Ferrous Hydroxide			150			8				"	"
Ferrous Nitrate			150			8				"	"
Ferrous Sulfate			150			8				"	"
Fluoboric Acid			135			8				"	"
Fluorine	gaseous		40			8				"	"
Fluosilicic Acid			135			8				"	"
Formaldehyde		37	110			8				"	"
Formic Acid			135			8				"	"
Freon 11			110			8				"	"
Freon 113			46	7		9	0.8	100	100		"
Freon 12			110			8				exp. temp. is max. recom.	"
Freon 22			110			8				"	"
Fuel Oils			150			8				"	"
Fumaric Acid			95			8				"	"
Furan			65			8				"	"
Furfural			100			8				"	"
Gallic Acid			100			8				"	"
Gases	manufactured		150			8				"	"
	natural		150			8				"	"

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Gasoline	leaded		150			8				exp. temp. is max. recom.	DuPont Tefzel
	sour		150			8				"	"
	unleaded		150			8				"	"
Glycerin			150			8				"	"
Glycolic Acid			120			8				"	"
Glycols			135			8				"	"
Heptane			140			8				"	"
Hexane			150			8				"	"
Hydrazine			40			8				"	"
	50/50 with UDMH		50			8				"	"
Hydrazine Dihydrochloride			50			8				"	"
Hydriodic Acid			150			8				"	"
Hydrobromic Acid		50	150			8				"	"
	concentrated		125	7		9		100	100		"
Hydrochloric Acid		10	23	7	0.25%	9		96.8			LNP; 20% carb.fib.
		10	23	7	0.25%	9		99.1			LNP; 20% gl.fib.
		10	23	7		9		98.4			LNP; 20% carb.fib.
		10	23	7		9		99.1			LNP; 20% gl.fib.
		10	82	3	0.25%	9		96.8			LNP; 20% carb.fib.
		10	82	3	0.25%	9		99.1			LNP; 20% gl.fib.
		10	82	3		9		98.4			LNP; 20% carb.fib.
		10	82	3		9		99.1			LNP; 20% gl.fib.
		10	149	1	0.25%	5		79			LNP; 20% carb.fib.
		10	149	1	0.25%	9		99.1			LNP; 20% gl.fib.
		10	149	1		9		96.8			LNP; 20% carb.fib.
		10	149	1		9		99.1			LNP; 20% gl.fib.
		20	150			8				exp. temp. is max. recom.	DuPont Tefzel
	concentrated		23	7		9	0	100	90		"
	"		106	7		9	0.1	96	100		"
	"		150			8				exp. temp. is max. recom.	"
	gas		150			8				"	"
Hydrocyanic Acid			150			8				"	"
Hydrofluoric Acid		35	135			8				"	"
		70	120			8				"	"
	concentrated		23	7		9	0.1	97	95		"
			110			8				exp. temp. is max. recom.	"
Hydrofluosilicic Acid			150			8				"	"
Hydrogen			150			8				"	"
Hydrogen Cyanide			150			8				"	"
Hydrogen Peroxide		30	23	7		9	0	99	98		"
		30	120			8				exp. temp. is max. recom.	"
		90	65			8				"	"
Hydrogen Phosphide			65			8				"	"
Hydrogen Sulfide	dry		150			8				"	"
	moist		150			8				"	"
Hydroquinone			120			8				"	"
Hypochlorous Acid			150			8				"	"
Inert Gases			150			8				"	"
Iodine	dry		110			8				"	"
	moist		110			8				"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Iodoform			110			8				exp. temp. is max. recom.	DuPont Tefzel
Isobutyl Alcohol			135			8				“	“
Isopropylamine			50			8				“	“
Jet Aircraft Fuels	JP 4		110			8				“	“
	JP 5		110			8				“	“
Lactic Acid			120			8				“	“
Lauric Acid			120			8				“	“
Lauryl Chloride			135			8				“	“
Lauryl Sulfate			120			8				“	“
Lead Acetate			150			8				“	“
Linoleic Acid			135			8				“	“
Linseed Oil			150			8				“	“
Lithium Bromide	saturated		120			8				“	“
Lithium Hydroxide			150			8				“	“
Lubricating Oils			150			8				“	“
Magnesium Carbonate			150			8				“	“
Magnesium Chloride			150			8				“	“
Magnesium Hydroxide			150			8				“	“
Magnesium Nitrate			150			8				“	“
Magnesium Sulfate			150			8				“	“
Maleic Acid			135			8				“	“
Maleic Anhydride			95			8				“	“
Malic Acid			135			8				“	“
Mercuric Chloride			135			8				“	“
Mercuric Cyanide			135			8				“	“
Mercuric Nitrate			135			8				“	“
Mercury			135			8				“	“
Metabromotoluene			100			8				“	“
Methacrylic Acid			95			8				“	“
Methane			120			8				“	“
Methanesulfonic Acid		50	110			8				“	“
Methyl Alcohol			150			8				“	“
Methyl Benzoate			120			8				“	“
Methyl Bromide			150			8				“	“
Methyl Cellosolve			150			8				“	“
Methyl Chloride			150			8				“	“
Methyl Chloromethyl Ether			80			8				“	“
Methyl Cyanoacetate			80			8				“	“
Methyl Ethyl Ketone			80	7		9	0	100	100		“
			110			8				exp. temp. is max. recom.	“
Methyl Isobutyl Ketone			110			8				“	“
Methyl Methacrylate			80			8				“	“
Methyl Salicylate			95			8				“	“
Methyl Sulfuric Acid			100			8				“	“
Methyl Trichlorosilane			95			8				“	“
Methylaniline	n-methyl aniline		120			8				“	“
	“		120	7		8		85	95		“
	“		120	30		9		100	100		“
Methylene Bromide			100			8				exp. temp. is max. recom.	“

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Methylene Chloride			40	7		8	0	85	85		DuPont Tefzel
			40	7		8	0	85	85	exp. temp. is max. recom.	"
			100			8				"	"
Methylene Iodide			100			8				"	"
Mineral Oils			150			8				"	"
			180	7		7	0	90	60		"
Morpholine			65			8				exp. temp. is max. recom.	"
Motor Oils			23	7	0.25%	9		95.2			LNP; 20% carb.fib.
			23	7	0.25%	9		99.1			LNP; 20% gl.fib.
			23	7		9		95.2			LNP; 20% carb.fib.
			23	7		9		99.1			LNP; 20% gl.fib.
			82	3	0.25%	8		91.9			LNP; 20% carb.fib.
			82	3	0.25%	8		91.2			LNP; 20% gl.fib.
			82	3		8		91.9			LNP; 20% carb.fib.
			82	3		8		91.2			LNP; 20% gl.fib.
			149	1	0.25%	8		90.3			LNP; 20% carb.fib.
			149	1	0.25%	7		89.5			LNP; 20% gl.fib.
			149	1		8		90.3			LNP; 20% carb.fib.
			149	1		7		89.5			LNP; 20% gl.fib.
Naphtha			100	7		9	0.5	100	100		DuPont Tefzel
			150			8				exp. temp. is max. recom.	"
Naphthalene			150			8				"	"
Natural Gas			150			8				"	"
Nickel Chloride			150			8				"	"
Nickel Nitrate			150			8				"	"
Nickel Sulfate			150			8				"	"
Nicotine			100			8				"	"
Nicotonic Acid			120			8				"	"
Nitric Acid		10	23	7	0.25%	9		100			LNP; 20% carb.fib.
		10	23	7	0.25%	7		86.8			LNP; 20% gl.fib.
		10	23	7		9		100			LNP; 20% carb.fib.
		10	23	7		7		86.8			LNP; 20% gl.fib.
		10	82	3	0.25%	9		98.4			LNP; 20% carb.fib.
		10	82	3	0.25%	6		82.5			LNP; 20% gl.fib.
		10	82	3		9		100			LNP; 20% carb.fib.
		10	82	3		6		81.6			LNP; 20% gl.fib.
Nitric Acid		10	149	1	0.25%	9		98.4			LNP; 20% carb.fib.
		10	149	1	0.25%	4		71.1			LNP; 20% gl.fib.
		10	149	1		9		100			LNP; 20% carb.fib.
		10	149	1		4		73.9			LNP; 20% gl.fib.
		25	100	14		9		100	100		DuPont Tefzel
		50	65			8				exp. temp. is max. recom.	"
		50	105	14		6		87	81		"
		70	23	105		9	0.5	100	100		"
		70	25			8				exp. temp. is max. recom.	"
	concentrated	70	60	53		9		100	100		"
	"	70	120	2		6		72	91		"
Nitric Acid	"	70	120	3		1		58	5		"
	"	70	120	7		0		0	0		"
	50/50 with sulfuric acid		100			8				exp. temp. is max. recom.	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Nitrobenzene			150			8				exp. temp. is max. recom.	DuPont Tefzel
Nitrogen	gas		150			8				"	"
Nitrogen Dioxide			100			8				"	"
Nitromethane			100			8				"	"
Nitrous Acid			100			8				"	"
Octane			150			8				"	"
Octene			150			8				"	"
Oleic Acid			135			8				"	"
Oleum			50			8				"	"
Orthophenylphenol			100			8				"	"
Oxalic Acid			110			8				"	"
Oxygen			150			8				"	"
Ozone	1% in air		100			8				"	"
Palmitic Acid			135			8				"	"
Perchloric Acid		10	110			8				"	"
		72	65			8				"	"
Perchloroethylene			135			8				"	"
Petrolatum			150			8				"	"
Petroleum			150			8				"	"
Petroleum Ether			100			8				"	"
Phenol		10	110			8				"	"
			100			8				"	"
	chlorinated phenol		100			8				"	"
Phenolsulfonic Acid			100			8				"	"
Phenylhydrazine			100			8				"	"
Phenylhydrazine Hydrochloride			100			8				"	"
Phosgene			100			8				"	"
Phosphoric Acid		30	150			8				"	"
		85	135			8				"	"
	concentrated		120	7		9	0	94	93		"
Phosphoric Oxychloride			104	7		9		100	100		"
Phosphoric Trichloride			75	7		9		100	98		"
Phosphorous Oxychloride			100			8				exp. temp. is max. recom.	"
Phosphorous Pentachloride			100			8				"	"
Phosphorous Pentoxide			110			8				"	"
Phosphorous Trichloride			120			8				"	"
Phthalic Acid			100			8				"	"
Phthalic Anhydride			100			8				"	"
Phthaloyl Chloride			120	30		9		100	100		"
Picric Acid			50			8				exp. temp. is max. recom.	"
Plating Solutions	brass		135			8				"	"
	cadmium		135			8				"	"
	chrome		135			8				"	"
	copper		135			8				"	"
	gold		135			8				"	"
Polyvinyl Acetate			150			8				"	"
Polyvinyl Alcohol			150			8				"	"
Potassium Aluminum Chloride			150			8				"	"
Potassium Aluminum Sulfate		50	150			8				"	"

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Potassium Bicarbonate			150			8				exp. temp. is max. recom.	DuPont Tefzel
Potassium Borate			150			8				"	"
Potassium Bromate			150			8				"	"
Potassium Bromide			150			8				"	"
Potassium Carbonate			150			8				"	"
Potassium Chlorate			150			8				"	"
Potassium Chloride			150			8				"	"
Potassium Chromate			150			8				"	"
Potassium Cyanide			150			8				"	"
Potassium Dichromate			150			8				"	"
Potassium Ferrocyanide			150			8				"	"
Potassium Fluoride			150			8				"	"
Potassium Hydroxide		20	100	7		9	0	100	100		"
		50	100			8				exp. temp. is max. recom.	"
Potassium Hypochlorite			135			8				"	"
Potassium Nitrate			150			8				"	"
Potassium Perborate			135			8				"	"
Potassium Perchlorate			100			8				"	"
Potassium Permanganate			150			8				"	"
Potassium Persulfate			65			8				"	"
Potassium Sulfate			150			8				"	"
Potassium Sulfide			150			8				"	"
Propane			135			8				"	"
Propionic Acid			100			8				"	"
Propyl Alcohol	1-propanol		100			8				"	"
Propylene Dibromide			100			8				"	"
Propylene Dichloride			100			8				"	"
Propylene Glycol Methyl Ether			100			8				"	"
Propylene Oxide			65			8				"	"
Pyridine			65			8				"	"
			116	7		8	1.5	100	100		"
Pyrogallic Acid	pyrogallol		65			8				exp. temp. is max. recom.	"
Salicylaldehyde			100			8				"	"
Salicylic Acid			120			8				"	"
Salt Brine			150			8				"	"
Sea Water			150			8				"	"
Sewage	sewage water		135			8				"	"
Silicon Tetrachloride			60	7		9		100	100		"
			120			8				exp. temp. is max. recom.	"
Silver Chloride			150			8				"	"
Silver Cyanide			150			8				"	"
Silver Nitrate			150			8				"	"
Skydrol			149	7		7	3	100	95		"
Sodium Acetate			150			8				exp. temp. is max. recom.	"
Sodium Benzenesulfonate			150			8				"	"
Sodium Benzoate			150			8				"	"
Sodium Bicarbonate			150			8				"	"
Sodium Bisulfate			150			8				"	"
Sodium Bisulfite			150			8				"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Sodium Borate			100			8				exp. temp. is max. recom.	DuPont Tefzel
Sodium Bromide			150			8				“	“
Sodium Carbonate			150			8				“	“
Sodium Chlorate			150			8				“	“
Sodium Chloride			150			8				“	“
Sodium Chromate			150			8				“	“
Sodium Cyanide			150			8				“	“
Sodium Dichromate	alkaline		100			8				“	“
Sodium Ferricyanide			150			8				“	“
Sodium Ferrocyanide			150			8				“	“
Sodium Fluoride			150			8				“	“
Sodium Glutamate			135			8				“	“
Sodium Hydroxide		10	110			8				“	“
		50	110			8				“	“
		50	120	7		8	0.2	94	80		“
Sodium Hypochlorite			150			8				exp. temp. is max. recom.	“
Sodium Hyposulfite			150			8				“	“
Sodium Iodide			150			8				“	“
Sodium Lignosulfonate			150			8				“	“
Sodium Metasilicate			150			8				“	“
Sodium Nitrate			150			8				“	“
Sodium Nitrite			150			8				“	“
Sodium Perborate			100			8				“	“
Sodium Perchlorate			65			8				“	“
Sodium Peroxide			150			8				“	“
Sodium Persulfate			80			8				“	“
Sodium Phosphate			150			8				“	“
Sodium Silicate			150			8				“	“
Sodium Silicofluoride			150			8				“	“
Sodium Sulfate			150			8				“	“
Sodium Sulfide			150			8				“	“
Sodium Sulfite			150			8				“	“
Sodium Thiosulfate			150			8				“	“
Sorbic Acid			135			8				“	“
Stannic Chloride			150			8				“	“
Stannous Chloride			150			8				“	“
Stannous Fluoride			120			8				“	“
Stearic Acid			150			8				“	“
Stoddard Solvents	white spirits		135			8				“	“
Stripper Solution	A-20		140	7		8		90	90		“
Styrene	monomer		100			8				exp. temp. is max. recom.	“
Succinic Acid			135			8				“	“
Sulfamic Acid			100			8				“	“
Sulfur	molten		120			8				“	“
Sulfur Dioxide			110			8				“	“
Sulfur Trioxide	liquid		25			8				“	“
Sulfuric Acid		10	23	7	0.25%	9		96.8			LNP; 20% carb.fib.
		10	23	7	0.25%	6		80.7			LNP; 20% gl.fib.
		10	23	7		9		100			LNP; 20% carb.fib.
		10	23	7		7		86.8			LNP; 20% gl.fib.

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Chemical Resistance - Ethylene Tetrafluoroethylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Sulfuric Acid		10	82	3	0.25%	9		95.2			LNP; 20% carb.fib.
		10	82	3	0.25%	5		76.3			LNP; 20% gl.fib.
		10	82	3		9		98.4			LNP; 20% carb.fib.
		10	82	3		5		78.9			LNP; 20% gl.fib.
Sulfuric Acid		10	149	1	0.25%	6		83.9			LNP; 20% carb.fib.
		10	149	1	0.25%	4		71.9			LNP; 20% gl.fib.
		10	149	1		9		96.8			LNP; 20% carb.fib.
		10	149	1		4		74.6			LNP; 20% gl.fib.
		60	150			8				exp. temp. is max. recom.	DuPont Tefzel
	fuming, 20% oleum		50			8				"	"
	50/50 with nitric acid		100			8				"	"
	concentrated		100	7		9	0	100	100		"
	"		120	7		9	0	98	95		"
	"		150			8				exp. temp. is max. recom.	"
	"		150	0.25		9	0	98	90		"
Sulfurous Acid			110			8				exp. temp. is max. recom.	"
Sulfuryl Chloride			68	7		6	8	86	100		"
Tall Oil			150			8				"	"
Tannic Acid			135			8				"	"
Tartaric Acid			135			8				"	"
Tetrachlorophenol (2,3,4,6-)			100			8				exp. temp. is max. recom.	"
Tetraethyllead			150			8				"	"
Tetrahydrofuran			66	7		6	3.5	86	93		"
			100			8				exp. temp. is max. recom.	"
Tetramethylammonium Hydroxide		50	100			8				"	"
Thionyl Chloride			100			8				"	"
Tin Tetrachloride			110			8				"	"
Titanium Dioxide			150			8				"	"
Titanium Tetrachloride			100			8				"	"
Toluene			120			8				"	"
Transmission Fluid			23	7	0.25%	9		95.2			LNP; 20% carb.fib.
			23	7	0.25%	9		100.9			LNP; 20% gl.fib.
			23	7		9		98.4			LNP; 20% carb.fib.
			23	7		9		101.8			LNP; 20% gl.fib.
			82	3	0.25%	9		95.2			LNP; 20% carb.fib.
			82	3	0.25%	9		96.5			LNP; 20% gl.fib.
			82	3		9		96.8			LNP; 20% carb.fib.
			82	3		9		99.1			LNP; 20% gl.fib.
			149	1	0.25%	9		95.2			LNP; 20% carb.fib.
			149	1	0.25%	9		99.1			LNP; 20% gl.fib.
			149	1		9		96.8			LNP; 20% carb.fib.
			149	1		9		97.4			LNP; 20% gl.fib.
Tributyl Phosphate			65			8				exp. temp. is max. recom.	DuPont Tefzel
Tributylamine	tri-n-butylamine		110			8				"	"
	"		120	7		6		81	80		"
	"		120	30		9		100	100		"
Trichloroacetic Acid			100			8				exp. temp. is max. recom.	"
			100	7		7	0	90	70		"
			120	30		9		100	100		"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Trichloroethane	methyl chloroform		65			8				exp. temp. is max. recom.	DuPont Tefzel
Trichloroethylene			135			8				"	"
Trichloromethane			100			8				"	"
Trichlorophenol (2,4,5-)			100			8				"	"
Triethanolamine			65			8				"	"
Triethylamine			110			8				"	"
Trisodium Phosphate			135			8				"	"
Turpentine			135			8				"	"
UDMH	50/50 with Hydrazine		50			8				"	"
Urea		50	135			8				"	"
Varsol			135			8				"	"
Vinyl Acetate			135			8				"	"
Vinyl Chloride	monomer		65			8				"	"
Water			23	7	0.25%	9		100			LNP; 20% carb.fib.
			23	7	0.25%	9		99.1			LNP; 20% gl.fib.
			23	7		9		100			LNP; 20% carb.fib.
			23	7		9		99.1			LNP; 20% gl.fib.
			82	3	0.25%	9		100			LNP; 20% carb.fib.
			82	3	0.25%	9		99.1			LNP; 20% gl.fib.
			82	3		9		100			LNP; 20% carb.fib.
			82	3		9		99.1			LNP; 20% gl.fib.
			100	7		9	0	100	100		DuPont Tefzel
	sewage water		135			8				exp. temp. is max. recom.	"
Water			149	1	0.25%	9		100			LNP; 20% carb.fib.
			149	1	0.25%	8		92.5			LNP; 20% gl.fib.
			149	1		9		100			LNP; 20% carb.fib.
			149	1		8		93			LNP; 20% gl.fib.
	0C ✓		150			8				exp. temp. is max. recom.	DuPont Tefzel
	boiling water		212	41.7		4		75	71		DuPont Tefzel HT2004; 25% gl.fib.
	" ok		212	125		9		100	93		DuPont Tefzel 200;
	"		212	125		3		68	71		DuPont Tefzel HT2004; 25% gl.fib.
Waxes			150			8				exp. temp. is max. recom.	DuPont Tefzel
Xylene			120			8				"	"
Zinc Acetate			120			8				"	"
Zinc Chloride		25	100	7		9	0	100	100		"
			150			8				exp. temp. is max. recom.	"
Zinc Hydrosulfite		10	120			8				"	"
Zinc Nitrate			150			8				"	"
Zinc Sulfate			150			8				"	"
Zinc Sulfide			150			8				"	"

Chemical Resistance - Fluorinated Ethylene Propylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Abietic Acid	up to the boiling point					8			compatible	DuPont Teflon FEP
Acetic Acid		10	23	7	0.25%	5		77.1		LNP; 15% carb.fib.
		10	23	7	0.25%	9		100		LNP; 20% gl.fib.
		10	23	7		9		94.3		LNP; 15% carb.fib.
		10	23	7		9		100		LNP; 20% gl.fib.
		10	82	3	0.25%	4		74.3		LNP; 15% carb.fib.
		10	82	3	0.25%	9		94		LNP; 20% gl.fib.
		10	82	3		7		88.6		LNP; 15% carb.fib.
		10	82	3		9		96		LNP; 20% gl.fib.
		10	149	1	0.25%	4		74.3		LNP; 15% carb.fib.
		10	149	1	0.25%	6		80		LNP; 20% gl.fib.
		10	149	1		6		82.9		LNP; 15% carb.fib.
		10	149	1		8		92		LNP; 20% gl.fib.
	up to the boiling point					8			compatible	DuPont Teflon FEP
Acetic Anhydride	“					8			“	“
Acetone	“					8			“	“
			25	365		9	0.3		no signif. chg. for longer expos.	“
			50	365		9	0.4		“	“
			70	14		9	0		“	“
Acetophenone	up to the boiling point					8			compatible	“
			201	7		8	0.6-0.8		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Acrylic Anhydride	up to the boiling point					8			compatible	DuPont Teflon FEP
Acrylonitrile	up to boiling pt.					8			“	“
Allyl Acetate	up to the boiling point					8			“	“
Allyl Methacrylate	“					8			“	“
Aluminum Chloride	“					8			“	“
Ammonia	liquid to boiling pt.					8			“	“
Ammonium Chloride	up to the boiling point					8			“	“
Ammonium Hydroxide		10	25	365		9	0		no signif. chg. for longer expos.	“
		10	70	365		9	0.1		“	“
			23	7	0.25%	4		71.4		LNP; 15% carb.fib.
			23	7	0.25%	9		100		LNP; 20% gl.fib.
			23	7		9		94.3		LNP; 15% carb.fib.
			23	7		9		100		LNP; 20% gl.fib.
			82	3	0.25%	4		71.4		LNP; 15% carb.fib.
			82	3	0.25%	7		88		LNP; 20% gl.fib.
			82	3		7		85.7		LNP; 15% carb.fib.
			82	3		7		88		LNP; 20% gl.fib.
			149	1	0.25%	4		71.4		LNP; 15% carb.fib.
			149	1	0.25%	7		88		LNP; 20% gl.fib.
			149	1		6		82.9		LNP; 15% carb.fib.
			149	1		7		88		LNP; 20% gl.fib.
Aniline	up to the boiling point					8			compatible	DuPont Teflon FEP
			185	7		9	0.3-0.4		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Animal Oils	up to the boiling point					8			compatible	DuPont Teflon FEP
Benzaldehyde			179	7		9	0.4-0.5		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Benzene			78	4		9	0.5		“	DuPont Teflon FEP
			100	0.33		8	0.6		“	“
			200	0.33		7	1		“	“
Benzonitrile	up to the boiling point					8			compatible	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Benzoyl Chloride	up to the boiling point					8			compatible	DuPont Teflon FEP
Benzyl Alcohol	"					8			"	"
			204	7		9	0.3-0.4		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Borax	up to the boiling point					8			compatible	DuPont Teflon FEP
Boric Acid	"					8			"	"
Bromine	"					8			"	"
	anhydrous		22	7		9	0.5		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Butyl Acetate	up to the boiling point					8			compatible	DuPont Teflon FEP
Butyl Methacrylate	"					8			"	"
Butylamine	up to boiling pt.					8			"	"
	n-butylamine		78	7		9	0.3-0.4		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Calcium Chloride	up to the boiling point					8			compatible	DuPont Teflon FEP
Carbon Tetrachloride			25	365		8	0.6		no signif. chg. for longer expos.	"
			50	365		5	1.6		"	"
			70	14		5	1.99		"	"
			78	7		4	2.3-2.4		"	DuPont Teflon FEP 160
			100	0.33		4	2.5		"	DuPont Teflon FEP
			200	0.33		3	3.7		"	"
Carbonisulfide	up to the boiling point					8			compatible	"
Cetane	"					8			"	"
Chlorine	"					8			"	"
	anhydrous		120	7		8	0.5-0.6		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Chloroform	up to the boiling point					8			compatible	DuPont Teflon FEP
Chlorosulfonic Acid	"					8			"	"
			150	7		8	0.7-0.8		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Chromic Acid		50	120	7		9	0.00-0.01		"	"
	up to the boiling point					8			compatible	DuPont Teflon FEP
Cyclohexane	"					8			"	"
Detergents	"					8			"	"
Dibutyl Phthalate	"					8			"	"
Dibutyl Sebacate	"					8			"	"
Diethyl Carbonate	"					8			"	"
Diisobutyl Adipate	"					8			"	"
Dimethyl Ether	"					8			"	"
Dimethyl Sulfoxide			190	7		9	0.1-0.2		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Dimethylformamide	up to the boiling point					8			compatible	DuPont Teflon FEP
Dimethylhydrazine	up to boiling pt.					8			"	"
Dioxane	up to the boiling point					8			"	"
Ethyl Acetate	"					8			"	"
			25	365		9	0.5		no signif. chg. for longer expos.	"
			50	365		8	0.7		"	"
			70	14		8	0.7		"	"
Ethyl Alcohol		95	25	365		9	0		"	"
		95	50	365		9	0		"	"
		95	70	14		9	0		"	"
		95	100	0.33		9	0.1		"	"
		95	200	0.33		9	0.3		"	"
	up to the boiling point					8			compatible	"
Ethyl Ether	"					8			"	"

Chemical Resistance - Fluorinated Ethylene Propylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Ethyl Hexoate	up to the boiling point					8			compatible	DuPont Teflon FEP
Ethylene Bromide	"					8			"	"
Ethylene Glycol	"					8			"	"
			23	7	0.25%	9		100		LNP; 15% carb.fib.
			23	7	0.25%	9		100		LNP; 20% gl.fib.
			23	7		9		100		LNP; 15% carb.fib.
			23	7		9		100		LNP; 20% gl.fib.
			82	3	0.25%	5		77.1		LNP; 15% carb.fib.
			82	3	0.25%	7		86		LNP; 20% gl.fib.
			82	3		4		71.4		LNP; 15% carb.fib.
			82	3		8		90		LNP; 20% gl.fib.
			149	1	0.25%	4		71.4		LNP; 15% carb.fib.
			149	1	0.25%	7		88		LNP; 20% gl.fib.
			149	1		4		74.3		LNP; 15% carb.fib.
			149	1		8		90		LNP; 20% gl.fib.
Ferric Chloride		25	100	7		9	0.00-0.01		no signif. chg. for longer expos.	DuPont Teflon FEP 160
	up to the boiling point					8			compatible	DuPont Teflon FEP
Ferric Phosphate	"					8			"	"
Fluoronaphthalene	"					8			"	"
Fluoronitrobenzene	"					8			"	"
Formaldehyde	"					8			"	"
Formic Acid	"					8			"	"
Furan	"					8			"	"
Gasoline	"					8			"	"
Hexachloroethane	"					8			"	"
Hexane	"					8			"	"
Hydrazine	"					8			"	"
Hydrochloric Acid		10	23	7	0.25%	4		74.3		LNP; 15% carb.fib.
		10	23	7	0.25%	9		100		LNP; 20% gl.fib.
		10	23	7		9		94.3		LNP; 15% carb.fib.
		10	23	7		9		100		LNP; 20% gl.fib.
		10	25	365		9	0		no signif. chg. for longer expos.	DuPont Teflon FEP
		10	50	365		9	0		"	"
		10	70	365		9	0		"	"
		10	82	3	0.25%	4		74.3		LNP; 15% carb.fib.
		10	82	3	0.25%	8		90		LNP; 20% gl.fib.
		10	82	3		7		85.7		LNP; 15% carb.fib.
		10	82	3		9		98		LNP; 20% gl.fib.
Hydrochloric Acid		10	149	1	0.25%	4		71.4		LNP; 15% carb.fib.
		10	149	1	0.25%	6		84		LNP; 20% gl.fib.
		10	149	1		6		80		LNP; 15% carb.fib.
		10	149	1		9		96		LNP; 20% gl.fib.
		20	100	0.33		9	0		no signif. chg. for longer expos.	DuPont Teflon FEP
		20	200	0.33		9	0		"	"
		37	120	7		9	0.00-0.03		"	DuPont Teflon FEP 160
	up to the boiling point					8			compatible	DuPont Teflon FEP
Hydrofluoric Acid	"					8			"	"
Hydrogen Peroxide	"					8			"	"
Isooctane			99	7		8	0.7-0.8		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Lead	up to the boiling point					8			compatible	DuPont Teflon FEP

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Magnesium Chloride	up to the boiling point					8			compatible	DuPont Teflon FEP
Mercury	“					8			“	“
Methacrylic Acid	“					8			“	“
Methyl Alcohol	“					8			“	“
Methyl Ethyl Ketone	“					8			“	“
Methyl Methacrylate	“					8			“	“
Motor Oils			23	7	0.25%	4		71.4		LNP; 15% carb.fib.
			23	7	0.25%	9		100		LNP; 20% gl.fib.
			23	7		7		88.6		LNP; 15% carb.fib.
			23	7		9		100		LNP; 20% gl.fib.
			82	3	0.25%	3		68.6		LNP; 15% carb.fib.
			82	3	0.25%	9		100		LNP; 20% gl.fib.
			82	3		6		82.9		LNP; 15% carb.fib.
			82	3		9		100		LNP; 20% gl.fib.
			149	1	0.25%	3		68.6		LNP; 15% carb.fib.
			149	1	0.25%	9		100		LNP; 20% gl.fib.
			149	1		5		77.1		LNP; 15% carb.fib.
			149	1		9		100		LNP; 20% gl.fib.
Naphthalene	up to the boiling point					8			compatible	DuPont Teflon FEP
Naphthols	“					8			“	“
Nitric Acid		10	23	7	0.25%	7		85.7		LNP; 15% carb.fib.
		10	23	7	0.25%	7		88		LNP; 20% gl.fib.
		10	23	7		9		94.3		LNP; 15% carb.fib.
		10	23	7		9		96		LNP; 20% gl.fib.
		10	25	365		9	0		no signif. chg. for longer expos.	DuPont Teflon FEP
		10	70	365		9	0.1		“	“
		10	82	3	0.25%	4		74.3		LNP; 15% carb.fib.
		10	82	3	0.25%	7		88		LNP; 20% gl.fib.
		10	82	3		7		88.6		LNP; 15% carb.fib.
		10	82	3		8		92		LNP; 20% gl.fib.
		10	149	1	0.25%	3		65.7		LNP; 15% carb.fib.
		10	149	1	0.25%	7		86		LNP; 20% gl.fib.
		10	149	1		7		85.7		LNP; 15% carb.fib.
		10	149	1		7		88		LNP; 20% gl.fib.
	up to the boiling point					8			compatible	DuPont Teflon FEP
Nitro-2-Methylpropanol (2-)	“					8			“	“
Nitrobenzene	“					8			“	“
			210	7		7	0.7-0.9		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Nitrobutanol (2-)	up to the boiling point					8			compatible	DuPont Teflon FEP
Nitrogen Tetraoxide	“					8			“	“
Nitromethane	“					8			“	“
Octadecyl Alcohol	up to boiling pt.					8			“	“
Ozone	up to the boiling point					8			“	“
Pentachlorobenzamide	“					8			“	“
Perchloroethylene	“					8			“	“
			121	7		4	2.0-2.3		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Perfluoroxylene	up to the boiling point					8			compatible	DuPont Teflon FEP
Phenol	“					8			“	“
Phosphoric Acid	“					8			“	“
	concentrated		100	7		9	0.00-0.01		no signif. chg. for longer expos.	DuPont Teflon FEP 160

Chemical Resistance - Fluorinated Ethylene Propylene Copolymer

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Phosphorous Pentachloride	up to the boiling point					8			compatible	DuPont Teflon FEP
Phthalic Acid	"					8			"	"
Pinene	"					8			"	"
Piperidine	"					8			"	"
Potassium Acetate	"					8			"	"
Potassium Hydroxide	"					8			"	"
Potassium Permanganate	"					8			"	"
Pyridine	"					8			"	"
Soap	"					8			"	"
Sodium Hydroxide		10	25	365		9	0		no signif. chg. for longer expos.	"
		10	70	365		9	0.1		"	"
		50	100	0.33		9	0		"	"
	up to the boiling point					8			compatible	"
Sodium Hypochlorite	"					8			"	"
Sodium Peroxide	"					8			"	"
Solvents	aliphatic					8			"	"
	up to boiling pt.					8			"	"
Stannous Chloride	up to the boiling point					8			"	"
Sulfur	"					8			"	"
Sulfuric Acid		10	23	7	0.25%	3		68.6		LNP; 15% carb.fib.
		10	23	7	0.25%	6		84		LNP; 20% gl.fib.
		10	23	7		9		97.1		LNP; 15% carb.fib.
		10	23	7		8		90		LNP; 20% gl.fib.
		10	82	3	0.25%	3		68.6		LNP; 15% carb.fib.
		10	82	3	0.25%	5		76		LNP; 20% gl.fib.
		10	82	3		9		97.1		LNP; 15% carb.fib.
		10	82	3		7		86		LNP; 20% gl.fib.
		10	149	1	0.25%	3		68.6		LNP; 15% carb.fib.
		10	149	1	0.25%	5		76		LNP; 20% gl.fib.
		10	149	1		9		97.1		LNP; 15% carb.fib.
		10	149	1		7		86		LNP; 20% gl.fib.
		30	25	365		9	0		no signif. chg. for longer expos.	DuPont Teflon FEP
		30	70	365		9	0		"	"
		30	100	0.33		9	0		"	"
		30	200	0.33		9	0.1		"	"
	up to the boiling point					8			compatible	"
Sulfuryl Chloride			68	7		4	1.7-2.7		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Tetrabromoethane	up to the boiling point					8			compatible	DuPont Teflon FEP
Tetrachloroethylene	"					8			"	"
Toluene			25	365		9	0.3		no signif. chg. for longer expos.	"
			50	365		8	0.6		"	"
			70	14		8	0.6		"	"
			110	7		8	0.7-0.8		"	DuPont Teflon FEP 160
Transmission Fluid			23	7	0.25%	3		68.6		LNP; 15% carb.fib.
			23	7	0.25%	9		106		LNP; 20% gl.fib.
			23	7		8		110		"
			23	7		7		88.6		LNP; 15% carb.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Transmission Fluid			82	3	0.25%	5		77.1		LNP; 15% carb.fib.
			82	3	0.25%	8		90		LNP; 20% gl.fib.
			82	3		6		80		LNP; 15% carb.fib.
			82	3		9		98		LNP; 20% gl.fib.
			149	1	0.25%	3		62.9		LNP; 15% carb.fib.
			149	1	0.25%	7		88		LNP; 20% gl.fib.
			149	1		4		74.3		LNP; 15% carb.fib.
			149	1		9		94		LNP; 20% gl.fib.
Tributyl Phosphate			200	7		5	1.8-2.0		no signif. chg. for longer expos.	DuPont Teflon FEP 160
Trichloroacetic Acid	up to the boiling point					8			compatible	DuPont Teflon FEP
Trichloroethylene	"					8			"	"
Tricresyl Phosphate	"					8			"	"
Triethanolamine	"					8			"	"
Vegetable Oils	"					8			"	"
Vinyl Methacrylate	"					8			"	"
Water	"					8			"	"
			23	7	0.25%	5		77.1		LNP; 15% carb.fib.
			23	7	0.25%	9		100		LNP; 20% gl.fib.
			23	7		9		100		"
			23	7		7		85.7		LNP; 15% carb.fib.
			82	3	0.25%	4		71.4		"
			82	3	0.25%	8		92		LNP; 20% gl.fib.
			82	3		9		94		"
			82	3		7		85.7		LNP; 15% carb.fib.
			149	1	0.25%	2		57.1		"
			149	1	0.25%	7		88		LNP; 20% gl.fib.
			149	1		8		90		"
			149	1		7		85.7		LNP; 15% carb.fib.
Xylene	up to the boiling point					8			compatible	DuPont Teflon FEP
Zinc Chloride		25	100	7		9	0.00-0.03		no signif. chg. for longer expos.	DuPont Teflon FEP 160
	up to the boiling point					8			compatible	DuPont Teflon FEP

Chemical Resistance - Perfluoroalkoxy Resin

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Abietic Acid	up to the boiling point					8				compatible	DuPont Teflon PFA
Acetic Acid		10	23	7	0.25%	7		85.7			LNP; 20% carb.fib.
		10	23	7	0.25%	8		90.6			LNP; 20% gl.fib.
		10	23	7	0.25%	8		92.3			LNP; 20% mil.gl.
		10	23	7		8		90.6			LNP; 20% gl.fib.
		10	23	7		8		92.3			LNP; 20% mil.gl.
		10	23	7		9		100			LNP; 20% carb.fib.
Acetic Acid		10	82	3	0.25%	3		65.7			"
		10	82	3	0.25%	8		93.8			LNP; 20% gl.fib.
		10	82	3	0.25%	3		69.2			LNP; 20% mil.gl.
		10	82	3		6		84.4			LNP; 20% gl.fib.
		10	82	3		3		69.2			LNP; 20% mil.gl.
		10	82	3		8		91.4			LNP; 20% carb.fib.
Acetic Acid		10	149	1	0.25%	2		54.3			"
		10	149	1	0.25%	3		60.9			LNP; 20% gl.fib.
		10	149	1	0.25%	3		65.4			LNP; 20% mil.gl.
		10	149	1		5		76.6			LNP; 20% gl.fib.
		10	149	1		3		65.4			LNP; 20% mil.gl.
		10	149	1		7		88.6			LNP; 20% carb.fib.
	up to the boiling point					8				compatible	DuPont Teflon PFA
	glacial		118	7		9	0.4	95	100		DuPont Teflon PFA; 1.27 mm thick
Acetic Anhydride	up to the boiling point					8				compatible	DuPont Teflon PFA
			139	7		9	0.3	91	99		"
Acetone	up to the boiling point					8				compatible	"
			25	365		9	0.3			no signif. chg. for longer expos.	"
			50	365		9	0.4			"	"
			70	14		9	0			"	"
Acetophenone	up to the boiling point					8				compatible	"
			201			8	0.7				"
			201	7		8	0.6-0.8			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			202	7		8	0.6	90	100		DuPont Teflon PFA
Acrylic Anhydride	up to the boiling point					8				compatible	"
Acrylonitrile	up to boiling pt.					8				"	"
Allyl Acetate	up to the boiling point					8				"	"
Allyl Methacrylate	"					8				"	"
Aluminum Chloride	"					8				"	"
Ammonia	liquid to boiling pt.					8				"	"
Ammonium Chloride	up to the boiling point					8				"	"
Ammonium Hydroxide		10	25	365		9	0			no signif. chg. for longer expos.	"
		10	70	365		9	0.1			"	"
			23	7	0.25%	9		94.3			LNP; 20% carb.fib.
			23	7	0.25%	8		90.6			LNP; 20% gl.fib.
			23	7	0.25%	6		84.6			LNP; 20% mil.gl.
			23	7		8		92.2			LNP; 20% gl.fib.
			23	7		7		88.5			LNP; 20% mil.gl.
			23	7		9		97.1			LNP; 20% carb.fib.
Ammonium Hydroxide	concentrated		66	7		9	0	98	100		DuPont Teflon PFA
			82	3	0.25%	4		71.4			LNP; 20% carb.fib.
			82	3	0.25%	6		82.8			LNP; 20% gl.fib.
			82	3	0.25%	3		65.4			LNP; 20% mil.gl.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Ammonium Hydroxide			82	3		7		85.9			LNP; 20% gl.fib.
			82	3		3		65.4			LNP; 20% mil.gl.
			82	3		9		94.3			LNP; 20% carb.fib.
			149	1	0.25%	3		60			"
			149	1	0.25%	4		70.3			LNP; 20% gl.fib.
			149	1	0.25%	3		61.5			LNP; 20% mil.gl.
			149	1		5		79.7			LNP; 20% gl.fib.
			149	1		3		61.5			LNP; 20% mil.gl.
			149	1		4		71.4			LNP; 20% carb.fib.
Aniline	up to the boiling point					8				compatible	DuPont Teflon PFA
			185			9	0.5				"
			185	7		9	0.3	94	100		"
			185	7		9	0.3-0.4			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Animal Oils	up to the boiling point					8				compatible	DuPont Teflon PFA
Aqua Regia			120	7		9	0	99	100		"
Benzaldehyde			179			9	0.5				"
			179	7		9	0.5	90	99		"
			179	7		9	0.4-0.5			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Benzene			78	4		9	0.5			"	DuPont Teflon PFA
			100	0.33		8	0.6			"	"
			200	0.33		7	1			"	"
Benzonitrile	up to the boiling point					8				compatible	"
Benzoyl Chloride	"					8				"	"
Benzyl Alcohol	"					8				"	"
			204			9	0.4				"
			204	7		9	0.3-0.4			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			205	7		9	0.3	93	99		DuPont Teflon PFA
Borax	up to the boiling point					8				compatible	"
Boric Acid	"					8				"	"
Bromine	"					8				"	"
	anhydrous		22			9	0.5				"
	"		22	7		9	0.5			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			23	7		9	0.5	99	100		DuPont Teflon PFA
			59	7		9		95	95		"
Butyl Acetate	up to the boiling point					8				compatible	"
			125	7		9	0.5	93	100		"
Butyl Methacrylate	up to the boiling point					8				compatible	"
Butylamine	up to boiling pt.					8				"	"
	n-butylamine		78			9	0.4				"
	"		78	7		8	0.4	86	97		"
	"		78	7		9	0.3-0.4			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Calcium Chloride	up to the boiling point					8				compatible	DuPont Teflon PFA
Carbon Tetrachloride			25	365		8	0.6			no signif. chg. for longer expos.	"
			50	365		5	1.6			"	"
			70	14		5	1.99			"	"
			77	7		7	2.3	87	100		"
			78			3	3.4				"
			78	7		4	2.3-2.4			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			100	0.33		4	2.5			"	DuPont Teflon PFA
			200	0.33		3	3.7			"	"

Chemical Resistance - Perfluoroalkoxy Resin

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Carbonisulfide	up to the boiling point					8				compatible	DuPont Teflon PFA
Cetane	"					8				"	"
Chlorine	up to the boiling point					8				compatible	"
	anhydrous		120			8	0.6				"
			120	7		9	0.5	92	100		"
	anhydrous		120	7		8	0.5-0.6			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Chloroform	up to the boiling point					8				compatible	DuPont Teflon PFA
Chlorosulfonic Acid	"					8				"	"
			150			7	0.8				"
			150	7		8	0.7-0.8			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			151	7		8	0.7	91	100		DuPont Teflon PFA
Chromic Acid		50	120			9	0.01				"
		50	120	7		9	0	93	97		"
		50	120	7		9	0.00-0.01			no signif. chg. for longer expos.	DuPont Teflon PFA 350
	up to the boiling point					8				compatible	DuPont Teflon PFA
Cresol (o-)			191	7		9	0.2	92	96		"
Cyclohexane	up to the boiling point					8				compatible	"
Cyclohexanone			156	7		9	0.4	92	100		"
Detergents	up to the boiling point					8				compatible	"
Dibutyl Phthalate	"					8				"	"
Dibutyl Sebacate	"					8				"	"
Diethyl Carbonate	"					8				"	"
Diisobutyl Adipate	"					8				"	"
Dimethyl Ether	"					8				"	"
Dimethyl Phthalate			220	7		9	0.3	98	100		"
Dimethyl Sulfoxide			189	7		9	0.1	95	100		"
			190	7		9	0.1-0.2			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Dimethylformamide	up to the boiling point					8				compatible	DuPont Teflon PFA
			154	7		9	0.2	96	100		"
Dimethylhydrazine	up to boiling pt.					8				compatible	"
Dioxane	up to the boiling point					8				"	"
			101	7		8	0.6	92	100		"
Ethyl Acetate	up to the boiling point					8				compatible	"
			25	365		9	0.5			no signif. chg. for longer expos.	"
			50	365		8	0.7			"	"
			70	14		8	0.7			"	"
Ethyl Alcohol		95	25	365		9	0			"	"
		95	50	365		9	0			"	"
		95	70	14		9	0			"	"
		95	100	0.33		9	0.1			"	"
		95	200	0.33		9	0.3			"	"
	up to the boiling point					8				compatible	"
Ethyl Ether	"					8				"	"
Ethyl Hexoate	"					8				"	"
Ethylene Bromide	"					8				"	"
Ethylene Glycol	"					8				"	"
			23	7	0.25%	8		91.4			LNP; 20% carb.fib.
			23	7	0.25%	8		93.8			LNP; 20% gl.fib.
			23	7	0.25%	7		88.5			LNP; 20% mil.gl.
			23	7		9		98.4			LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Ethylene Glycol			23	7		7		88.5			LNP; 20% mil.gl.
			23	7		9		97.1			LNP; 20% carb.fib.
Ethylene Glycol			82	3	0.25%	6		80			LNP; 20% carb.fib.
			82	3	0.25%	7		87.5			LNP; 20% gl.fib.
			82	3	0.25%	6		80.8			LNP; 20% mil.gl.
			82	3		8		93.8			LNP; 20% gl.fib.
			82	3		6		80.8			LNP; 20% mil.gl.
			82	3		8		91.4			LNP; 20% carb.fib.
			149	1	0.25%	4		71.4			“
			149	1	0.25%	5		79.7			LNP; 20% gl.fib.
			149	1	0.25%	3		69.2			LNP; 20% mil.gl.
			149	1		6		81.3			LNP; 20% gl.fib.
			149	1		3		69.2			LNP; 20% mil.gl.
			149	1		7		88.6			LNP; 20% carb.fib.
Ethylenediamine			117	7		9	0.1	96	100		DuPont Teflon PFA
Ferric Chloride		25	100			9	0.01				“
		25	100	7		9	0.00-0.01			no signif. chg. for longer expos.	DuPont Teflon PFA 350
	up to the boiling point					8				compatible	DuPont Teflon PFA
			100	7		9	0	93	98		“
Ferric Phosphate	up to the boiling point					8				compatible	“
Fluoronaphthalene	“					8				“	“
Fluoronitrobenzene	“					8				“	“
Formaldehyde	“					8				“	“
Formic Acid	“					8				“	“
Freon 113			47			6	1.2				“
			47	7		6	1.2				DuPont Teflon PFA 350
Furan	up to the boiling point					8				compatible	DuPont Teflon PFA
Gasoline	“					8				“	“
Hexachloroethane	“					8				“	“
Hexane	“					8				“	“
Hydrazine	“					8				“	“
Hydrochloric Acid		10	23	7	0.25%	9		97.1			LNP; 20% carb.fib.
		10	23	7	0.25%	7		87.5			LNP; 20% gl.fib.
		10	23	7	0.25%	8		92.3			LNP; 20% mil.gl.
		10	23	7		9		100			LNP; 20% carb.fib.
		10	23	7		7		89.1			LNP; 20% gl.fib.
		10	23	7		9		100			LNP; 20% mil.gl.
		10	25	365		9	0			no signif. chg. for longer expos.	DuPont Teflon PFA
		10	50	365		9	0			“	“
		10	70	365		9	0			“	“
		10	82	3	0.25%	3		68.6			LNP; 20% carb.fib.
		10	82	3	0.25%	6		82.8			LNP; 20% gl.fib.
		10	82	3	0.25%	5		76.9			LNP; 20% mil.gl.
		10	82	3		9		100			LNP; 20% carb.fib.
		10	82	3		7		85.9			LNP; 20% gl.fib.
		10	82	3		6		84.6			LNP; 20% mil.gl.
Hydrochloric Acid		10	149	1	0.25%	5		77.1			LNP; 20% carb.fib.
		10	149	1	0.25%	5		76.6			LNP; 20% gl.fib.
		10	149	1	0.25%	3		65.4			LNP; 20% mil.gl.
		10	149	1		5		79.7			LNP; 20% gl.fib.

Chemical Resistance - Perfluoroalkoxy Resin

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Hydrochloric Acid		10	149	1		3		69.2			LNP; 20% mil.gl.
		10	149	1		8		91.4			LNP; 20% carb.fib.
		20	100	0.33		9	0			no signif. chg. for longer expos.	DuPont Teflon PFA
		20	200	0.33		9	0			"	"
		37	120			9	0.03				"
		37	120	7		9	0.00-0.03			no signif. chg. for longer expos.	DuPont Teflon PFA 350
	up to the boiling point					8				compatible	DuPont Teflon PFA
	concentrated		120	7		9	0	98	100		"
Hydrofluoric Acid		60	23	7		9	0	99	99		"
	up to the boiling point					8				compatible	"
Hydrogen Peroxide		30	23	7		9	0	93	95		"
	up to the boiling point					8				compatible	"
Isooctane			99			7	0.8				"
			99	7		9	0.7	94	100		"
			99	7		8	0.7-0.8			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Lead	up to the boiling point					8				compatible	DuPont Teflon PFA
Magnesium Chloride	"					8				"	"
Mercury	"					8				"	"
Methacrylic Acid	"					8				"	"
Methyl Alcohol	"					8				"	"
Methyl Ethyl Ketone	"					8				"	"
			80	7		9	0.4	90	100		"
Methyl Methacrylate	up to the boiling point					8				compatible	"
Methylene Chloride			40	7		8	0.8	94	100		"
Mineral Oils			180	7		8	0	87	95		"
Motor Oils			23	7	0.25%	3		65.7			LNP; 20% carb.fib.
			23	7	0.25%	8		90.6			LNP; 20% gl.fib.
			23	7	0.25%	8		92.3			LNP; 20% mil.gl.
			23	7		9		100			LNP; 20% carb.fib.
			23	7		8		92.2			LNP; 20% gl.fib.
			23	7		8		92.3			LNP; 20% mil.gl.
			82	3	0.25%	3		62.9			LNP; 20% carb.fib.
			82	3	0.25%	8		90.6			LNP; 20% gl.fib.
			82	3	0.25%	3		65.4			LNP; 20% mil.gl.
			82	3		7		85.7			LNP; 20% carb.fib.
			82	3		8		90.6			LNP; 20% gl.fib.
			82	3		7		88.5			LNP; 20% mil.gl.
			149	1	0.25%	3		65.7			LNP; 20% carb.fib.
			149	1	0.25%	8		90.6			LNP; 20% gl.fib.
			149	1	0.25%	7		88.5			LNP; 20% mil.gl.
			149	1		6		82.9			LNP; 20% carb.fib.
			149	1		8		90.6			LNP; 20% gl.fib.
			149	1		7		88.5			LNP; 20% mil.gl.
Naphtha			100	7		9	0.5	91	100		DuPont Teflon PFA
Naphthalene	up to the boiling point					8				compatible	"
Naphthols	"					8				"	"
Nitric Acid		10	23	7	0.25%	4		74.3			LNP; 20% carb.fib.
		10	23	7	0.25%	8		92.2			LNP; 20% gl.fib.
		10	23	7	0.25%	8		92.3			LNP; 20% mil.gl.
		10	23	7		9		100			LNP; 20% carb.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Nitric Acid		10	23	7		8		93.8			LNP; 20% gl.fib.
		10	23	7		9		96.2			LNP; 20% mil.gl.
		10	25	365		9	0			no signif. chg. for longer expos.	DuPont Teflon PFA
		10	70	365		9	0.1			"	"
Nitric Acid		10	82	3	0.25%	4		71.4			LNP; 20% carb.fib.
		10	82	3	0.25%	5		78.1			LNP; 20% gl.fib.
		10	82	3	0.25%	3		69.2			LNP; 20% mil.gl.
		10	82	3		7		88.6			LNP; 20% carb.fib.
		10	82	3		5		78.1			LNP; 20% gl.fib.
		10	82	3		3		69.2			LNP; 20% mil.gl.
Nitric Acid		10	149	1	0.25%	3		62.9			LNP; 20% carb.fib.
		10	149	1	0.25%	3		67.2			LNP; 20% gl.fib.
		10	149	1	0.25%	3		61.5			LNP; 20% mil.gl.
		10	149	1		4		71.4			LNP; 20% carb.fib.
		10	149	1		3		68.8			LNP; 20% gl.fib.
		10	149	1		3		65.4			LNP; 20% mil.gl.
	up to the boiling point					8				compatible	DuPont Teflon PFA
	fuming		23	7		9	0	99	99		"
	concentrated		120	7		9	0	95	98		"
Nitro-2-Methylpropanol (2-)	up to the boiling point					8				compatible	"
Nitrobenzene	"					8				"	"
			210			7	0.9				"
			210	7		8	0.7	90	100		"
			210	7		7	0.7-0.9			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Nitrobutanol (2-)	up to the boiling point					8				compatible	DuPont Teflon PFA
Nitrogen Tetraoxide	"					8				"	"
Nitromethane	"					8				"	"
Octadecyl Alcohol	up to boiling pt.					8				"	"
Ozone	up to the boiling point					8				"	"
Pentachlorobenzamide	"					8				"	"
Perchloroethylene	"					8				"	"
			121			4	2.2				"
			121	7		7	2	86	100		"
			121	7		4	2.0-2.3			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Perfluoroxylene	up to the boiling point					8				compatible	DuPont Teflon PFA
Phenol	"					8				"	"
Phosphoric Acid	"					8				"	"
	concentrated		100			9	0.01				"
	"		100	7		9	0	93	100		"
	"		100	7		9	0.00-0.01			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Phosphorous Pentachloride	up to the boiling point					8				compatible	DuPont Teflon PFA
Phthalic Acid	"					8				"	"
Pinene	"					8				"	"
Piperidine	"					8				"	"
Potassium Acetate	"					8				"	"
Potassium Hydroxide	"					8				"	"
Potassium Permanganate	"					8				"	"
Pyridine	"					8				"	"
Soap	"					8				"	"

Chemical Resistance - Perfluoroalkoxy Resin

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Sodium Hydroxide		10	25	365		9	0			no signif. chg. for longer expos.	DuPont Teflon PFA
		10	70	365		9	0.1			"	"
Sodium Hydroxide		50	100	0.33		9	0			no signif. chg. for longer expos.	"
		50	120	7		9	0.4	93	99		"
	up to the boiling point					8				compatible	"
Sodium Hypochlorite	"					8				"	"
Sodium Peroxide	"					8				"	"
Solvents	aliphatic					8				"	"
	up to boiling pt.					8				"	"
Stannous Chloride	up to the boiling point					8				"	"
Sulfur	"					8				"	"
Sulfuric Acid		10	23	7	0.25%	3		68.6			LNP; 20% carb.fib.
		10	23	7	0.25%	9		95.3			LNP; 20% gl.fib.
		10	23	7	0.25%	9		96.2			LNP; 20% mil.gl.
		10	23	7		7		88.6			LNP; 20% carb.fib.
		10	23	7		9		98.4			LNP; 20% gl.fib.
		10	23	7		9		96.2			LNP; 20% mil.gl.
		10	82	3	0.25%	3		60			LNP; 20% carb.fib.
		10	82	3	0.25%	8		90.6			LNP; 20% gl.fib.
		10	82	3	0.25%	4		73.1			LNP; 20% mil.gl.
		10	82	3		9		97.1			LNP; 20% carb.fib.
		10	82	3		8		92.2			LNP; 20% gl.fib.
		10	82	3		5		76.9			LNP; 20% mil.gl.
Sulfuric Acid		10	149	1	0.25%	3		60			LNP; 20% carb.fib.
		10	149	1	0.25%	4		73.4			LNP; 20% gl.fib.
		10	149	1	0.25%	3		65.4			LNP; 20% mil.gl.
		10	149	1		9		97.1			LNP; 20% carb.fib.
		10	149	1		5		75			LNP; 20% gl.fib.
		10	149	1		3		69.2			LNP; 20% mil.gl.
		30	25	365		9	0			no signif. chg. for longer expos.	DuPont Teflon PFA
		30	70	365		9	0			"	"
		30	100	0.33		9	0			"	"
		30	200	0.33		9	0.1			"	"
	up to the boiling point					8				compatible	"
	fuming, 20% oleum		23	7		9	0	95	96		"
	concentrated		120	7		9	0	95	98		"
Sulfuryl Chloride			68			4	2.2				"
			68	7		4	1.7-2.7			no signif. chg. for longer expos.	DuPont Teflon PFA 350
			69	7		6	2.7	83	100		DuPont Teflon PFA
Tetrabromoethane	up to the boiling point					8				compatible	"
Tetrachloroethylene	"					8				"	"
Tetrahydrofuran			66	7		8	0.7	88	100		"
Toluene			25	365		9	0.3			no signif. chg. for longer expos.	"
			50	365		8	0.6			"	"
			70	14		8	0.6			"	"
			110			7	0.8				"
			110	7		8	0.7	88	100		"
			110	7		8	0.7-0.8			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Transmission Fluid			23	7	0.25%	5		77.1			LNP; 20% carb.fib.
			23	7	0.25%	8		90.6			LNP; 20% gl.fib.

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained		Resistance Note	Material Note
							Weight	Tensile Strength	Elongation		
Transmission Fluid			23	7	0.25%	8		92.3			LNP; 20% mil.gl.
			23	7		7		85.7			LNP; 20% carb.fib.
			23	7		8		92.2			LNP; 20% gl.fib.
			23	7		8		92.3			LNP; 20% mil.gl.
Transmission Fluid			82	3	0.25%	3		65.7			LNP; 20% carb.fib.
			82	3	0.25%	5		78.1			LNP; 20% gl.fib.
			82	3	0.25%	6		80.8			LNP; 20% mil.gl.
			82	3		7		85.7			LNP; 20% carb.fib.
			82	3		5		79.7			LNP; 20% gl.fib.
			82	3		8		92.3			LNP; 20% mil.gl.
Transmission Fluid			149	1	0.25%	3		60			LNP; 20% carb.fib.
			149	1	0.25%	5		75			LNP; 20% gl.fib.
			149	1	0.25%	6		80.8			LNP; 20% mil.gl.
			149	1		7		85.7			LNP; 20% carb.fib.
			149	1		5		78.1			LNP; 20% gl.fib.
			149	1		8		92.3			LNP; 20% mil.gl.
Tributyl Phosphate			200			5	1.9				DuPont Teflon PFA
	tri-n-butyl phosphate		200	7		7	2	91	100		“
			200	7		5	1.8-2.0			no signif. chg. for longer expos.	DuPont Teflon PFA 350
Trichloroacetic Acid	up to the boiling point					8				compatible	DuPont Teflon PFA
			196	7		7	2.2	90	100		“
Trichloroethylene	up to the boiling point					8				compatible	“
Tricresyl Phosphate	“					8				“	“
Triethanolamine	“					8				“	“
Vegetable Oils	“					8				“	“
Vinyl Methacrylate	“					8				“	“
Water	“					8				“	“
			23	7	0.25%	6		80			LNP; 20% carb.fib.
			23	7	0.25%	9		98.4			LNP; 20% gl.fib.
			23	7	0.25%	9		96.2			LNP; 20% mil.gl.
			23	7		9		97.1			LNP; 20% carb.fib.
			23	7		9		100			LNP; 20% gl.fib.
			23	7		9		100			LNP; 20% mil.gl.
			82	3	0.25%	3		68.6			LNP; 20% carb.fib.
			82	3	0.25%	9		98.4			LNP; 20% gl.fib.
			82	3	0.25%	3		69.2			LNP; 20% mil.gl.
			82	3		7		88.6			LNP; 20% carb.fib.
			82	3		9		100			LNP; 20% gl.fib.
			82	3		4		73.1			LNP; 20% mil.gl.
Water			149	1	0.25%	3		60			LNP; 20% carb.fib.
			149	1	0.25%	5		79.7			LNP; 20% gl.fib.
			149	1	0.25%	3		61.5			LNP; 20% mil.gl.
			149	1		6		80			LNP; 20% carb.fib.
			149	1		5		79.7			LNP; 20% gl.fib.
			149	1		3		65.4			LNP; 20% mil.gl.
Xylene	up to the boiling point					8				compatible	DuPont Teflon PFA
Zinc Chloride		25	100			9	0.03				“
		25	100	7		9	0	96	100		“
		25	100	7		9	0.00-0.03			no signif. chg. for longer expos.	DuPont Teflon PFA 350
	up to the boiling point					8				compatible	DuPont Teflon PFA

Chemical Resistance - Polychlorotrifluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Acetic Acid		3	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		3	23	14	9	0	“	Allied Sig. Aclar 28; film
		3	23	14	9	0	“	Allied Sig. Aclar 33; film
		5	25	7	9	0		3M Kel-F 81; amorphous form
		50	175	7	9	0.1		“
	glacial		23	14	9	0.09	no visible change	Allied Sig. Aclar 22; film
	“		23	14	9	0.09	“	Allied Sig. Aclar 28; film
	“		23	14	9	0.03	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
	glacial		70	7	9	0.2		“
	“		80	7	6	1.5		“
			118	11	4	2.7		“
	glacial		175	7	4	2.5		3M Kel-F 81; amorphous form
Acetic Anhydride			25	7	9	0		“
			70	7	9	0.1		“
			139	1	3	3.6		“
Acetone			23	14	3	5.17	clouded, extremely flexible	Allied Sig. Aclar 22; film
			23	14	3	5.17	“	Allied Sig. Aclar 28; film
			23	14	9	0.5	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0.1		3M Kel-F 81; amorphous form
			56	1	7	1		“
Acetophenone			23	14	9	0	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Acetyl Chloride			25	7	9	0.1		“
Allyl Chloride			25	7	9	0.2		“
Aluminum Chloride	saturated		175	7	9	0		“
Ammonia	anhydrous		25	7	9	0		“
Ammonium Chloride	saturated		175	7	9	0.1		“
Ammonium Hydroxide		10	25	7	9	0		“
		28	90	7	9	0.3		“
		28	175	7	8	0.6		“
			23	14	9	0	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
Ammonium Persulfate	saturated		175	7	9	0		3M Kel-F 81; amorphous form
Ammonium Sulfate	“		175	7	9	0.1		“
Amyl Acetate			25	7	9	0		“
			70	7	7	0.9		“
Amyl Acid Phosphate			25	7	9	0		“
Aniline			23	14	9	0.01	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0.01	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			70	7	9	0		“
Antimony Pentachloride			25	7	9	0		“
Aqua Regia	boiling point			7	9	0.3		“
			23	14	8	0.1	clear, yellow discoloration	Allied Sig. Aclar 22; film
			23	14	8	0.1	“	Allied Sig. Aclar 28; film

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Aqua Regia			23	14	9	0.04	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Aroclor 1242			25	7	9	0		“
Aroclor 1248	Monsanto		25	7	9	0		“
Aroclor 1254	“		25	7	9	0		“
Arsenic Acid			175	7	9	-0.1		“
Benzaldehyde			23	14	9	0.02	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0.02	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Benzene			23	14	4	2.4	clouded, flexible	Allied Sig. Aclar 22; film
			23	14	4	2.4	“	Allied Sig. Aclar 28; film
			23	14	9	0.6	no visible change	Allied Sig. Aclar 33; film
Benzene			25	7	9	0.2		3M Kel-F 81; amorphous form
			81	1	1	6.6		“
			90	7	1	7		“
			135	7	1	107		“
Benzoic Acid	saturated		90	7	9	0.1		“
Benzonitrile			25	7	9	0		“
Benzoyl Chloride			23	14	9	0.14	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0.14	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Benzyl Alcohol			25	7	9	0		“
Bleach Lye			25	30	9	0		“
Bromine			23	14	8	0.15	clear, amber discoloration	Allied Sig. Aclar 22; film
			23	14	8	0.15	“	Allied Sig. Aclar 28; film
			23	14	8	0.1	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Bromobenzene			25	7	9	0		“
			70	7	5	1.9		“
Butyl Acetate			25	7	9	0.3		“
			80	7	2	5.1		“
			90	7	2	5.8		“
			125	1	1	6.7		“
			135	7	1	6.5		“
Butyl Alcohol	butanol		23	14	9	0	no visible change	Allied Sig. Aclar 33; film
	“		25	7	9	0		3M Kel-F 81; amorphous form
	“		70	7	9	0		“
	“		117	1	8	0.6		“
Butyl Ether	n-butyl ether		25	7	9	0		“
Butyl Sebacate	n-butyl sebacate		25	7	9	0		“
Calcium Chloride	saturated solution		25	7	9	0		“
	saturated		80	7	9	0		“
	“		175	7	3	3.9		“
Carbitol Acetate			25	7	9	0		“
Carbon Disulfide	ACS		23	14	7	0.4	clouded	Allied Sig. Aclar 22; film
	“		23	14	7	0.4	“	Allied Sig. Aclar 28; film
	“		23	14	9	0.2	no visible change	Allied Sig. Aclar 33; film

Chemical Resistance - Polychlorotrifluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Carbon Disulfide			25	7	9	0.1		3M Kel-F 81; amorphous form
			25	30	9	0.5		"
Carbon Tetrachloride			23	14	3	4.1	flexible	Allied Sig. Aclar 22; film
			23	14	3	4.1	"	Allied Sig. Aclar 28; film
			23	14	5	1.6	slightly flexible	Allied Sig. Aclar 33; film
			25	7	9	0.4		3M Kel-F 81; amorphous form
			25	60	7	0.9		"
			70	7	1	9.7		"
			90	7	1	18		"
			135	7	1	600		"
Cellosolve Acetate			25	7	9	0		"
Chlorine	gas				1		tends to plasticize the film	Allied Sig. Aclar 22; film
	liquid		-40	0.083	9	0		3M Kel-F 81; amorphous form
	"		25	6	1	12.3		"
Chlorine	gas		25	60	9	0	tends to plasticize the film	3M Kel-F 81; amorphous form
	liquid		50	6	1	9		"
Chloroacetic Acid			140	7	5	1.7		"
Chlorobenzene	boiling point		132	1	1	21.8		"
Chloroform			90	7	1	8.5		"
Chloronitropropane			25	7	9	0		"
Chloropropane (2-)			25	7	9	0.3		"
Chlorosulfonic Acid			25	30	9	0		"
			140	7	9	0.2		"
Chlorotoluene (p-)			25	7	9	0		"
Chlorotrifluoroethylene			25	7	1	9.1		"
	oil		25	7	9	0		"
Chromic Acid	boiling point	50		7	9	0		"
	cleaning solution		25	7	9	0		"
			80	7	9	-0.1		"
			175	7	9	0		"
Chromosulfuric Acid	saturated		140	7	4		slight swelling	"
Citric Acid		3	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		3	23	14	9	0	"	Allied Sig. Aclar 28; film
		3	23	14	9	0	"	Allied Sig. Aclar 33; film
Cresol			25	7	9	0		3M Kel-F 81; amorphous form
			140	7	5	2		"
Cupric Chloride	saturated		175	7	9	0		"
Cupric Sulfate	"		175	7	9	0		"
Cyclohexanone			23	14	7	0.35	clouded	Allied Sig. Aclar 22; film
			23	14	7	0.35	"	Allied Sig. Aclar 28; film
			23	14	9	0	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			155	1	1	10.5		"
Dibutyl Phthalate			25	7	9	0		"
Dibutyl Sebacate			25	7	9	0		"
Dichlorobutane (1,2-)			25	7	9	0		"
Dichloroethane (1,2-)			23	14	8	0.11	clouded	Allied Sig. Aclar 22; film
			23	14	8	0.11	"	Allied Sig. Aclar 28; film
			23	14	9	0.03	no visible change	Allied Sig. Aclar 33; film

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Dichloroethyl Ether			25	7	9	0		3M Kel-F 81; amorphous form
Dichloroethylene			25	7	9	0		"
			70	7	6	1.2		"
Dichlorohexafluorocyclobutane (1,2-)			25	7	9	0.1		"
Dichloropropylene			25	7	9	0		"
Dichlorotoluene (2,4-)			23	14	8	0.15	clouded	Allied Sig. Aclar 22; film
			23	14	8	0.15	"	Allied Sig. Aclar 28; film
			23	14	9	0.06	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Dichlorotoluene (3,4-)			25	7	9	0		"
Dicyclopentadiene			25	7	9	0		"
Diethyl Carbitol			25	7	9	0.1		"
Diethyl Cellosolve			25	7	7	0.8		"
Diethyl Phthalate			23	14	8	0	clouded	Allied Sig. Aclar 22; film
Diethyl Phthalate			23	14	8	0	clouded	Allied Sig. Aclar 28; film
			23	14	9	0	no visible change	Allied Sig. Aclar 33; film
Diethylamine			25	7	5	1.9		3M Kel-F 81; amorphous form
Diethylenetriamine	DETA		25	7	9	0		"
Diisobutyl Ketone			25	7	6	1.2		"
Dimethylhydrazine	anhydrous		23	14	3	3.9	blistered	Allied Sig. Aclar 22; film
	"		23	14	3	3.9	"	Allied Sig. Aclar 28; film
	"		23	14	5	1.8	amber discoloration	Allied Sig. Aclar 33; film
	unsymmetrical		25	7	9	0.1		3M Kel-F 81; amorphous form
Dioxane			23	14	5	1.9	flexible	Allied Sig. Aclar 22; film
			23	14	5	1.9	"	Allied Sig. Aclar 28; film
			23	14	9	0.15	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			90	7	9	0		"
Ethyl Acetate			23	14	2	7.65	extremely flexible	Allied Sig. Aclar 22; film
			23	14	2	7.65	"	Allied Sig. Aclar 28; film
			23	14	3	6	very flexible	Allied Sig. Aclar 33; film
			25	7	6	1.2		3M Kel-F 81; amorphous form
			25	30	2	5.5		"
			70	7	1	6.5		"
			77	1	2	5.9		"
Ethyl Alcohol		50	25	7	2	5.7		"
		95	25	7	9	0		"
		95	135	7	9	0.4		"
	anhydrous, denatured		23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	"		23	14	9	0	"	Allied Sig. Aclar 28; film
	"		23	14	9	0	"	Allied Sig. Aclar 33; film
	absolute		78	1	9	0.1		3M Kel-F 81; amorphous form
	"		80	7	9	0.2		"
Ethyl Butyrate			25	7	9	0.5		"
Ethyl Ether			23	14	3	5.6	clouded, extremely flexible	Allied Sig. Aclar 22; film
			23	14	3	5.6	"	Allied Sig. Aclar 28; film
			23	14	3	5.2	very flexible	Allied Sig. Aclar 33; film
			25	7	3	3.8		3M Kel-F 81; amorphous form
			35	1	2	5.2		"

Chemical Resistance - Polychlorotrifluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Ethyl Formate			25	7	9	0.2		3M Kel-F 81; amorphous form
Ethyl Propionate			25	7	7	1		"
Ethylene Bromide			131	1	1	6.6		"
Ethylene Chloride			25	7	9	0		"
			70	7	6	1.2		"
Ethylene Glycol			175	7	9	0		"
Ethylene Oxide			23	14	3	5.8	clouded, extremely flexible	Allied Sig. Aclar 22; film
			23	14	3	5.8	"	Allied Sig. Aclar 28; film
			23	14	3	4	very flexible	Allied Sig. Aclar 33; film
			25		3		swelling	3M Kel-F 81; amorphous form
Ferric Chloride	saturated		175	7	9	0		"
Ferrous Chloride	"		175	7	9	0		"
Ferrous Sulfate	"		175	7	9	0		"
Fluorine	gas		85	14	9	0		"
Formaldehyde			135	7	8	0.7		"
Formic Acid		87	90	7	9	0		3M Kel-F 81; amorphous form
		87	135	0.21	4	2.9		"
			23	14	9	0	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0	"	Allied Sig. Aclar 28; film
			23	14	9	0	"	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			25	12	9	0		"
	up to the boiling point		101	12	8	0.7		"
Freon 11			25	7	1	6.4		"
Freon 113			25	7	6	1.2		"
			90	7	1	22.4		"
Freon 12			25	7	4	3		"
Freon 22			25	7	4	2.1		"
Furan	boiling point 31-32 deg-C		23	14	3	5.4	discolor., extremely flexible	Allied Sig. Aclar 22; film
	"		23	14	3	5.4	"	Allied Sig. Aclar 28; film
	"		23	14	3	3.7	very flexible	Allied Sig. Aclar 33; film
			25	7	4	2.4		3M Kel-F 81; amorphous form
Gallic Acid			175	7	9	0.2		"
Gasoline	premium grade		23	14	6	0.83	clear, amber discoloration	Allied Sig. Aclar 22; film
	"		23	14	6	0.83	"	Allied Sig. Aclar 28; film
	"		23	14	9	0.2	no visible change	Allied Sig. Aclar 33; film
			60-95	1	9	0.5		3M Kel-F 81; amorphous form
Glycerin			175	7	9	-0.1		"
Halowax 1000			25	7	9	0		"
Heptane			23	14	8	0	slightly clouded	Allied Sig. Aclar 22; film
			23	14	8	0	"	Allied Sig. Aclar 28; film
			23	14	9	0	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			80	7	4	2.8		"
			90	7	5	1.8		"
Hexachloroacetone	20% deeprock heavy cycle oil		23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	20% kerosene		23	14	9	0	"	"
	20% deeprock heavy cycle oil		23	14	9	0	"	Allied Sig. Aclar 28; film
	20% kerosene		23	14	9	0	"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Hexachloroacetone	20% deeprock heavy cycle oil		23	14	9	0	no visible change	Allied Sig. Aclar 33; film
	20% kerosene		23	14	9	0	“	“
Hexane			80	7	2	4.3		3M Kel-F 81; amorphous form
			90	7	2	4.5		“
Hydraulic Fluids	Monsanto fluid OS-45		23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	Pydraul F9, Monsanto		23	14	9	0	“	“
	Monsanto fluid OS-45		23	14	9	0	“	Allied Sig. Aclar 28; film
	Pydraul F9, Monsanto		23	14	9	0	“	“
	Monsanto fluid OS-45		23	14	9	0	“	Allied Sig. Aclar 33; film
	Pydraul F9, Monsanto		23	14	9	0	“	“
Hydrobromic Acid	boiling point	48		7	9	0.2		3M Kel-F 81; amorphous form
Hydrochloric Acid		10	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		10	23	14	9	0	“	Allied Sig. Aclar 28; film
		10	23	14	9	0	“	Allied Sig. Aclar 33; film
		10	25	7	9	0		3M Kel-F 81; amorphous form
	boiling point	20		7	9	0		“
Hydrochloric Acid		36	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		36	23	14	9	0	“	Allied Sig. Aclar 28; film
	concentrated	36	23	14	9	0	“	Allied Sig. Aclar 33; film
		37	175	7	9	0.3		3M Kel-F 81; amorphous form
Hydrofluoric Acid		50	25	7	9	0		“
	concentrated	60	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	“	60	23	14	9	0	“	Allied Sig. Aclar 28; film
		60	23	14	9	0	“	Allied Sig. Aclar 33; film
	anhydrous		25	7	9	0		3M Kel-F 81; amorphous form
	“		50	60	9	0		“
Hydrogen Peroxide		3	25	7	9	0		“
		30	23	14	8	0.23	clouded	Allied Sig. Aclar 22; film
		30	23	14	8	0.23	“	Allied Sig. Aclar 28; film
		30	23	14	9	0	no visible change	Allied Sig. Aclar 33; film
		30	25	7	9	0		3M Kel-F 81; amorphous form
		30	25	30	9	0		“
Hydrogen Sulfide	saturated		175	7	9	0.1		“
Hydrolube	Hollingshead H-2		25	8	9	0		“
	“		80	8	9	0		“
Isoamyl Alcohol			135	7	6	1.4		“
Isopropyl Ether			25	7	9	0.2		“
Jet Aircraft Fuels	JP 4 flight grade		23	14	9	0.02	no visible change	Allied Sig. Aclar 22; film
	JP 4 referee grade		23	14	9	0.09	“	“
	JP 4 flight grade		23	14	9	0.02	“	Allied Sig. Aclar 28; film
	JP 4 referee grade		23	14	9	0.09	“	“
	JP 4 flight grade		23	14	9	0.01	“	Allied Sig. Aclar 33; film
	JP 4 referee grade		23	14	9	0.03	“	“
Lactic Acid		3	23	14	9	0	“	“
		3	23	14	9	0	“	Allied Sig. Aclar 22; film
		3	23	14	9	0	“	Allied Sig. Aclar 28; film
Machining Oils			100	1	9	0		3M Kel-F 81; amorphous form
Malathion	EM-J		23	14	9	0.05	no visible change	Allied Sig. Aclar 22; film
	“		23	14	9	0.05	“	Allied Sig. Aclar 28; film
	“		23	14	9	0	“	Allied Sig. Aclar 33; film

Chemical Resistance - Polychlorotrifluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Mercuric Chloride	saturated		175	7	2	-5.6		3M Kel-F 81; amorphous form
Methallyl Chloride			25	7	9	0.1		“
Methyl Acetate			25	7	7	1		“
Methyl Alcohol			23	14	9	0.1	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0.1	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
Methyl Butyrate			25	7	7	0.8		“
Methyl Ether			25	7	9	0.2		“
Methyl Ethyl Ketone			23	14	3	5.9	extremely flexible	Allied Sig. Aclar 22; film
			23	14	3	5.9	“	Allied Sig. Aclar 28; film
			23	14	6	1.2	slightly flexible	Allied Sig. Aclar 33; film
			25	7	9	0.2		3M Kel-F 81; amorphous form
			90	7	2	4.6		“
Methyl Formate			25	7	9	0.1		“
Methyl Proprionate			25	7	6	1.4		“
Methylal			25	7	6	1.3		3M Kel-F 81; amorphous form
Mineral Oils			25	7	9	0		“
Motor Oils	premium grade		23	14	9	0.01	no visible change	Allied Sig. Aclar 22; film
	“		23	14	9	0.01	“	Allied Sig. Aclar 28; film
	“		23	14	9	0.01	“	Allied Sig. Aclar 33; film
Naphtha	solvent		25	7	9	0		3M Kel-F 81; amorphous form
Nickel Ammonium Sulfate	saturated		175	7	9	0.3		“
Nitric Acid		10	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		10	23	14	9	0	“	Allied Sig. Aclar 28; film
		10	23	14	9	0	“	Allied Sig. Aclar 33; film
		10	25	7	9	0		3M Kel-F 81; amorphous form
		30	175	7	9	0.1		“
	boiling point	60		7	9	0		“
	concentrated	70	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	“	70	23	14	9	0	“	Allied Sig. Aclar 28; film
	“	70	23	14	9	0	“	Allied Sig. Aclar 33; film
		70	25	7	9	0		3M Kel-F 81; amorphous form
		70	70	7	9	0		“
Nitric Acid	fuming	95	25	7	9	0		“
	with hydrofluoric acid		23	14	9	0	no visible change	Allied Sig. Aclar 22; film
	red fuming		23	14	9	0.07	“	“
	with hydrofluoric acid		23	14	9	0	“	Allied Sig. Aclar 28; film
	red fuming		23	14	9	0.07	“	“
	with hydrofluoric acid		23	14	9	0	“	Allied Sig. Aclar 33; film
	red fuming		23	14	9	0.04	“	“
	white fuming		90	7	9	0.3		3M Kel-F 81; amorphous form
Nitrobenzene			25	7	9	0		“
			140	7	6	1.5		“
Nitrogen Tetraoxide					1		tends to plasticize the film	Allied Sig. Aclar 22; film
			5	7	1	9.9		3M Kel-F 81; amorphous form
			23	14	5		flexible, yellows	Allied Sig. Aclar 22; film
			23	14	5		“	Allied Sig. Aclar 28; film
			23	14	5		“	Allied Sig. Aclar 33; film
Nitromethane			25	7	9	0		3M Kel-F 81; amorphous form

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Oleic Acid			25	7	9	0		3M Kel-F 81; amorphous form
Oleum			25	2	9	0.1		"
Orthochlorotoluene			25	7	9	0		"
Oxalic Acid			175	7	9	-0.2		"
Oxygen	liquid		23	14	8		passes lox impact test	Allied Sig. Aclar 22; film
	"		23	14	8		"	Allied Sig. Aclar 28; film
	"		23	14	8		"	Allied Sig. Aclar 33; film
Ozone	5% in oxygen		150	2	9	0	no molecular degrad.	3M Kel-F 81; amorphous form
Pentachloroethane			25	7	9	0		"
Pentanedione (2,4-)			23	14	8	0.17	clouded	Allied Sig. Aclar 22; film
			23	14	8	0.17	"	Allied Sig. Aclar 28; film
			23	14	9	0.2	no visible change	Allied Sig. Aclar 33; film
Perchloric Acid		70	25	30	9	0		3M Kel-F 81; amorphous form
			25	14	9	-0.2		"
Perfluorotriethylamine			25	7	9	0		"
Phenol		5	70	7	9	0		"
Phosphoric Acid		30	175	7	9	0.1		3M Kel-F 81; amorphous form
		85	175	7	9	0		"
			140	7	9	0		"
Piperidine			25	7	9	0		"
Potassium Dichromate	saturated solution		175	7	9	0		"
Potassium Hydroxide		10	25	7	9	-0.2		"
		10	80	7	9	0.1		"
	boiling point	50		7	9	0.1		"
Potassium Permanganate	saturated		25	30	9	0		"
Potassium Persulfate	"		25	30	9	0		"
Propyl Acetate	n-propyl acetate		25	7	8	0.6		"
Propyl Ether	n-propyl ether		25	7	9	0.3		"
Propyl Formate	n-propyl Formate		25	7	9	0.1		"
Propyl Propionate	n-propyl propionate		25	7	9	0.4		"
Propylene Chloride			25	7	9	0		"
Pyridine			23	14	7	0.55	clouded	Allied Sig. Aclar 22; film
			23	14	7	0.55	"	Allied Sig. Aclar 28; film
			23	14	9	0.1	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form
			115	1	1	7.4		"
Pyrogallic Acid	saturated		175	7	9	0.1		"
Salicylic Acid	"		175	7	9	0.2		"
Santicizer 8			25	7	9	0		"
Santicizer B16			25	7	9	0		"
Santicizer E15			25	7	9	0		"
Santicizer M17			25	7	9	0		"
Santolube 31			25	7	9	0		"
Silicone Oils	DC-200		70	7	9	0.1		"
	"		175	7	9	0.1		"
	"		190	7	9	-0.3		"
Sodium Bisulfite	saturated		175	7	8	-0.7		"
Sodium Borate	"		175	7	9	0.2		"
Sodium Carbonate		2	25	7	9	0		"

Chemical Resistance - Polychlorotrifluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Sodium Chloride		10	25	7	9	0		3M Kel-F 81; amorphous form
	saturated		175	7	9	0		“
Sodium Hydroxide		1	25	7	9	0		“
		10	25	7	9	0		“
		30	175	7	6	-1.2		“
	boiling point	50		7	9	0.1		“
		50	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		50	23	14	9	0	“	Allied Sig. Aclar 28; film
		50	23	14	9	0	“	Allied Sig. Aclar 33; film
Sodium Hypochlorite			23	14	9	0	“	Allied Sig. Aclar 28; film
			23	14	9	0	“	Allied Sig. Aclar 33; film
			23	14	9	0	“	Allied Sig. Aclar 22; film
Sodium Phosphate	saturated		175	7	9	0		3M Kel-F 81; amorphous form
Stannic Chloride	“		25	7	9	0		“
	“		175	7	9	0.1		“
Sulfur Dioxide	anhydrous		25	7	9	0.1		“
Sulfuric Acid		3	25	7	9	0		“
	fuming, 20% oleum	20	23	14	9	0.03	no visible change	Allied Sig. Aclar 22; film
	“	20	23	14	9	0.03	“	Allied Sig. Aclar 28; film
	“	20	23	14	9	0.02	“	Allied Sig. Aclar 33; film
		20	25	7	9	0		3M Kel-F 81; amorphous form
		30	23	14	9	0	no visible change	Allied Sig. Aclar 22; film
		30	23	14	9	0	“	Allied Sig. Aclar 28; film
		30	23	14	9	0	“	Allied Sig. Aclar 33; film
		30	25	7	9	0		3M Kel-F 81; amorphous form
		30	175	7	9	0		“
		50	140	30	9	0		“
		92	140	30	9	0		“
		95	175	7	9	0		“
		96	70	7	9	0		“
Tetrachloroethane	symmetrical		25	7	9	0		“
Tetrachloroethylene			25	7	7	0.8		“
Tetrahydrofuran			25	7	1	8.5		“
			64	1	1	8.2		“
Thionyl Chloride			90	7	1	8.5		“
Titanium Tetrachloride			90	7	4	2.6		“
Toluene			23	14	4	2.8	flexible	Allied Sig. Aclar 22; film
			23	14	4	2.8	“	Allied Sig. Aclar 28; film
			23	14	6	1.1	slightly flexible	Allied Sig. Aclar 33; film
			25	7	9	0.4		3M Kel-F 81; amorphous form
			110	7	2	5		“
Toluene Diisocyanate			23	14	9	0.44	no visible change	Allied Sig. Aclar 22; film
			23	14	9	0.44	“	Allied Sig. Aclar 28; film
Trichloroacetic Acid			70	7	9	0		3M Kel-F 81; amorphous form
Trichloroethane			25	7	9	0.1		“
Trichloroethane (1,1,2-)	technical		23	14	8	0.04	clouded	Allied Sig. Aclar 22; film
	“		23	14	8	0.04	“	Allied Sig. Aclar 28; film
	“		23	14	9	0.02	no visible change	Allied Sig. Aclar 33; film
			25	7	9	0		3M Kel-F 81; amorphous form

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Weight Change	Resistance Note	Material Note
Trichloroethylene			23	14	2	10.9	clouded, extremely flexible	Allied Sig. Aclar 22; film
			23	14	2	10.9	“	Allied Sig. Aclar 28; film
			23	14	2	7.8	clear, very flexible	Allied Sig. Aclar 33; film
			25	7	4	2.3		3M Kel-F 81; amorphous form
			80	7	1	9.2		“
Trichloropropane (1,2,3-)			25	7	9	0		3M Kel-F 81; amorphous form
Trichlorotrifluoroethane	Genesolv D		23	14	4		clouded, extremely flexible	Allied Sig. Aclar 22; film
	“		23	14	4		“	Allied Sig. Aclar 28; film
	“		23	14	4		“	Allied Sig. Aclar 33; film
Tricresyl Phosphate			25	7	9	0		3M Kel-F 81; amorphous form
			140	7	9	0		“
Triethylaluminum			23	14	7	0.13	slightly crazed	Allied Sig. Aclar 22; film
			23	14	7	0.13	“	Allied Sig. Aclar 28; film
			23	14	7	0.01	“	Allied Sig. Aclar 33; film
Triethylamine			25	7	9	0.2		3M Kel-F 81; amorphous form
Water			77	21	9	0		3M Kel-F 81
Xylene			25	7	9	0.4		3M Kel-F 81; amorphous form
			90	7	1	6.5		“
			138	7	1	27		“
Zinc Sulfate	saturated		174	7	9	0.4		“

Chemical Resistance - Polytetrafluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained		Resistance Note	Material Note
						Weight	Tensile Strength	Elongation		
Abietic Acid	up to the boiling point				8				compatible	DuPont Teflon PTFE
Acetic Acid		10	23		8				no effect	Furon Rulon J;
	up to the boiling point				8				compatible	DuPont Teflon PTFE
	concentrated		23		8				no effect	Furon Rulon J
Acetic Anhydride	up to the boiling point				8				compatible	DuPont Teflon PTFE
Acetone	“				8				“	“
			25	365	9	0.3			no signif. chg. for longer expos.	“
			50	365	9	0.4			“	“
			70	14	9	0			“	“
Acetophenone	up to the boiling point				8				compatible	“
Acrylic Anhydride	“				8				“	“
Acrylonitrile	up to the boiling point				8				“	“
Allyl Acetate	“				8				“	“
Allyl Methacrylate	“				8				“	“
Aluminum Chloride	“				8				“	“
Ammonia	liquid to boiling point				8				“	“
Ammonium Chloride	up to the boiling point				8				“	“
Ammonium Hydroxide		0.88	50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib. 50.8x0.38 mm tape
		0.88	50	28	9	0	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
		0.88	50	28	9	0	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
		10	25	365	9	0			no signif. chg. for longer expos.	DuPont Teflon PTFE
		10	70	365	9	0.1			“	“
		30	23		2				vigorous attack	Furon Rulon J
	concentrated		23		2				“	“
Aniline	up to the boiling point				8				compatible	DuPont Teflon PTFE
Animal Oils	“				8				“	“
Benzene			50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
			78	4	9	0.5			no signif. chg. for longer expos.	DuPont Teflon PTFE
			100	0.33	8	0.6			“	“
			200	0.33	7	1			“	“
Benzonitrile	up to the boiling point				8				compatible	“
Benzoyl Chloride	“				8				“	“
Benzyl Alcohol	“				8				“	“
Borax	“				8				“	“
Boric Acid	“				8				“	“
Bromine	“				8				“	“
Butyl Acetate	“				8				“	“
Butyl Methacrylate	“				8				“	“
Butylamine	“				8				“	“
Calcium Chloride	“				8				“	“
Carbon Tetrachloride			25	365	8	0.6			no signif. chg. for longer expos.	“
			50	365	5	1.6			“	“
			70	14	5	1.99			“	“
			100	0.33	4	2.5			“	“
			200	0.33	3	3.7			“	“
Carbonisulfide	up to the boiling point				8				compatible	“
Cetane	“				8				“	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained		Resistance Note	Material Note
						Weight	Tensile Strength	Elongation		
Chlorine	up to the boiling point				8				compatible	DuPont Teflon PTFE
Chloroform	“				8				“	“
Chlorosulfonic Acid	up to the boiling point				8				“	“
Chromic Acid	“				8				“	“
Cyclohexane	“				8				“	“
Detergents	“				8				“	“
Dibutyl Phthalate	“				8				“	“
Dibutyl Sebacate	“				8				“	“
Diethyl Carbonate	“				8				“	“
Diisobutyl Adipate	“				8				“	“
Dimethyl Ether	“				8				“	“
Dimethylformamide	“				8				“	“
Dimethylhydrazine	“				8				“	“
Dioxane	“				8				“	“
Ethyl Acetate	“				8				“	“
			25	365	9	0.5			no signif. chg. for longer expos.	“
			50	365	8	0.7			“	“
			70	14	8	0.7			“	“
Ethyl Alcohol		95	25	365	9	0			“	“
		95	50	365	9	0			“	“
		95	70	14	9	0			“	“
		95	100	0.33	9	0.1			“	“
		95	200	0.33	9	0.3			“	“
	up to the boiling point				8				compatible	“
			50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
Ethyl Ether	up to the boiling point				8				compatible	DuPont Teflon PTFE
Ethyl Hexoate	“				8				“	“
Ethylene Bromide	“				8				“	“
Ethylene Glycol	“				8				“	“
Ferric Chloride	“				8				“	“
Ferric Phosphate	“				8				“	“
Fluoronaphthalene	“				8				“	“
Fluoronitrobenzene	“				8				“	“
Formaldehyde	“				8				“	“
Formic Acid	“				8				“	“
Furan	“				8				“	“
Gasoline	“				8				“	“
Hexachloroethane	“				8				“	“
Hexane	“				8				“	“
Hydrazine	“				8				“	“
Hydrobromic Acid		48	23		8				no effect	Furon Rulon J
Hydrochloric Acid		10	23		8				“	“
		10	25	365	9	0			no signif. chg. for longer expos.	DuPont Teflon PTFE
		10	50	365	9	0			“	“
		10	70	365	9	0			“	“
		20	100	0.33	9	0			“	“
		20	200	0.33	9	0			“	“
	up to the boiling point				8				compatible	“

Chemical Resistance - Polytetrafluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained		Resistance Note	Material Note
						Weight	Tensile Strength	Elongation		
Hydrochloric Acid	concentrated solution		23		8				no effect	Furon Rulon J
	concentrated		50	28	5	7	100		possibly unsatisfactory	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
	“		50	28	5	7	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
	“		50	28	5	7	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
Hydrofluoric Acid		60	23		7				dielectric reduced; no other effect	Furon Rulon J
	up to the boiling point				8				compatible	DuPont Teflon PTFE
Hydrogen Peroxide	“				8				“	“
Lead	“				8				“	“
Magnesium Chloride	“				8				“	“
Mercury	“				8				“	“
Methacrylic Acid	“				8				“	“
Methyl Alcohol	“				8				“	“
Methyl Ethyl Ketone	“				8				“	“
Methyl Methacrylate	“				8				“	“
Naphthalene	“				8				“	“
Naphthols	“				8				“	“
Nitric Acid		10	23		3				strongly attacks	Furon Rulon J
		10	25	365	9	0			no signif. chg. for longer expos.	DuPont Teflon PTFE
		10	70	365	9	0.1			“	“
		40	23		3				strongly attacks	Furon Rulon J
	up to the boiling point				8				compatible	DuPont Teflon PTFE
	concentrated		23		3				strongly attacks	Furon Rulon J
	“		50	28	5	7	100		possibly unsatisfactory	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
	“		50	28	5	7	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
	“		50	28	5	7	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
Nitro-2-Methylpropanol (2-)	up to the boiling point				8				compatible	DuPont Teflon PTFE
Nitrobenzene	“				8				“	“
Nitrobutanol (2-)	“				8				“	“
Nitrogen Tetraoxide	“				8				“	“
Nitromethane	“				8				“	“
Octadecyl Alcohol	up to the boiling point				8				“	“
Ozone	“				8				“	“
Pentachlorobenzamide	“				8				“	“
Perchloroethylene	“				8				“	“
Perfluoroxylene	“				8				“	“
Phenol	“				8				“	“
			50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		“	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
Phosphoric Acid		10	23		8				no effect	Furon Rulon J
		30	23		8				“	“
	up to the boiling point				8				compatible	DuPont Teflon PTFE
	concentrated		23		8				no effect	Furon Rulon J
Phosphorous Pentachloride	up to the boiling point				8				compatible	DuPont Teflon PTFE
Phthalic Acid	“				8				“	“
Pinene	“				8				“	“
Piperidine	“				8				“	“
Potassium Acetate	“				8				“	“
Potassium Hydroxide		10	50		5				attacked	Furon Rulon J
		10	100		7				slight effects on dielectrics	“

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained		Resistance Note	Material Note
						Weight	Tensile Strength	Elongation		
Potassium Hydroxide		10	100		2				vigorous attack	Furon Rulon J
		30	23		7				sl. effects on density & dielectrics	"
		30	100		5				mild effects	"
		60	23		8				no effect	"
	up to the boiling point				8				compatible	DuPont Teflon PTFE
Potassium Permanganate	"				8				"	"
Pyridine	"				8				"	"
Soap	"				8				"	"
Sodium Hydroxide		10	25	365	9	0			no signif. chg. for longer expos.	"
		10	70	365	9	0.1			"	"
		23	100		2				strong attack	Furon Rulon J
		30	100		4		80	80	strongly attacks	"
		40	50	28	5	7	100		possibly unsatisfactory	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
		40	50	28	5	7	100		"	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
		40	50	28	5	7	100		"	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
		50	100	0.33	9	0			no signif. chg. for longer expos.	DuPont Teflon PTFE
		60	23		8				no effect	Furon Rulon J
	up to the boiling point				8				compatible	DuPont Teflon PTFE
Sodium Hypochlorite	"				8				"	"
Sodium Peroxide	"				8				"	"
Solvents	aliphatic				8				"	"
	up to the boiling point				8				"	"
Stannous Chloride	"				8				"	"
Sulfur	"				8				"	"
Sulfuric Acid		30	25	365	9	0			no signif. chg. for longer expos.	"
		30	70	365	9	0			"	"
		30	100	0.33	9	0			"	"
		30	200	0.33	9	0.1			"	"
		50	50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
		50	50	28	9	0	100		"	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
		50	50	28	9	0	100		"	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
	up to the boiling point				8				compatible	DuPont Teflon PTFE
Tartaric Acid		10	23		8				no effect	Furon Rulon J
		30	23		8				"	"
		60	23		8				"	"
Tetrabromoethane	up to the boiling point				8				compatible	DuPont Teflon PTFE
Tetrachloroethylene	"				8				"	"

Chemical Resistance - Polytetrafluoroethylene

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	PDL Rating	% Change	% Retained		Resistance Note	Material Note
						Weight	Tensile Strength	Elongation		
Toluene			25	365	9	0.3			no signif. chg. for longer expos.	DuPont Teflon PTFE
			50	365	8	0.6			"	"
			70	14	8	0.6			"	"
Trichloroacetic Acid	up to the boiling point				8				compatible	"
Trichloroethylene	"				8				"	"
			50	28	9	0	100		satisfactory for use	ICI Fluon VG15; 15% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		"	ICI Fluon VG25; 25% gl.fib.; 50.8x0.38 mm tape
			50	28	9	0	100		"	ICI Fluon VX1; 30% gl.fib./misc.; 50.8x0.38 mm tape
Tricresyl Phosphate	up to the boiling point				8				compatible	DuPont Teflon PTFE
Triethanolamine	"				8				"	"
Vegetable Oils	"				8				"	"
Vinyl Methacrylate	"				8				"	"
Water	"				8				"	"
Xylene	up to the boiling point				8				compatible	DuPont Teflon PTFE
Zinc Chloride	"				8				"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Acetaldehyde			23			2			not recommended for use	Atochem Kynar
Acetamide			24			8			exp. temp. is max. recom.	“
Acetic Acid		10	23	7	0.25%	7		85		LNP; 15% carb.fib.
		10	23	7		7		87		“
		10	82	3	0.25%	5		76		“
		10	82	3		9		94		“
	in water	10	107			8			exp. temp. is max. recom.	Atochem Kynar
		10	149	1	0.25%	3		67		LNP; 15% carb.fib.
		10	149	1		9		103		“
	in water	50	93			8			exp. temp. is max. recom.	Atochem Kynar
		50	125	7		7	<1	>90	no visual change	Atochem Foraflon
		50	130	365		8			satisfactory resist.	“
		50	130	365	bent specimen	8			“	“
	in water	80	79			8			exp. temp. is max. recom.	Atochem Kynar
			25	7		7	<1	>90	no visual change	Atochem Foraflon
			49			8			exp. temp. is max. recom.	Atochem Kynar
Acetic Anhydride				7		2			not recommended for use	Atochem Foraflon
			23			2			“	Atochem Kynar
			23	90		5			questionable	Atochem Foraflon
			23	90	bent specimen	5			“	“
Acetone	in water	10	52			8			exp. temp. is max. recom.	Atochem Kynar
				7		2			not recommended for use	Atochem Foraflon
			23			2			“	Atochem Kynar
Acetonitrile			25	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Acetophenone				7		2			not recommended for use	Atochem Foraflon
			23			2			“	Atochem Kynar
Acetyl Bromide			52			8			exp. temp. is max. recom.	“
Acetyl Chloride			50	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Acetylacetone				7		2			not recommended for use	Atochem Foraflon
			23			2			“	Atochem Kynar
Acetylene			121			8			exp. temp. is max. recom.	“
Acrolein				7		2			not recommended for use	Atochem Foraflon
Acrylonitrile			24			8			exp. temp. is max. recom.	Atochem Kynar
	propenoic nitrile		25	7		7	<1	>90	no visual change	Atochem Foraflon
	“		25	7		7	<1	>90	“	“
Adipic Acid			66			8			exp. temp. is max. recom.	Atochem Kynar
Air			141			8			“	“
Alchoholic Spirits	with ethyl alcohol	40	93			8			“	“
Allyl Alcohol			52			8			“	“
Allyl Chloride			100			8			“	“
			100	7		7	<1	>90	no visual change	Atochem Foraflon
Aluminum Acetate	aqueous solution or solid		141			8			exp. temp. is max. recom.	Atochem Kynar
Aluminum Bromide			141			8			“	“
Aluminum Chloride	in water	<=40	141			8			“	“
Aluminum Fluoride	aqueous solution or solid		135			8			“	“
Aluminum Hydroxide			135			8			“	“
Aluminum Nitrate	aqueous solution or solid		135			8			“	“
Aluminum Oxychloride			135			8			“	“

Chemical Resistance - Polyvinylidene Fluoride

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Aluminum Sulfate	aqueous solution or solid		135			8			exp. temp. is max. recom.	Atochem Kynar
Ammonia	gas		23			2			not recommended for use	“
	liquefied		23			2			“	“
	gas		150	7		7	<1	>90	no visual change	Atochem Foraflon
Ammonium Acetate	aqueous solution or solid		79			8			exp. temp. is max. recom.	Atochem Kynar
Ammonium Alum	“		135			8			“	“
Ammonium Bifluoride	“		66			8			“	“
Ammonium Bromide	“		121			8			“	“
Ammonium Carbonate	“		135			8			“	“
Ammonium Chloride	“		135			8			“	“
Ammonium Dichromate	“		121			8			“	“
Ammonium Fluoride	“		135			8			“	“
Ammonium Hydroxide		20	23	180		8			satisfactory resist.	Atochem Foraflon
		20	23	180	bent specimen	8			“	“
		20	50	90		8			“	“
		20	50	90	bent specimen	8			“	“
		20	90	30		2			not recommended for use	“
		20	90	30	bent specimen	2			“	“
		29	75	14		8			satisfactory resist.	“
		29	75	14	bent specimen	2			not recommended for use	“
		30	150	7		7	<1	>90	no visual change	“
Ammonium Hydroxide			23	7	0.25%	5		76		LNP; 15% carb.fib.
			23	7		7		89		“
			82	3	0.25%	5		75		“
			82	3		8		90		“
	aqueous solution or solid		110			8			exp. temp. is max. recom.	Atochem Kynar
			149	1	0.25%	4		73		LNP; 15% carb.fib.
			149	1		5		76		“
Ammonium Metaphosphate	aqueous solution or solid		135			8			exp. temp. is max. recom.	Atochem Kynar
Ammonium Nitrate	“		135			8			“	“
Ammonium Persulfate	“		25			8			“	“
Ammonium Phosphate	“		135			8			“	“
Ammonium Sulfate	“		135			8			“	“
Ammonium Sulfide	“		52			8			“	“
Ammonium Thiocyanate	“		135			8			“	“
Amyl Acetate			50	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Amyl Alcohol			135			8			“	“
	Pentanol		150	7		7	<1	>90	no visual change	Atochem Foraflon
	pentanol		150	7		7	<1	>90	“	“
Amyl Alcohol (sec-)			52			8			exp. temp. is max. recom.	Atochem Kynar
Amyl Chloride			100	7		7	<1	>90	“	“
			141			8			exp. temp. is max. recom.	Atochem Kynar
Aniline			38			8			“	“
			38	7		7	<1	>90	no visual change	Atochem Foraflon
Aniline Hydrochloride	aqueous solution or solid		24			8			exp. temp. is max. recom.	Atochem Kynar
Animal Oils	lard oil		141			8			“	“
Antimony Trichloride			75	7		7	<1	>90	no visual change	Atochem Foraflon
Aqua Regia			24			8			exp. temp. is max. recom.	Atochem Kynar
			100	7		7	<1	>90	no visual change	Atochem Foraflon

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Arsenic Acid	aqueous solution		135			8			exp. temp. is max. recom.	Atochem Kynar
Asphalt			121			8			"	"
Barium Carbonate			141			8			"	"
Barium Chloride	aqueous solution or solid		141			8			"	"
Barium Hydroxide			135			8			"	"
Barium Nitrate	aqueous solution or solid		135			8			"	"
Barium Sulfate			141			8			"	"
Barium Sulfide			135			8			"	"
Beer			100			8			"	"
Beet Sugar Liquors			107			8			"	"
Benzaldehyde			21			8			"	"
			25	7		2			not recommended for use	Atochem Foraflon
Benzene	50/50 with chlorobenzene	50	130	180		5			questionable	Atochem Foraflon
	"	50	130	180	bent specimen	5			"	"
			38	7		7	<1	>90	no visual change	"
			77			8			exp. temp. is max. recom.	Atochem Kynar
Benzenesulfonic Acid	concentrated		25	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or solid		52			8			exp. temp. is max. recom.	Atochem Kynar
Benzoic Acid			107			8			"	"
	saturated		125	7		7	<1	>90	no visual change	Atochem Foraflon
Benzoyl Chloride			75	7		7	<1	>90	"	"
			77			8			exp. temp. is max. recom.	Atochem Kynar
Benzoyl Peroxide			77			8			"	"
Benzyl Alcohol			121			8			"	"
Benzyl Chloride			100	7		7	<1	>90	no visual change	Atochem Foraflon
			141			8			exp. temp. is max. recom.	Atochem Kynar
Benzyl Ether			38			8			"	"
Benzylamine	aqueous solution or liquid		24			8			"	"
Benzylic Alcohol			125	7		7	<1	>90	no visual change	Atochem Foraflon
Black Liquor			79			8			exp. temp. is max. recom.	Atochem Kynar
Bleach	liquid		90	15		8			satisfactory resist.	Atochem Foraflon
	"		90	15	bent specimen	2			not recommended for use	"
	"		90	90		8			satisfactory resist.	"
	"		90	90	bent specimen	2			not recommended for use	"
	"		130	90		5			questionable	"
	"		130	90	bent specimen	2			not recommended for use	"
	bleaching agents		135			8			exp. temp. is max. recom.	Atochem Kynar
Borax			135			8			"	"
Boric Acid			135			8			"	"
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Boron Trifluoride			24			8			exp. temp. is max. recom.	Atochem Kynar
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Brines	chlorinated acid		93			8			exp. temp. is max. recom.	Atochem Kynar
			141			8			"	"
	acid		141			8			"	"
	basic		141			8			"	"
Bromic Acid	aqueous solution		93			8			"	"
Bromine			60	365		8			satisfactory resist.	Atochem Foraflon
			60	365	bent specimen	8			"	"

Chemical Resistance - Polyvinylidene Fluoride

Chemical Resistance - Polyvinylidene Fluoride

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Bromine	bromine liquid		66			8			exp. temp. is max. recom.	Atochem Kynar
	dry gas		66			8			"	"
	bromine water		100			8			"	"
	dry		100	7		7	<1	>90	no visual change	Atochem Foraflon
	moist		100	7		7	<1	>90	"	"
Bromobenzene			66			8			exp. temp. is max. recom.	Atochem Kynar
Bromoform			66			8			"	"
Butadiene			100	7		7	<1	>90	no visual change	Atochem Foraflon
			121			8			exp. temp. is max. recom.	Atochem Kynar
Butane			121			8			"	"
Butanediol	aqueous solution or liquid		135			8			"	"
Butanone				7		2			not recommended for use	Atochem Foraflon
Butene			150	7		7	<1	>90	no visual change	Atochem Foraflon
Butyl Acetate			25	7		7	<1	>90	"	"
			27			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Acrylate			25	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Alcohol	n-butanol		75	7		7	<1	>90	no visual change	Atochem Foraflon
			107			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Alcohol (sec-)			75	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or liquid		93			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Alcohol (tert-)			75	7		7	<1	>90	no visual change	"
	aqueous solution or liquid		93			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Bromide			100	7		7	<1	>90	no visual change	Atochem Foraflon
			141			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Chloride			141			8			"	"
Butyl Ether			38			8			"	"
Butyl-2-Hydroxybenzene-butylphenol (1-)			100	7		7	<1	>90	no visual change	Atochem Foraflon;
Butyl Mercaptan			141			8			exp. temp. is max. recom.	Atochem Kynar
Butyl Methyl Ether (tert-)			50	120		8			satisfactory resist.	Atochem Foraflon
			50	120	bent specimen	8			"	"
Butyl Phenol			107			8			"	"
Butyl Stearate			38			8			"	"
Butylamine	n-butylamine			7		2			not recommended for use	Atochem Foraflon
	aqueous solution or liquid		23			2			"	Atochem Kynar
Butylamine (sec-)	"		21			8			"	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Butylamine (tert-)	aqueous solution or solid		21			8			exp. temp. is max. recom.	Atochem Kynar
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Butylene			141			8			exp. temp. is max. recom.	"
Butyraldehyde			66			8			"	"
Butyric Acid			107			8			"	"
Calcium Acetate	aqueous solution or solid		141			8			"	"
Calcium Bisulfate	"		141			8			"	"
Calcium Bisulfite	"		93			8			"	"
Calcium Bromide	"		141			8			"	"
Calcium Carbonate			141			8			"	"
Calcium Chlorate	aqueous solution or solid		141			8			"	"
Calcium Chloride	"		141			8			"	"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Calcium Hydroxide			135			8			exp. temp. is max. recom.	Atochem Foraflon
Calcium Hypochlorite	aqueous solution or solid		93			8			"	"
Calcium Nitrate	"		135			8			"	"
Calcium Oxide			121			8			"	"
Calcium Phosphate			141			8			"	"
Calcium Sulfate			141			8			"	"
Cane Sugar	can sugar liquors		141			8			"	"
Caprylic Acid			79			8			"	"
Carbon Dioxide			141			8			"	"
Carbon Disulfide			24			8			"	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Carbon Monoxide			141			8			exp. temp. is max. recom.	Atochem Kynar
Carbon Tetrachloride			90	180		5			questionable	Atochem Foraflon
			90	180	bent specimen	5			"	"
			135			8			exp. temp. is max. recom.	Atochem Kynar
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Carbonic Acid			135			8			exp. temp. is max. recom.	Atochem Kynar
Casein			121			8			"	"
Castor Oil			141			8			"	"
Chloral			25	7		7	<1	>90	no visual change	Atochem Foraflon
Chloral Hydrate			24			8			exp. temp. is max. recom.	Atochem Kynar
Chlorine	in carbon tetrachloride	5	93			8			"	"
	saturated with sulfuric acid	65-98	23	240		8			satisfactory resist.	Atochem Foraflon
	"	65-98	23	240	bent specimen	8			"	"
	chlorine gas with UV light		30	11		8			"	"
	"		30	11	bent specimen	2			not recommended for use	"
	gas		93			8			exp. temp. is max. recom.	Atochem Kynar
	liquid		93			8			"	"
	dry		100	7		7	<1	>90	no visual change	Atochem Foraflon
	moist		100	7		7	<1	>90	"	"
	chlorine gas without light		100	11		8			satisfactory resist.	"
	"		100	11	bent specimen	8			"	"
	chlorine water		107			8			exp. temp. is max. recom.	Atochem Kynar
Chlorine Dioxide			66			8			"	"
Chloroacetic Acid		75	75	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or pure		23			2			not recommended for use	Atochem Kynar
			100	7		2			"	Atochem Foraflon
Chloroacetyl Chloride			25	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Chlorobenzene	50/50 with benzene	50	130	180		5			questionable	Atochem Foraflon
	"	50	130	180	bent specimen	5			"	"
			50	7		7	<1	>90	no visual change	"
			77			8			exp. temp. is max. recom.	Atochem Kynar
			90	120	bent specimen	8			satisfactory resist.	Atochem Foraflon
			130	120		5			questionable	"
Chlorobenzenesulfonic Acid	aqueous solution or pure		93			8			exp. temp. is max. recom.	Atochem Kynar
Chlorobenzyl Chloride			52			8			"	"
Chloroform	with sulfuric acid (98%)	10	50	180		8			satisfactory resist.	Atochem Foraflon
	"	10	50	180	bent specimen	8			"	"
	with methanol & HCl		50	180		8			"	"

Chemical Resistance - Polyvinylidene Fluoride

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Chloroform	with methanol & HCl		50	180	bent specimen	8			satisfactory resist.	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
	trichloromethane		100	7		7	<1	>90	no visual change	Atochem Foraflon
Chlorohexanol (6-)			77			8			"	"
Chlorohydrin			52			8			exp. temp. is max. recom.	Atochem Kynar
Chloromethyl Methyl Ether				7		5			questionable	Atochem Foraflon
Chloropicrin			66			8			exp. temp. is max. recom.	Atochem Kynar
Chlorosulfonic Acid		98	25	7		7	<1	>90	no visual change	Atochem Foraflon
			23			2			not recommended for use	Atochem Kynar
Chlorotrimethylsilane			52			8			exp. temp. is max. recom.	"
Chrome Alum	aqueous solution or solid		93			8			"	"
Chromic Acid	in water	<=40	79			8			"	"
	"	50	52			8			"	"
	930 g/l + surfactant		90	120		8			satisfactory resist.	Atochem Foraflon
	"		90	120	bent specimen	8			"	"
Chromic Anhydride	saturated		100	7		7	<1	>90	no visual change	"
Chromyl Chloride			52			8			exp. temp. is max. recom.	Atochem Kynar
Cider			60			8			"	"
Citric Acid		50	150	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or solid		135			8			exp. temp. is max. recom.	Atochem Kynar
Coal Gas			107			8			"	"
Coconut Oil			141			8			"	"
Copper Acetate	aqueous solution or solid		121			8			"	"
Copper Carbonate	basic		141			8			"	"
Copper Chloride	aqueous solution or solid		141			8			"	"
Copper Cyanide			135			8			"	"
Copper Fluoride			135			8			"	"
Copper Nitrate	aqueous solution or solid		135			8			"	"
Copper Sulfate	"		141			8			"	"
Corn Oil			141			8			"	"
Corn Syrup			121			8			"	"
Cottonseed Oil			141			8			"	"
Cresol			66			8			"	"
			75	7		7	<1	>90	no visual change	Atochem Foraflon
Cresylic Acid			66			8			exp. temp. is max. recom.	Atochem Kynar
Crotonaldehyde			50	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Crude Oils			90	365		8			satisfactory resist.	Atochem Foraflon
			90	365	bent specimen	8			"	"
			130	365		8			"	"
			130	365	bent specimen	8			"	"
			141			8			exp. temp. is max. recom.	Atochem Kynar
	sour crude oil		141			8			"	"
			150	7		7	<1	>90	no visual change	Atochem Foraflon
			150	365		8			satisfactory resist.	"
			150	365	bent specimen	8			"	"
Cryolite			121			8			exp. temp. is max. recom.	Atochem Kynar
Cuprous Chloride			121			8			"	"
Cyclohexane			141			8			"	"
			150	7		7	<1	>90	no visual change	Atochem Foraflon

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Cyclohexanone				7		2			not recommended for use	Atochem Foraflon
			24			8			exp. temp. is max. recom.	Atochem Kynar
Cyclohexyl Acetate			50	7		7	<1	>90	no visual change	Atochem Foraflon
			93			8			exp. temp. is max. recom.	Atochem Kynar
Cyclohexyl Alcohol			75	7		7	<1	>90	no visual change	Atochem Foraflon
			121			8			exp. temp. is max. recom.	Atochem Kynar
Decalin			100	7		7	<1	>90	no visual change	Atochem Foraflon
Decane			121			8			exp. temp. is max. recom.	Atochem Kynar
Dextrin	aqueous solution or solid		121			8			"	"
Diacetone Alcohol				7		5			questionable	Atochem Foraflon
			24			8			exp. temp. is max. recom.	Atochem Kynar
Dibromobenzene (p-)			93			8			"	"
Dibromoethane (1,2-)			50	7		7	<1	>90	no visual change	Atochem Foraflon
Dibromopropane (1,2-)			93			8			exp. temp. is max. recom.	Atochem Kynar
Dibutyl Phthalate			23			2			not recommended for use	"
Dibutyl Sebacate			23			2			"	"
Dibutylamine	aqueous solution or liquid		21			8			exp. temp. is max. recom.	"
Dichloroacetic Acid	"		52			8			"	"
Dichlorobenzene (o-)			66			8			"	"
			130	120		8			satisfactory resist.	Atochem Foraflon
			130	120	bent specimen	8			"	"
Dichlorodifluoromethane	R12		100	7		7	<1	>90	no visual change	"
Dichlorodimethylsilane			52			8			exp. temp. is max. recom.	Atochem Kynar
Dichloroethane	with hydrochloric acid	10	90	180		8			satisfactory resist.	Atochem Foraflon
	"	10	90	180	bent specimen	8			"	"
	"	10	130	180		8			"	"
	"	10	130	180	bent specimen	5			questionable	"
Dichloroethane (1,2-)			90	365		8			satisfactory resist.	"
			90	365	bent specimen	8			"	"
Dichloroethylene			107			8			exp. temp. is max. recom.	Atochem Kynar
Dichloropropionic Acid (2,2-)			52			8			"	"
Dichlorotetrafluoroethane	R114; Freon 114		50	7		7	<1	>90	no visual change	Atochem Foraflon
Dichlorotoluene (α)			66			8			exp. temp. is max. recom.	Atochem Kynar
Diesel Fuels			141			8			"	"
Diethanolamine	aqueous solution or liquid		23			2			not recommended for use	"
Diethyl Ether	with sulfuric acid (98%)	10	50	180		8			satisfactory resist.	Atochem Foraflon
	"	10	50	180	bent specimen	8			"	"
			25	7		7	<1	>90	no visual change	"
Diethyl Malonate			23			2			not recommended for use	Atochem Kynar
Diethylamine	aqueous solution or liquid		24			8			exp. temp. is max. recom.	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Diethylenetriamine	DETA		50	7		7	<1	>90	"	"
	"		52			8			exp. temp. is max. recom.	Atochem Kynar
Diglycolic Acid			24			8			"	"
Diisobutyl Ketone			50	7		7	<1	>90	no visual change	Atochem Foraflon
			52			8			exp. temp. is max. recom.	Atochem Kynar
Diisobutylene			141			8			"	"
Diisopropyl Ketone			21			8			"	"

Chemical Resistance - Polyvinylidene Fluoride

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Dimethyl Phthalate			24			8			exp. temp. is max. recom.	Atochem Kynar
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Dimethyl Sulfate			24			8			exp. temp. is max. recom.	Atochem Kynar
Dimethyl Sulfoxide			23			2			not recommended for use	"
Dimethyl-1,5-Hexadiene (2,5-)			121			8			"	"
Dimethyl-4-Heptanol (2,6-)			93			8			exp. temp. is max. recom.	"
Dimethylacetamide			23			2			not recommended for use	"
Dimethylamine				7		2			"	Atochem Foraflon
	aqueous solution or gas		24			8			exp. temp. is max. recom.	Atochem Kynar
Dimethylaniline			24			8			"	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Dimethylformamide			23			2			not recommended for use	Atochem Kynar
Dioctyl Phthalate			24			8			exp. temp. is max. recom.	"
Dioxane				7		2			not recommended for use	Atochem Foraflon
Dioxane (1,4-)			23			2			"	Atochem Kynar
Dioxolane			23			2			"	"
Dipropylene Glycol Methyl Ether			24			8			exp. temp. is max. recom.	"
Dishwashing Detergents			90	42		8			satisfactory resist.	Atochem Foraflon
			90	42	bent specimen	8			"	"
	dish washer detergent		90	42		8			"	"
	"		90	42	bent specimen	8			"	"
Disodium Phosphate	aqueous solution or solid		93			8			exp. temp. is max. recom.	Atochem Kynar
Divinylbenzene			52			8			"	"
Epichlorohydrin				7		2			not recommended for use	Atochem Foraflon
			23			2			"	Atochem Kynar
Epsom Salts	aqueous solution or solid		93			8			exp. temp. is max. recom.	"
Ethanethiol			24			8			"	"
Ethoxyethyl Acetate (2-)			50	120		5			questionable	Atochem Foraflon
			50	120	bent specimen	5			"	"
	aqueous solution or liquid		93			8			exp. temp. is max. recom.	Atochem Kynar
Ethyl Acetate			23			2			not recommended for use	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Ethyl Acetoacetate			24			8			exp. temp. is max. recom.	Atochem Kynar
Ethyl Acrylate			24			8			"	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Ethyl Alcohol	in alcoholic spirits	40	93			8			exp. temp. is max. recom.	Atochem Kynar
				7		2			not recommended for use	Atochem Foraflon
	aqueous solution or liquid		23			2			"	Atochem Kynar
			100	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or liquid		141			8			exp. temp. is max. recom.	Atochem Kynar
Ethyl Benzene			52			8			"	"
Ethyl Chloride			100	7		7	<1	>90	no visual change	Atochem Foraflon
			141			8			exp. temp. is max. recom.	Atochem Kynar
Ethyl Chloroacetate			24			8			"	"
Ethyl Chloroformate			52			8			"	"
Ethyl Cyanoacetate			24			8			"	"
Ethyl Ether			52			8			"	"
Ethyl Formate			24			8			"	"
Ethylene Chloride			100	7		7	<1	>90	no visual change	Atochem Foraflon

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Ethylene Chlorohydrin	aqueous solution or liquid		24			8			exp. temp. is max. recom.	Atochem Kynar
Ethylene Dichloride			135			8			"	"
Ethylene Glycol			23	7	0.25%	6		82		LNP; 15% carb.fib.
			23	7		7		85		"
			82	3	0.25%	3		61		"
			82	3		6		82		"
209			130	365		8			satisfactory resist.	Atochem Foraflon
			130	365	bent specimen	8			"	"
	aqueous solution or liquid		141			8			exp. temp. is max. recom.	Atochem Kynar
			149	1	0.25%	1		10		LNP; 15% carb.fib.
			149	1		1		10		"
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Ethylene Oxide			50	7		7	<1	>90	"	"
			93			8			exp. temp. is max. recom.	Atochem Kynar
Ethylenediamine				7		2			not recommended for use	Atochem Foraflon
	aqueous solution or liquid		107			8			exp. temp. is max. recom.	Atochem Kynar
Ethylhexyl Alcohol (2-)	2-ethylhexanol		121			8			"	"
Fatty Acids	sulfonates		79			8			"	"
			141			8			"	"
Ferric Chloride	aqueous solution or solid		141			8			"	"
Ferric Hydroxide			121			8			"	"
Ferric Nitrate	aqueous solution or solid		135			8			"	"
Ferric Sulfate			141			8			"	"
Ferric Sulfide			121			8			"	"
Ferrous Chloride			141			8			"	"
Ferrous Hydroxide			121			8			"	"
Ferrous Nitrate			135			8			"	"
Ferrous Sulfate			141			8			"	"
Fluoboric Acid	aqueous solution		135			8			"	"
Fluorine			24			8			"	"
			25	7		7	<1	>90	no visual change	Atochem Foraflon
Fluosilicic Acid			135			8			exp. temp. is max. recom.	Atochem Kynar
Fluosulfonic Acid		97	25	7		7	<1	>90	no visual change	Atochem Foraflon
Formaldehyde		30	50	7		7	<1	>90	"	"
	in water	37	52			8			exp. temp. is max. recom.	Atochem Kynar
Formic Acid		98	75	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution or liquid		121			8			exp. temp. is max. recom.	Atochem Kynar
Freon 11	chlorofluorocarbon 11		93			8			"	"
			100	7		7	<1	>90	no visual change	Atochem Foraflon
Freon 113	chlorofluorocarbon 113		93			8			exp. temp. is max. recom.	Atochem Kynar
Freon 114	chlorofluorocarbon 114		93			8			"	"
Freon 12	chlorofluorocarbon 12		93			8			"	"
Freon 13	chlorofluorocarbon 13		93			8			"	"
Freon 14	chlorofluorocarbon 14		93			8			"	"
Freon 21	chlorofluorocarbon 21		93			8			"	"
Freon 22	chlorofluorocarbon 22		93			8			"	"
	chlorodifluoromethane		100	7		7	<1	>90	no visual change	Atochem Foraflon
Fructose	aqueous solution or solid		141			8			exp. temp. is max. recom.	Atochem Kynar
Fruit Juices	and pulp		100			8			"	"
Fuel Oils			141			8			"	"

Chemical Resistance - Polyvinylidene Fluoride

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change Weight	% Retained Tensile Strength	Resistance Note	Material Note
Fuels	light fuel		125	7		7	<1	>90	no visual change	Atochem Foraflon
	diesel		141			8			exp. temp. is max. recom.	Atochem Kynar
Fumaric Acid			77			8			"	"
Furan				7		2			not recommended for use	Atochem Foraflon
			23			2			"	Atochem Kynar
Furfural				7		5			questionable	Atochem Foraflon
			24			8			exp. temp. is max. recom.	Atochem Kynar
Furfuryl Alcohol	aqueous solution or liquid		38			8			"	"
Gallic Acid			24			8			"	"
	saturated		25	7		7	<1	>90	no visual change	Atochem Foraflon
Gases	manufactured		141			8			exp. temp. is max. recom.	Atochem Kynar
Gasoline	E		125	7		7	<1	>90	no visual change	Atochem Foraflon
	leaded		141			8			exp. temp. is max. recom.	Atochem Kynar
	sour		141			8			"	"
	unleaded		141			8			"	"
Gelatins			121			8			"	"
Gin			93			8			"	"
Glucose	aqueous solution or solid		141			8			"	"
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Glues			121			8			exp. temp. is max. recom.	Atochem Kynar
Glutamic Acid			93			8			"	"
Glycerin			125	7		7	<1	>90	no visual change	Atochem Foraflon
			130	365		8			satisfactory resist.	"
			130	365	bent specimen	8			"	"
	aqueous solution or liquid		141			8			exp. temp. is max. recom.	Atochem Kynar
Glycine	aqueous solution or solid		24			8			"	"
Glycolic Acid			24			8			"	"
	saturated		25	7		7	<1	>90	no visual change	Atochem Foraflon
Heptane			141			8			exp. temp. is max. recom.	Atochem Kynar
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Hexachloro-1,3-Butadiene			52			8			exp. temp. is max. recom.	Atochem Kynar
Hexamethylenediamine			23			2			not recommended for use	"
Hexamethylphosphoric Triamide	hexamethylphosphotriamide		23			2			"	"
Hexane			141			8			exp. temp. is max. recom.	"
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Hexyl Alcohol			79			8			exp. temp. is max. recom.	Atochem Kynar
Hydrazine	aqueous solution or liquid		93			8			"	"
Hydrazine Dihydrochloride	aqueous solution or solid		24			8			"	"
Hydrazine Hydrate	aqueous solution or liquid		52			8			"	"
Hydriodic Acid	aqueous solution		135			8			"	"
Hydrobromic Acid	in water	<=50	135			8			"	"
		50	150	7		7	<1	>90	no visual change	Atochem Foraflon
		66	90	365		8			satisfactory resist.	"
		66	90	365	bent specimen	8			"	"
Hydrochloric Acid		10	23	7	0.25%	6		80		LNP; 15% carb.fib.
		10	23	7		8		91		"
		10	82	3	0.25%	6		83		"
		10	82	3		8		90		"

Reagent	Reagent Note	Conc. (%)	Temp. (°C)	Time (days)	Load	PDL Rating	% Change	% Retained	Resistance Note	Material Note
							Weight	Tensile Strength		
Hydrochloric Acid		10	149	1	0.25%	5		78		LNP; 15% carb.fib.
		10	149	1		7		87		"
		35	130	365		8			satisfactory resist.	Atochem Foraflon
		35	130	365	bent specimen	8			"	"
		35	150	7		7	<1	>90	no visual change	"
	with 10% methanol		50	180		8			satisfactory resist.	"
	"		50	180	bent specimen	8			"	"
	with methanol + chloroform		50	180		8			"	"
	"		50	180	bent specimen	8			"	"
	with 10% dichloroethane		90	180		8			"	"
	"		90	180	bent specimen	8			"	"
	"		130	180		8			"	"
	"		130	180	bent specimen	5			questionable	"
	up to concentrated		141			8			exp. temp. is max. recom.	Atochem Kynar
	gas		150	7		7	<1	>90	no visual change	Atochem Foraflon
Hydrocyanic Acid			25	7		7	<1	>90	"	"
	aqueous solution		135			8			exp. temp. is max. recom.	Atochem Kynar
Hydrofluoric Acid	in water	<=40	121			8			"	"
		40	100	7		7	<1	>90	no visual change	Atochem Foraflon
		70	75	7		7	<1	>90	"	"
	in water	41-100	93			8			exp. temp. is max. recom.	Atochem Kynar
			50	7		7	<1	>90	no visual change	Atochem Foraflon
Hydrofluosilicic Acid			100	7		7	<1	>90	"	"
Hydrogen			141			8			exp. temp. is max. recom.	Atochem Kynar
			150	7		7	<1	>90	no visual change	Atochem Foraflon
Hydrogen Chloride			141			8			exp. temp. is max. recom.	Atochem Kynar
Hydrogen Cyanide			135			8			"	"
Hydrogen Fluoride			93			8			"	"
Hydrogen Peroxide	in water	<=30	93			8			"	"
		50	100	7		7	<1	>90	no visual change	Atochem Foraflon
	in water	90	21			8			exp. temp. is max. recom.	Atochem Kynar
Hydrogen Sulfide			100	7		7	<1	>90	no visual change	Atochem Foraflon
	aqueous solution		107			8			exp. temp. is max. recom.	Atochem Kynar
			135			8			"	"
Hydroquinone			121			8			"	"
Hypochlorous Acid	aqueous solution		21			8			"	"
Iodine	in non-aqueous solvent	10	66			8			"	"
	gas		66			8			"	"
	dry		75	7		7	<1	>90	no visual change	Atochem Foraflon
	moist		75	7		7	<1	>90	"	"
Iodoform			75	7		7	<1	>90	"	"
			93			8			exp. temp. is max. recom.	Atochem Kynar
Isoamyl Ether			121			8			"	"
Isobutyl Alcohol			121			8			"	"
Isooctane			121			8			"	"
Isophorone			79			8			"	"
Isopropyl Alcohol			60			8			"	"
Isopropyl Benzene			38			8			"	"
Isopropyl Chloride			38			8			"	"

Abrasion Resistance - Wear rate or abrasion rate is an important property of materials during motion in contact with other materials. Abrasion or wear resistance is measured by a number of methods such as ASTM D3389, also known as the *Taber Test.*

Abused Particles - Particles of fine powder (dispersion or emulsion polymerized) polytetrafluoroethylene subjected to shear resulting in fibrillation during handling and transportation prior to paste extrusion.

Adhesion Promoter - A coating applied to a substrate prior to adhesive application, in order to improve adhesion of the material, such as plastic**.** Also called a *primer.*

Adhesive - A material, usually polymeric, capable of forming permanent or temporary surface bonds with another material as-is or after processing such as curing. Used for bonding and joining. Some of the classes of adhesives include hot-melt, pressure-sensitive, contact, UV cured, emulsion, etc.

Adhesive Bonding - A method of joining two plastics or other materials in which an adhesive is applied to the parts' surfaces. Bonding occurs through mechanical or chemical interfacial forces between the adhesive and adherend and/or by molecular interlocking. Surface preparation of the adherends and curing of the adhesive may be required.

Adhesive Bond Strength - The strength of a bond formed by joining two materials using an adhesive. Bond strength can be measured by a technique such as extensiometry. See also ***Adhesive Bonding.***

Adhesive Failure - Failure of an adhesive bond at the adhesive-adherend interface. An example is an adhesive failure that leaves adhesive all on one adherend, with none on the other. Adhesive failure is less desirable than cohesive failure because it is indicative of a joint with lower adhesive strength. See also ***Cohesive Failure.***

Adhesive Joining - See ***Adhesive Bonding.***

Adhesiveless Joining - Joining or welding of two materials without the use of an adhesive. See also ***Welding by Distance*** and ***Welding by Pressure.***

Agglomerates - Polytetrafluoroethylene fine powder particles (dispersion polymerized) are small (<0.25 μm) and form loosely associated clusters that are called *agglomerates*.

Amorphous Phase - See ***Amorphous Polymer*** and ***Semicrystalline Plastic.***

Amorphous Polymer - Amorphous polymers are polymers having noncrystalline or amorphous supramolecular structure or morphology. Amorphous polymers may have some molecular order but usually are substantially less ordered than crystalline polymers and, subsequently, have inferior mechanical properties.

Attrition Bar - A bar parallel to the rotation axis of a v-shaped blender which can be operated at different speeds. Various attrition bar designs are available which subject the powder being mixed to different shear rates. Also see ***V-Shaped Blender.***

Autopolymerization - Spontaneous polymerization of a monomer in the absence of an added initiator that usually occurs in monomer storage tanks and transport lines. Inhibitors can be added to prevent autopolymerization. For example, tetrafluoroethylene autopolymerization can be prevented by the addition of *a*-pinene or Terpene B.

Bar - A metric unit of measurement of pressure equal to 1.0×10^6 dynes/cm^2 or 1.0×10^5 pascals. It has a dimension of a unit of force per unit of area. Used to denote the pressure of gases, vapors, and liquids.

Barrier Material - Materials such as plastic films, sheeting, wood laminates, particle board, paper, fabrics, etc., with low permeability to gases and vapors. Used in construction as water vapor insulation, food packaging, protective clothing, etc.

Bearing Pad - Slide bearings used in support systems for bridges and some buildings to accommodate thermal and seismic movement without damage to the structures they support. An example of a design is one in which a steel plate rides against a filled PTFE sheet surface, which allows one end of the bridge to move.

Biaxial Orientation - Orientation in which the material is drawn in two directions, usually perpendicular to one another. Commonly used in films and sheets. See also ***Orientation.***

Billet - Refers to a solid or hollow cylindrical object usually made from polytetrafluoroethylene and occasionally made from other fluoropolymers.

Bleaching - A process to obtain white polytetrafluoroethylene yarn, accomplished by heating the yarn in an oven at 300°C for a period of five days.

Blender - This is the name of the family of equipment used for blending combinations of solid and liquid ingredients. A specific variety is V-cone blenders which are common in producing mixtures of polytetrafluoroethylene fine powder, lubricant, and pigment. Some blenders have a simple cylindrical shape where blending is achieved by tumbling or rolling.

Braiding - The name of the process in which fluoropolymer tubes, wires, and cables are reinforced. Strands of metal and plastic and other thin wire shape materials are formed into braids and wrapped around the fluoropolymer tube or wire to improve pressure rating, and wear and puncture resistance.

Breaking Elongation - See ***Elongation.***

Burst Strength - The pressure at which a tube fails mechanically (i.e., breaks open) is called *burst strength.*

Bursting Strength - Bursting strength of a material, such as plastic film, is the minimum force per unit area or pressure required to produce rupture. The pressure is applied with a ram or a diaphragm at a controlled rate to a specified area of the material held rigidly and initially flat but free to bulge under the increasing pressure.

C8 - An alternative name for perfluoroammonium octanoate.

Calendar - This is the equipment by which a lower thickness is obtained from a thicker bead. The equipment consists of twin rolls with an adjustable gap. The thicker sheet is fed into the calendar opening where it is “squeezed” by the force of the rolls into a thinner sheet or other forms.

Carbon Black - A black colloidal carbon filler made by the partial combustion and/or thermal cracking of natural gas, oil, or another hydrocarbon. Depending upon the starting material and the method of manufacture, carbon black can be called acetylene black, channel black, furnace black, etc. For example, channel black is made by impinging gas flames against steel plates or channel irons, from which the deposit is scraped at intervals. The properties and the uses of each carbon black type can also vary. Thus, furnace black comes in high abrasion, fast extrusion, high modulus, general purpose, and semireinforcing grades, among others. Carbon black is widely used as a filler and pigment in PVC, phenolic resins, and polyolefins. It increases the resistance to UV light and electrical conductivity, and sometimes acts as a crosslinking agent. Also called *colloidal carbon.*

Carbon Disulfide - $S{=}C{=}S$

Carbon Fiber - Carbon fibers are high-performance reinforcement consisting essentially of carbon. They are made by a variety of methods including pyrolysis of cellulosic (e.g., rayon) and acrylic fibers, burning-off binder from a pitch precursor, and growing single crystals (whiskers) via thermal cracking of hydrocarbon gas. The properties of carbon fibers depend on the morphology of carbon in them and are at their highest levels for crystalline carbon (graphite). These properties include high modulus and tensile strength, high thermal stability, electrical conductivity, chemical resistance, wear resistance, and relatively low weight. They are used as continuous or short fibers and in mats in autoclave and die molding, filament winding, injection molding, and pultrusion. Carbon fibers are used at loading levels of 20–60 vol% or more in both thermosets and thermoplastics such as epoxy resins and ABS. Carbon fibers are often used in combination with other fibers such as glass fibers to make hybrid composites. The end products containing carbon fibers include wheel chairs, tennis racquets, auto parts, machine tools, and support structures in electronic equipment. Also called *graphite fiber.*

Carbon Filler - Carbon fillers are a family of fillers based on carbon in various forms, such as carbon black and graphite. It is used as a black pigment, to improve lubricity, and to increase electrical conductivity of plastics. Also called *powdered carbon, carbon powder.*

Carbon Powder - See ***Carbon Filler.***

Cast Film - Film produced by pouring or spreading resin dispersion, resin solution, or melt over a suitable temporary substrate, followed by curing via solvent evaporation or melt cooling, and removing the cured film from the substrate.

Casting - Method to produce a cast film. See also ***Cast Film.***

Charge-to-Charge Weld - This is the mechanism by which a continuous rod or tube is formed in ram extrusion of polytetrafluoroethylene. Under heat and pressure, the polymer melts and is welded to the previous charge.

Chemical Resistance - Degradation of a material caused by chemical reaction.

Chlorotrifluoroethylene (CTFE) - $CF_2{=}CFCl$

Coagulated Dispersion Powder - An alternative name for fine powder polytetrafluoroethylene. See also ***Fine Powder PTFE.***

Coagulation - This is a process for separation of PTFE (polytetrafluoroethylene) solids from its dispersion. The emulsion or dispersion containing this polymer (dispersion polymerization) has to be broken (destabilized) in order to cause precipitation of PTFE particles. Dilution to reduce solids concentration below 20%, addition of water-soluble organic compounds, and addition of soluble inorganic salts are the common techniques used to break PTFE emulsions.

Coalescence - Refers to the mechanism for melting and consolidating polytetrafluoroethylene parts. After the polymer melts, adjacent particles begin to combine (i.e., coalesce) under the driving force of surface tension.

Co-coagulation - This is a process in which other species are added to polytetrafluoroethylene dispersion, followed by coagulation. See also ***DU Bearing Process*** and ***Coagulation.***

Coefficient of Linear Thermal Expansion (CLTE) - The change in unit of length or volume that occurs due to a unit change in temperature. The expansion and contraction of a material with changes in temperature depend on its coefficient of linear thermal expansion, and movement of a part that is attached to another part with a lower CLTE value may be restricted.

Cohesive Failure - Failure of an adhesive bond that occurs within the adhesive leaving adhesive present on both adherends. Optimum failure is 100% cohesive failure when both shear areas are completely covered. See also ***Adhesive Failure.***

Cold Flow - See ***Creep.***

Compressive Strain - The relative length deformation exhibited by a specimen subjected to a compressive force. See also ***Strain, Flexural Strain, Tensile Strain.***

Conduction - In heat transfer, migration of energy due to a temperature gradient. Heat energy is transferred by the movement of molecules at hotter or colder temperatures, with different degrees of thermal motion, into colder or hotter regions, respectively.

Contact Adhesive - An adhesive that will adhere to itself on contact. When applied to both adherends, it forms a bond after drying, without sustained pressure on the adherends. Composed of neoprene or, less commonly, nitrile elastomers. See also ***Pressure-Sensitive Adhesive.***

Convection - The mass movement of particles arising from the movement of a streaming fluid due to difference in a physical property such as density, temperature, etc. Mass movement due to a temperature difference results in heat transfer, as in the upward movement of a warm air current.

Copolymer - See ***Copolymerization.***

Copolymerization - A polymerization where more than one monomer takes part in the reaction and form the polymer chain.

Corrosion - It refers to chemical reaction of metal surfaces with oxygen, acids, and bases. The properties of corrosion products are vastly different from those of metals, thus causing difficulties for the operation of the equipment.

Cracking - Appearance of external and/or internal cracks in the material as a result of stress that exceeds the strength of the material. The stress can be external and/or internal and can be caused by a variety of adverse conditions: structural defects, impact, aging, corrosion, etc., or a combination thereof. Also called *resistance to cracking, grazing, cracking resistance.*

Creep - Nonrecoverable deformation in a part subjected to a continuous load. Creep is dependent on temperature, and the duration and amount of the load.

Critical Cracking Thickness - The maximum thickness which can be coated in a single layer (pass) of polytetrafluoroethylene dispersion without crack formation. This thickness is measured after sintering has been completed.

Critical Shear Rate - Fluoropolymers, and generally thermoplastic materials, must be processed below the velocity at which *melt fracture* occurs, referred to as the *critical shear rate*. Melt fracture in molten plastics takes place when the velocity of the resin in flow exceeds the critical velocity, the point where the melt strength of the polymer is surpassed by internal stresses. Critical velocity of most fluoropolymers is usually much lower than most thermoplastics.

Crosslinking - Reaction or formation of covalent bonds between chain-like polymer molecules or between polymer molecules and low-molecular compounds such as carbon black fillers. As a result of crosslinking, polymers such as thermosetting resins may become hard and infusible. Crosslinking is induced by heat, UV or electron-beam radiation, oxidation, etc. Crosslinking can be achieved either between polymer molecules alone as in unsaturated polyesters or with the help of multifunctional crosslinking agents such as diamines that react with functional side groups of the polymers. Crosslinking can be catalyzed by the presence of transition metal complexes, thiols, and other compounds.

Crystalline Form - See ***Crystalline Phase.***

Crystalline Melting Point - The temperature of melting of the crystalline phase of a crystalline polymer. It is higher than the temperature of melting of the surrounding amorphous phase.

Crystalline Phase - This is an organized structural arrangement for polymer molecules. In this arrangement, polymer chains are aligned into a closely-packed ordered state called *crystalline phase*.

Crystalline Plastic - See ***Semicrystalline Plastic.***

Crystallization Temperature - Temperature (or range of temperatures) at which polytetrafluoroethylene crystallizes. PTFE chains which were randomly distributed in the molten or gel state become aligned into a close-packed ordered arrangement during the crystallization process.

Crystallinity - Crystalline content of a polymer expressed in weight percent. See also ***Crystalline Phase.***

CTFE See ***Chlorotrifluoroethylene.***

Deflagration - A violent reaction whereby tetrafluoroethylene is degraded into carbon and tetrafluoromethane.

Deflection Temperature Under Load - See ***Heat Deflection Temperature.***

Deformation Under Load - See ***Creep.***

Degradation - Loss or undesirable change in plastic properties as a result of aging, chemical reactions, wear, use, exposure, etc. The properties include color, size, strength, etc.

Dehalogenation - Loss of a halogen atom (such as fluorine and chlorine) from a molecule is called dehalogenation. For example, alkaline metals like sodium can abstract fluorine atoms from fluoropolymers upon contact.

Dehydrochlorination - See ***Dehydrohalogenation.***

Dehydrohalogenation - Removal of a hydrohalogen such as hydrogen chloride or hydrogen fluoride from a molecule is called dehydrohalogenation. This reaction usually takes place at elevated temperatures or by assistance from a catalyst.

Denier - Unit of yarn/fiber size described as the weight (in grams) of a length of 9,000 yards. See also ***Tex.***

Density - The mass of any substance (gas, liquid, or solid) per unit volume at specified temperature and pressure. The density is called *absolute* when measured under standard conditions, e.g., 760 mm Hg pressure and 0°C temperature. Note: for plastics, it is the weight in air per volume of the impermeable portion of the material measured at 23°C according to ASTM D792. Also called *mass density, absolute gravity, absolute density.*

Die Cone Angle - The angle that the wall of the convergent section of the die forms with the axis of the paste extruder barrel (parallel to extrusion direction).

Die Land - The part of the die (orifice) that is downstream from the convergent section where both cross-sectional area and shape are constant.

Dielectric Breakdown Strength or Voltage - The voltage (minimum) required to breakdown through the thickness of a dielectric (insulation material), i.e., create a puncture. ASTM D149 is used to measure dielectric breakdown strength of plastic insulation material.

Dielectric Constant - The dielectric constant of an insulating material is the ratio of the capacitance of a capacitor insulated with that material to the capacitance of the same capacitor insulated with a vacuum.

Dielectric Dissipation Factor - The ratio of the power dissipated in a dielectric to the product of the effective voltage and the current; or the cotangent of the dielectric phase angle; or the tangent of dielectric loss angle. Note: measured according to ASTM D150 for plastics. Also called *tan delta, permittivity loss factor, dissipation factor, dielectric loss tangent.*

Dielectric Loss Tangent - See ***Dielectric Dissipation Factor.***

Differential Scanning Calorimetry - DSC is a technique in which the energy absorbed or produced is measured by monitoring the difference in energy input into the substance and a reference material as a function of temperature. Absorption of energy produces an endotherm; production of energy results in an exotherm. May be applied to processes involving an energy change, such as melting, crystallization, resin curing, and loss of solvents, or to processes involving a change in heat capacity, such as the glass transition.

Dip Coating - This method is the most popular way to coat cloth and fibers with polytetrafluoroethylene dispersion. Typically, the substrate is dipped in the dispersion and excess dispersion is removed by a device such as a doctor blade. The wet coated substrate is then further processed. Viscosity of the dispersion determines the initial thickness of the wet coating immediately after removal from the dip tank.

Direct Contact Hot Tool Welding - A form of heated tool welding in which the thermoplastic parts are pressed directly against the hot tool or plate. Part surfaces are heated until the melting or glass transition is reached. The hot tool is then removed, and the parts are pressed together until cooled. The hot tool can be coated with polytetrafluoroethylene to reduce melt sticking. See also ***Heated Tool Welding, Hot Tool Welding.***

Dispersing Agent - See ***Surfactant.***

Dispersion - A dispersion is often defined as a uniform mixture of solids particles and a liquid. It may contain other agents such as a surfactant and a resin soluble in the liquid (solvent). An example of a dispersion is a house paint. A feature of most dispersions is stability which means little or no settling of the solid particles.

Dispersion Polymerization - This technique is a heterogenous regime where a significant amount of surfactant is added to the polymerization medium. Characteristics of the process include small uniform polymer particles which may be unstable and coagulate if they are not stabilized.

Hydrocarbon oil is added to the dispersion polymerization reactor to stabilize the polytetrafluoroethylene emulsion. Temperature and agitation control are easier in this mode than suspension polymerization. Polytetrafluoroethylene fine powder and dispersion are produced by this technique.

Dissipation Factor - See ***Dielectric Dissipation Factor.***

Dope - Any thick liquid or pasty preparation used for further processing such as coating or fiber spinning. A polytetrafluoroethylene (PTFE) dope prepared by the addition of viscose, to PTFE dispersion, is spun to manufacture yarn.

Dry Bag Isostatic Molding - A method producing parts from PTFE powder. The powder is compressed between a hard mandrel and an elastic bag in which the pressure is supplied by a fluid inside the annular space formed between an outer shell and the elastic bag. See also ***Wet Bag Isostatic Molding.***

DSC - See ***Differential Scanning Calorimetry.***

Dual Laminate - FRP (fiberglass reinforced polyester) piping lined with fluoropolymer is manufactured by forming FRP over a fluoropolymer tube. The resulting structure is called a *dual laminate.*

DU Bearing Process - A process which was originally developed by Glacier Company (US Patent 2,689,380) in which fillers are added to polytetrafluoroethylene (PTFE) dispersion and the mixture is co-coagulated. An aluminum salt is added to the mixture to convert the surfactant in the dispersion to insoluble species and coagulate the mixture. The viscosity of the resulting paste (or mush) is adjusted by the addition of an organic solvent such as a toluene. This paste is calendared onto the surface of a steel-backed porous bronze strip. After sintering, the steel strip is rolled into bearing such that the filled PTFE would form its inside surface.

Durometer Hardness - Indentation hardness of a material as determined by either the depth of an indentation made with an indentor under specified load or the indentor load required to produce a specified indentation depth. The tool used to measure indentation hardness of polymeric materials is called a *durometer,* e.g., Shore-type durometer.

Dyne - Solutions made from a mixture of two chemicals that produce liquids with surface tension in the range of 30–70 dynes/cm used to estimate surface energy of plastics treated to enhance adhesion bond strength. The test consists of placing droplets of the various "dyne" liquids on the treated surface and observing the spreading of the drops in two seconds. Successive liquids with different surface tensions allow narrowing of the surface tension range of the web.

Dynodes - A name for glass rings positioned as insulation between metal rings that make up the vacuum cylinder in electron beam irradiation equipment.

ECTFE - See ***Ethylene Chlorotrifluoroethylene Copolymer.***

EHMW-FEP - Abbreviation for extra high molecular weight fluorinated ethylene propylene copolymer. See also ***Fluorinated Ethylene Propylene Copolymer (FEP).***

Elasticity - Property whereby a solid material changes its shape and size under action of opposing forces, but recovers its original configuration when the forces are removed.

Elongation - The increase in gauge length of a specimen in tension, measured at or after the fracture, depending on the viscoelastic properties of the material. Note: elongation is usually expressed as a percentage of the original gauge length. Also called *ultimate elongation, tensile negation, breaking elongation.*

Elongation at Break - The increase in distance between two gauge marks, resulting from stressing the specimen in tension, at the exact point of break. Measurement taken at the exact point of break according to ASTM D638.

Emulsion - See ***Dispersion.***

Emulsion Polymerization - See ***Dispersion Polymerization.***

Encapsulation - This term means to enclose as in a capsule. Polytetrafluoroethylene (PTFE) can be used to encapsulate metal articles to impart chemical resistance to them. Examples include encapsulated metal gaskets and butterfly valve gates. The metal provides mechanical strength and resistance to creep.

End Groups - The functional groups appear at the ends of polymer chains and, in effect, “end” the chain growth.

Environmental Stress Cracking - Cracking or crazing that occurs in a thermoplastic material subjected to stress or strain in the presence of particular chemicals or weather conditions or as a result of aging. Also called *ESC.*

Epoxides - Organic compounds containing three-membered cyclic group(s) in which two carbon atoms are linked with an oxygen atom as in an ether. This group is called an epoxy group and is quite reactive, allowing the use of epoxides as intermediates in preparation of certain fluorocarbons and cellulose derivatives and as monomers in preparation of epoxy resins.

Epoxy - See ***Epoxy Resin.***

Epoxy Resin - Epoxy resins are a family of thermoset polyethers containing crosslinkable glycidyl groups. The largest group of epoxy resins is prepared by polymerization of bisphenol A and epichlorohydrin. These resins have a wide viscosity range, depending on their molecular weight, and are cured at room or elevated temperatures with catalyzed polyamines and/or anhydrides. Aliphatic and cycloaliphatic epoxy resins are produced by peroxidation of olefins with peracetic acid or epoxidation of polyols with epichlorohydrin. Novolak epoxy resins are prepared by reacting novolak phenolic resins with epichlorohydrin. Vinyl ester or acrylic epoxy resins are prepared by treating epoxy resins with unsaturated carboxylic acids such as acrylic acid. There are other specialty types of epoxy resins such as halogenated epoxy and phenoxy resins. Bisphenol A epoxy resins exhibit excellent adhesion and very low shrinkage during curing. Additionally, cured novolak and cycloaliphatic resins have good UV stability and dielectric properties, while cured vinyl ester resins show high strength and chemical resistance and brominated epoxy resins show fire-retardant properties. Some epoxy resins have poor oxidative stability. Processed by injection, compression, transfer, and structural foam molding, casting, coating, and lamination. Widely used as protective coatings, adhesives, potting compounds, and binders in laminates, flooring, civil engineering, electrical, and electronic products. Also called e*poxy, EP, bisphenol A, epoxy resin.*

Etching - In adhesive and solvent bonding, a process used to prepare plastic surfaces for bonding. Exposure of the plastic parts to a reactive chemical, such as chromic acid, or to an electrical discharge results in oxidation of the surface and an increase in surface roughness by removal of surface material.

ETFE - See ***Ethylene Tetrafluoroethylene Copolymer.***

Ethane - An alkane (saturated aliphatic hydrocarbon) with two carbon atoms, CH_3CH_3. A colorless, odorless, flammable gas. Relatively inactive chemically. Obtained from natural gas. Used in petrochemical synthesis and as fuel.

Ethylene - An alkene (unsaturated aliphatic hydrocarbon) with two carbon atoms, $CH_2{=}CH_2$. A colorless, highly flammable gas with a sweet odor. Autoignition point: 543°C. Derived by thermal cracking of hydrocarbon gases or from gas synthesis. Used as monomer in polymer synthesis, refrigerants, and anesthetics. Also called *ethene*.

Ethylene Chlorotrifluoroethylene Copolymer - Thermoplastic comprised of an alternating copolymer of ethylene and chlorotrifluoroethylene. It has good impact resistance and good abrasion resistance, chemical resistance, weatherability, and electrical properties. It can be molded, extruded, and powder-coated with uses in tubing, cable and wire insulation, valves, pump parts, wraps, and tower packing and chemical equipment applications.

Ethylene Polymers - Ethylene polymers include ethylene homopolymers and copolymers with other unsaturated monomers, most importantly olefins such as propylene and polar substances such as vinyl acetate. The properties and uses of ethylene polymers depend on the molecular structure and weight.

Ethylene Tetrafluoroethylene Copolymer - Thermoplastic comprised of an alternating copolymer of ethylene and tetrafluoroethylene. Has high impact resistance and good abrasion resistance, chemical resistance, weatherability, and electrical properties approaching those of fully fluorinated polymers. Retains mechanical properties from cryogenic temperatures to 356°F. Can be molded, extruded, and powder-coated. Used in tubing, cable and wire products, valves, pump parts, wraps, and tower packing in aerospace and chemical equipment applications. Also called *ETFE.*

Extrusion - Process for converting an ingot or billet into lengths of uniform cross section by forcing material to flow plastically through a die orifice; a product form produced by this process. Many variations of this process are used widely in working metals and processing plastics.

Fatigue - Process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations, according to ASTM E1150. See also ***Flexural Fatigue, Tensile Fatigue.***

Fatigue Life - Number of loading-unloading cycles of a specified type of material that can endure before failing in a fatigue test.

Fatigue Strength - The limiting value of the median fatigue strength as the number of loading cycles sustained before failure becomes very large. Fatigue strength, here, is the maximum stress that can be sustained without failure at this number of loading cycles.

FEP - See ***Fluorinated Ethylene Propylene Copolymer.***

Fibrillation - This phenomenon occurs when polytetrafluoroethylene fine powder particles are subjected to shear usually at above its transition point (19°C). For example, when fine powder particles rub against each other, groups of polymer chains are pulled out of crystallites. These fibrils can connect polymer particles together. They have a width of less than 50 nm.

Filament - A filament is a small individual strand that is melt-extruded during fiber spinning. Bundles of filaments are called fiber or yarn.

Film - A product, e.g., plastic, that is extremely thin compared to its width and length. There are supported and unsupported films such as coatings and packagings, respectively.

Fine Cut PTFE - Particles of suspension polymerized polytetrafluoroethylene (PTFE) which has undergone size reduction (usually by cutting) to less than 50 µm average size.

Fine Powder PTFE - Polytetrafluoroethylene (PTFE) polymerized by dispersion polymerization method.

Finishes - Highly formulated dispersions of polytetrafluoroethylene containing a variety of fillers such as pigments, resins, extenders, and others. Finishes are used to coat different surfaces such as cookware, houseware, and industrial equipment.

Fishtail Guide - A guide used in calendaring polytetrafluoroethylene (fine powder) bead into tape. It allows safe feeding of the bead into the nip point of calendar rolls. It is called *fish tail* guide because of the similarity of its shape to the tail of a fish.

Flame Retardant - A substance that reduces the flammability of materials such as plastics or textiles in which it is incorporated. There are inorganic flame retardants such as antimony trioxide (Sb_2O_3) and organic flame retardants such as brominated polyols. The mechanisms of flame retardation vary depending on the nature of material and flame retardant. For example, some flame retardants yield a substantial volume of coke on burning, which prevents oxygen from reaching inside the material and blocks further combustion. Also called *fireproofing agent.*

Flash - In welding thermoplastics, molten plastic that seeps out of the joint area during the welding process. In molding, surplus plastic attached to the molding along the parting line. Flash must usually be removed before parts are considered to be finished.

Flex Life - Flex fatigue life is the total number of cycles that a specimen can be "flexed" in a prescribed manner before failure occurs. Failure is defined as physical breakdown of the specimen material. A number of methods such as MIT, Ross and De Mattia are used to measure flex life. See also ***Fatigue Life.***

Flexural Fatigue - Progressive localized permanent structural change occurring in a material subjected to cyclic flexural stress that may culminate in cracks or complete fracture after a sufficient number of cycles.

Flexural Fatigue Strength - Maximum stress that can be sustained for a specified number of bending cycles without failure.

Flexural Modulus of Elasticity - The ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.

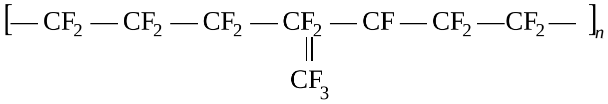
Flexural Properties - Properties describing the reaction of physical systems to flexural stress and strain.

Flexural Strain - The tensile elongation on the surface of a cross section opposite to that experiencing a locally impinging force in bending at any time of the test. See also ***Strain, Compressive Strain, Tensile Strain.***

Flexural Strength - The maximum stress in the extreme fiber of a specimen loaded to failure in bending. Note: Flexural strength is calculated as a function of load, support span, and specimen geometry. Also called *modulus of rupture, bending strength.*

Flexural Stress - The maximum fiber stress in a specimen at a given strain in a bending test. The maximum fiber stress is a function of load, support span, and specimen width and depth. It depends on the method of load application relative to the supports and on the specimen geometry. It has to be calculated. Note: Flexural stress is calculated as a function of load at a given strain or at failure, support span, and specimen geometry.

Fluorinated Ethylene Propylene Copolymer - A random copolymer of tetrafluoroethylene and hexafluoropropylene:



$$\left[-CF_2-CF_2-CF_2-\underset{\underset{CF_3}{\|}}{CF_2}-CF-CF_2-CF_2-\right]_n$$

Fluorinated Ethylene Propylene Terpolymer - Refers to FEP containing a third fluorinated monomer. See also ***Fluorinated Ethylene Propylene Copolymer.***

Fluoroalkenes - Unsaturated linear perfluorinated hydrocarbons containing at least one double bond are called fluoroalkenes.

Fluorohydrocarbon Resin - See ***Fluoropolymer.***

Fluoromethanes - These are methane compounds in which one or more hydrogen has been replaced by fluorine, e.g., CH_2F_2.

Fluoroplastic - See ***Fluoropolymer.***

Fluoroplastic Homopolymer - A fluoropolymer entirely compiled of one monomer is called fluoroplastic homopolymer. Examples include polytetrafluoroethylene, polyvinylidene fluoride, and polyvinyl fluoride.

Fluoropolymer - Thermoplastics (mostly polyolefins) in which all or some of the hydrogen atoms are replaced by fluorine. Characterized by excellent chemical resistance, antifriction properties, thermal stability, anti-adhesive properties, low flammability, and weatherability. The disadvantages include low creep resistance and strength, and difficulty of processing. The properties of fluoropolymers depend on fluorine content. The processing is achieved by extrusion and molding. The uses are chemical apparatus, bearings, films, coatings, and containers. A polymer containing fluorine in its monomer is called fluoropolymer. Also called *polyfluorohydrocarbon, polyfluorocarbon, fluoroplastic, fluorohydrocarbon resin, fluorocarbon resin.*

Free Flow PTFE - Suspension polymerized PTFE (polytetrafluoroethylene) particles first undergo size reduction followed by granulation and drying which result in a free flowing powder. Free flow PTFE has a similar consistency to sugar contrasted with fine cut PTFE which resembles flour.

Free Radicals - An atom or group of atoms with an odd or unpaired electron. Free radicals are highly reactive and participate in free radical chain reactions such as combustion and polymer oxidation reactions. Scission of a covalent bond by thermal degradation or radiation in air can produce a molecular fragment named a free radical. Most free radicals are highly reactive because of their unpaired electrons, and have short half lives.

$$R - R' \rightarrow R\cdot + R'$$

Frenkel Model - A model developed by Russian scientist Frenkel to describe coalescence/sintering of particles of metals and plastics. See the following references for more information: Mascia, L., Thermoplastics, *Materials Eng.*, 2nd ed., Elsevier Applied Science, New York (1989) and Lontz,J. F., in: *Fundamental Phenomena in the Material Sciences*, Vol. 1 (L. J. Borris and H. H. Hansner, eds.), p. 37, Plenum Press, New York (1964).

FTIR - Fourier transform infrared spectroscopy (FTIR), is a spectroscopic technique in which a sample is irradiated with electromagnetic energy from the infrared region of the electromagnetic spectrum (wavelength ~0.7 to 500 mm). The sample is irradiated with all infrared wavelengths simultaneously, and mathematical manipulation of the Fourier transform is used to produce the absorption spectrum or “fingerprint” of the material. Molecular absorptions in the infrared region are due to rotational and vibrational motion in molecular bonds, such as stretching and bending. FTIR is commonly used for the identification of plastics, additives, and coatings.

Gamma Radiation - Ionizing radiation propagated by high-energy protons, e.g., emitted by a nucleus in transition between two energy levels.

Gamma Ray Irradiation - A technique for reducing the molecular weight of polytetrafluoroethylene by exposing this polymer to gamma rays from a source such as ^{60}Co.

Generator - An electronic device that converts standard 120/240 volt, 50/60 Hz line voltage into high-frequency electrical energy.

Glass Fiber - Glass fibers are a large family of short (staple, chopped, milled) or continuous fiber reinforcement, used widely in both thermosets and thermoplastics for increased strength, dimensional stability, thermal stability, corrosion resistance, and dielectric properties. The fibers are made by the melt-drawing of various grades (electric, chemical, high tensile strength) of glass and are comprised of strands of filaments (roving) that can be further processed by size reduction, twisting, or weaving into fabrics or mats. Used in molding compounds, sprayup processes, die molding, layup, and other lamination processes. Glass fibers are often surface-modified, e.g., with coupling agents, to improve bonding with polymer matrix or to impart special properties such as electrical conductivity (by coating with nickel). Also called *glass roving.*

Glass Filler - Glass fillers are a widely used family of fillers in the form of beads, hollow spheres, flakes, or milled particles. They increase dimensional stability, chemical resistance, moisture resistance, and thermal stability of plastics.

Glass Roving - See ***Glass Fiber.***

Granular Polytetrafluoroethylene (PTFE) - This name is used to refer to the products of suspension polymerization of tetrafluoroethylene.

Granular PTFE - See ***Granular Polytetrafluoroethylene.***

Graphite Fiber - See ***Carbon Fiber.***

Graphite Filler - A crystalline form of carbon in powder form. Graphite occurs naturally and also is produced by heating petroleum coke, carbon black, and organic materials. Used as a lubricating filler for nylons and fluoropolymers. Also called *powdered graphite, plumbago, graphite powder, carbon graphite, black lead.*

Graphite Powder - See ***Graphite Filler.***

Gravure Coating - A coating technique using engraved rolls capable of picking up a precise amount of coating (dispersion) from a trough and transferring it to a web that is in contact with the roll. The engravings on the surface act as small reservoirs for the dispersion.

Halogenated Solvents - Organic liquids containing at least one atom of a halogen (Cl, F, I, Br) are called halogenated solvents.

HDT - See ***Heat Deflection Temperature***.

Heat Affected Zone - In welding, the region of the part that is affected by heat used to melt the joining surface. Microstructure of the heat affected zone is an important determinant of the mechanical strength of the weld. Also called *HAZ.*

Heat Deflection Temperature - The temperature at which a material specimen (standard bar) is deflected by a certain degree under specified load. Also called *tensile heat distortion temperature, heat distortion temperature, HDT, deflection temperature under load.*

Heat Distortion Temperature (HDT) - See ***Heat Deflection Temperature.***

Heat Seal Temperature - Temperature of a thermoplastic film or sheet required to join two or more films or sheets in contact by fusion.

Heat Sealing - A method of joining plastic films by the simultaneous application of heat and pressure to the areas in contact. Heat can be applied using hot plate welding, dielectric heating, or radiofrequency welding.

Heat Stability - See ***Thermal Stability***.

Heat Stabilizer - Also called *thermal stabilizers* or *thermostabilizers*. Compounds that help avert and/or neutralize the factors that damage a polymer as a result of heating during its preparation, compounding, fabrication, or use. The purpose of heat stabilization is to maintain the original properties/characteristics of the product and assure its desired service life.

Heated Tool Welding - A method for joining thermoplastic parts in which a hot plate or hot tool is used to provide heat to melt the joining surfaces. The tool is then removed, and the parts are pressed together. While in the molten state, molecular diffusion across the joint interface occurs, and a homogeneous, permanent bond is formed after the parts are allowed to cool. A hot plate is used for flat surfaces and a hot tool in the shape of the joint for irregularly shaped surfaces. Also called *fusion bonding, heat sealing, hot shoe welding, butt fusion, hot plate welding.*

Hexafluoropropylene, (HFP) - $CF_3—CF=CF_2$

HFP - See ***Hexafluoropropylene.***

Hold Time - In welding, the length of time allotted for the melted plastic to solidify. In process engineering, the residence time of an individual ingredient in reaction vessel or other processing apparatus. Also called *holding time, holdup time.*

Homopolymer - A polymer that contains only a single type of monomer (i.e., propylene).

Hot Melt Adhesive - An adhesive that is applied in a molten state which forms a bond after cooling to a solid state. Acquires adhesive strength through cooling, unlike adhesives that achieve strength through solvent evaporation or chemical cure.

Hot Stamping - This is a process for obtaining a specific geometry in a polytetrafluoroethylene stock shape. Hot stamping is conducted using a stamp which is heated well above (>360°C) the polymer melt point. Pressure and time are the other variables that can be manipulated to obtain the desired pattern.

Hot Tool Welding - See ***Heated Tool Welding.***

Hourglassing - Refers to the change in the shape of a cylindrical object made of polytetrafluoroethylene during sintering. A reduction in the diameter of the cylinder near the middle and an increase in the bottom diameter creates a resemblance in the shape of the sintered part to an hourglass.

Hydrocarbon - A chemical compound that contains only hydrogen and carbon atoms.

Hydrocarbon Lubricant - A hydrocarbon liquid added to dispersion polymerized polytetrafluoroethylene powder (fine powder) to form a paste for extrusion.

Hydrofluoric Acid - HF is a highly corrosive acid**.**

Hydrophilic Surface - Surface of a hydrophilic substance that has a strong ability to bind, adsorb or absorb water; a surface that is readily wettable with water. Hydrophilic substances include carbohydrates such as starch.

Impact Strength - The energy required to break a specimen, equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact with the specimen and the energy remaining after complete fracture of the specimen. Also called *impact energy.*

Impregnation - A term applied to filling or saturation of porous material such as glass cloth and flax with polytetrafluoroethylene dispersion.

Infrared Oven - An oven equipped with infrared lamps where heat is generated by infrared rays.

Injection Molding - A molding procedure in which a heat-softened plastic material is forced from a cylinder into a cavity which gives the article the desired shape. It is used for all thermoplastics and some thermosets.

Interference Fit - A mechanical fastening method used to join two parts, such as a hub and a shaft, in which the external diameter of the shaft is larger than the internal diameter of the hub. This interference produces high stress in the material and must be determined carefully to avoid exceeding the allowable stress for the material. Stress relaxation can occur in interference fits, causing the joint to loosen over time. Also called *press fit.*

Isoparaffinic Hydrocarbon - A hydrocarbon which contains branches in its chemical structure.

Isostatic Molding - A molding method for producing parts (often with complex geometry) from polytetrafluoroethylene powder. The resin powder is compressed between a hard mandrel and an elastic bag. Pressure for compaction is supplied by a high pressure fluid. The fluid can be introduced in pressure vessel by dry bag method or by submerging the mold in a vessel containing the fluid and pressurizing the vessel (wet bag). See also ***Dry Bag Isostatic Molding*** and ***Wet Bag Isostatic Molding.***

Izod - See ***Izod Impact Energy***.

Izod Impact Energy - The energy required to break a v-notched specimen equal to the difference between the energy in the striking member of the impact apparatus at the instant of impact with the specimen and the energy remaining after complete fracture of the specimen. For metals, it is measured according to ASTM E23. Also called *notched Izod strength, notched Izod impact strength, Izod v-notch impact strength, Izod strength, Izod impact strength, Izod, IVN.*

Izod Impact Strength - See ***Izod Impact Energy.***

Izod Strength - See ***Izod Impact Energy.***

Izod V-Notch Impact Strength - See ***Izod Impact Energy.***

Joining - See ***Adhesiveless Joining*** and ***Adhesive Bonding.***

Lap Joint - A joint in which one adherend is placed partly over the other adherend; overlapped areas are bonded together.

Lap Shear Test - Test method defined in ASTM D1002.

Laser - A device used to produce an intense light beam with a narrow band width. Laser is an acronym for *light amplification by stimulated emission of radiation.*

Limiting Oxygen Index (LOI) - LOI is defined as the required minimum percentage of oxygen in a mixture with nitrogen, which would allow a flame to be sustained by an organic material such as a plastic.

Linear Polyethylenes - Linear polyethylenes are polyolefins with linear carbon chains. They are prepared by copolymerization of ethylene with small amounts of higher alpha-olefins such as 1-butene. Linear polyethylenes are stiff, tough, and have good resistance to environmental cracking and low temperatures. Processed by extrusion and molding. Used to manufacture film, bags, containers, liners, profiles, and pipe.

Linings - Inserts, usually made from plastics to protect metallic or nonmetallic substrates. Linings or liners are either inserted or formed in-place and are usually thicker than coatings fabricated from a dispersion.

Liquid Crystal Polymer (LCP) - Among the stiffest and highest strength plastics are those with substantial aromatic groups along their backbones. These polymers have high melting points, high glass transition temperatures, and usually good chemical resistance. Examples of these polymers are *polyaramids* and *liquid crystal polymers*. The polymer backbones are so stiff that the crystal structures are partially retained even in the liquid phase. The mechanical properties of solid LCPs are directional and can be quite high.

LOI - See ***Limiting Oxygen Index.***

Macroscopic Flaws - Defects such as cracks or inclusions in fluoropolymer parts which can be detected visually or by the use of a simple magnifying glass.

Mandrels - Hard parts (normally metallic) which are inserted in molds to obtain desired part geometries. For example, a solid metal mandrel is placed inside an isostatic cylindrical mold in order to obtain a polytetrafluoroethylene liner.

Mason and Pierce Equation - An equation for calculating viscosity of a suspension based on the volume fraction of solids.

$$\eta = -\frac{1}{\left[1-\left(\frac{\phi}{A}\right)^2\right]}$$

where f = volume fraction of solids, and A is a constant in the range of 0.64–0.68 for spherical solid particles. For other shapes, A is <0.64.

Matched Die Forming - A type of thermoforming process consisting of preheating the plastic sheet prior to forming and then subjecting it to simultaneous motion of the two mold halves.

Melt Creep Viscosity - A viscosity value measured for polytetrafluoroethylene using a dynamic mechanical analyzer (DMA).

Melting Point - The temperature at which the solid crystalline and liquid phases of a substance are in thermodynamic equilibrium. The melting point is usually referenced to normal pressure of 1 atm.

Melt Processible Polymer - A polymer that melts when heated to its melting point and forms a molten material with definite viscosity value at or somewhat above its melting temperature. Such a melt should be pumpable and flow when subjected to shear rate using commercial processing equipment such as extruders and molding machines.

Mica - Mica is a crystalline platy filler made by wet or dry grinding of muscovite or phlogopite, minerals consisting mainly of aluminum and potassium orthosilicates, or by chemical reaction between potassium fluorosilicate and alumina. Used as a filler in thermosetting resins to impart good dielectric properties and heat resistance, and in thermoplastics such as polyolefins to improve dimensional stability, heat resistance, and mechanical strength. Mica fillers also reduce vapor permeability and increase wear resistance. Mica fillers having increased flake size or platiness increase flexural modulus, strength, heat deflection temperature, and moisture resistance. Surface modified grades of mica are available for specialty applications.

Micron - A unit of length equal to 1×10^{-6} meter. Its symbol is Greek small letter mu (μ).

Microporosity - Defects such as small voids or inclusions in fluoropolymer parts that can be detected by a microscope or the use of a fluorescent dye.

Milled Glass Filler - Milled glass fillers are made by hammer-milling continuous glass strands. Used as anticrazing reinforcing fillers for adhesives and in plastics. Also called *milled glass fiber.*

Mineral Filler - Mineral fillers are a large subclass of inorganic fillers comprised of ground rocks or natural or refined minerals. Some fillers, so-called commodity minerals, are relatively inexpensive and are used mostly as extenders. A good example of these is ground limestone. Other fillers, so-called specialty minerals, are usually reinforcing fillers. These are inherently small particle size fillers such as talc and chemically surface-modified fillers. See also ***Organic Filler.***

Modified PTFE - See ***Modifier.***

Modifier - Generally a modifier refers to an additive which alters the properties of the host system. In the case of PTFE (polytetrafluoroethylene), a modifier is a comonomer which modifies the properties of PTFE and is present at low concentration (<1%). An example is perfluoropropyl vinyl ether.

Moisture Vapor Permeation - Refers to permeation of water vapor through films and membranes which can be measured by a number of standard methods (e.g., ASTM).

Mold Shrinkage - The difference between the dimension(s) of the mold cavity at 23°C and the dimension(s) of molded specimen. Measured for plastics after cooling the molding to room temperature according to ASTM D955.

Molecular Weight - The molecular weight (formula weight) is the sum of the atomic weights of all the atoms in a molecule (molecular formula). Also called *MW, formula weight, average molecular weight.*

Molecular Weight Distribution - The relative amounts of polymers of different molecular weights that comprise a given specimen of a polymer. It is often expressed in terms of the ratio between weight- and number-average molecular weights, M_w/M_n.

Monomer - The individual molecules from which a polymer is formed, i.e., ethylene, propylene.

Multifilament - In textiles, a fiber or yarn composed of several individual filaments, each of 75 denier or less, that are gathered into a single continuous bundle.

Multilayer Coating - A coating that is produced by multiple passes of the substrate through the coating process. After each pass, the thickness of the coating increases. Multilayer coating is a means of overcoming critical cracking thickness when relatively thick coatings are required.

Nanometer - A unit of length equal to 1×10^{9} meter. Often used to denote the wavelength of radiation, especially in UV and visible spectral region. Also called *nm.*

Newtonian Fluid - A term to describe an ideal fluid in which shear stress and shear rate is proportional (e.g., water). The proportionality coefficient is called viscosity, which is independent of shear rate, contrary to non-ideal fluids where viscosity is a function of shear rate. Paints and polymer melts are examples of non-Newtonian liquids.

Nonpolar - In molecular structure, a molecule in which positive and negative electrical charges coincide. Most hydrocarbons, such as polyolefins, are nonpolar.

Notch Effect - The effect of the presence of specimen notch or its geometry on the outcome of a test such as an impact strength test of plastics. Notching results in local stresses and accelerates failure in both static and cycling testing (mechanical, ozone cracking, etc.).

Notched Izod Impact Strength - See ***Izod Impact Energy.***

Notched Izod Strength - See ***Izod Impact Energy.***

Nylon - Nylons are thermoplastic, mostly aliphatic polyamides prepared usually either by polymerization of dicarboxylic acid with diamine, or polymerization of amino acid, or ring opening polymerization of lactam. Nylons have good resistance to solvents, bases, and oils, and to impact, abrasion, and creep. They have also high tensile strength and barrier properties, and a low coefficient of friction. The disadvantages include high moisture pickup, light degradation, and high mold shrinkage. Processing is achieved by injection, blow, and rotational molding, extrusion, and powder coating. Uses are automotive parts, electrical and electronic devices such as plugs, machine parts such as gears and pumps, housings for appliances and power tools, wire and cable jacketing, pipes, films, and fibers.

OI - See ***Orientation Index.***

Optical Properties - The effects of a material or medium on light or other electromagnetic radiation passing through it, such as absorption, reflection, etc.

Organic Compound - A chemical compound that contains one or more carbon atoms in its molecular structure.

Organic Filler - Organic fillers are made from natural or synthetic organic materials. Natural material derived organic fillers include wood and shell flours. Synthetic material derived fillers include fluoropolymer spheres and milled polymer waste. Organic fillers are characterized by relatively low cost and low density. They might increase the flammability and decrease the moisture resistance of plastics. See also ***Mineral Filler.***

Organometallic Compound - A chemical compound in which carbon is bonded to a metal. Many organometallic compounds are used as catalysts in polymerization reactions.

Orientation - A process of drawing or stretching of as-spun synthetic fibers or hot thermoplastic films to orient polymer molecules in the direction of stretching. The fibers are drawn uniaxially and the films are stretched either uniaxially or biaxially (usually longitudinally or longitudinally and transversely, respectively). Oriented fibers and films have enhanced mechanical properties. The films will shrink in the direction of stretching when reheated to the temperature of stretching.

Orientation Index (OI) - This is a factor that characterizes the orientation of polymers in polytetrafluoroethylene tubing in machine and transverse directions. Orientation index (OI) provides a numerical value to monitor the disparity of orientation:

$$\mathrm{OI} = 1 - \frac{\text{Yield strength in transverse direction}}{\text{Yield strength in machine direction}}$$

$$\mathrm{OI} = 0 \quad \text{means balanced orientation}$$

Oriented Film - See ***Orientation.***

OSHA - Occupational Safety and Health Administration.

Oxygen Sensor - A sensor in automobiles that senses the oxygen content of the exhaust gas.

Ozone - O_3.

Paraffins - Linear saturated hydrocarbons with the general chemical formula of C_nH_{2n+2}.

Parison - A parison is a tube used for blow molding, which in principle at least has a constant wall thickness at all points around its circumference and along its length. Thickness along the parison length may vary due to tensile thinning caused by the weight of the dependent parison.

Pascal - An SI unit of measurement of pressure equal to the pressure resulting from a force of one newton acting uniformly over an area of one square meter. Used to denote the pressure of gases, vapors, or liquids and the strength of solids. Abbreviated Pa.

Paste Extrusion - Process by which dispersion polymerized polytetrafluoroethylene (PTFE) is extruded with the aid of a hydrocarbon lubricant. A paste of the PTFE and hydrocarbon is made and formed into a preform in a separate step. The preform is ram-extruded through a die, dried, and sintered.

PCTFE - See ***Polychlorotrifluoroethylene.***

PEEK - See ***Polyetheretherketone.***

Peel Strength - The bond strength of a film adhered by an adhesive to a substrate is measured by different techniques and is called *peel strength.* An extensiometer can be used to measure peel strength.

Peen - Flattening or drawing by or as if by hammering with a peen.

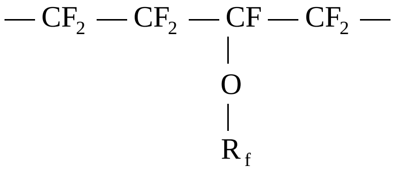
PEK - See ***Polyetherketone.***

Pendant Methyl Group - A methyl (CH_3) functional group attached to the main chain of a polymer molecule.

Perfluorinated Fluoropolymers - These are polymers consisting of only carbon and fluorine (and an occasional oxygen atom) atoms.

Perfluorinated Paraffins - Refers to a linear saturated hydrocarbon where all hydrogen atoms have been replaced with fluorine, with the general chemical formula of C_nF_{2n+2}.

Perfluoroalkoxy (PFA) Polymer - R_f is a perfluorinated alkyl group containing one or more carbon atoms, typically a maximum of four carbon atoms.



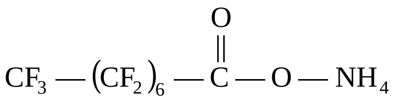
$$-CF_2-CF_2-\underset{\underset{\displaystyle R_f}{|}}{\underset{\displaystyle O}{\underset{|}{CF}}}-CF_2-$$

Perfluoroalkyl Vinyl Ether (PAVE) -

$$R_f{-}O{-}CF{=}CF_2$$

where R_f is a perfluorinated alkyl group containing one or more carbon atoms, typically a maximum of four carbon atoms.

Perfluoroammonium Octanoate - (C8).

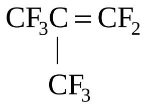


$$CF_3-(CF_2)_6-\overset{\overset{\displaystyle O}{\|}}{C}-O-NH_4$$

Perfluoroethyl Vinyl Ether - Also see ***Perfluoroalkyl Vinyl Ether.***

$$CF_3{-}CF_2{-}O{-}CF{=}CF_2$$

Perfluoroisobuthylene (PFIB) -



$$CF_3\underset{\underset{\displaystyle CF_3}{|}}{C}=CF_2$$

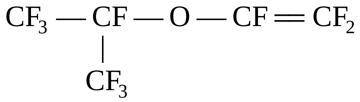
Animal studies of PFIB inhalation indicate occurrence of severe adverse including pulmonary edema as a result of exposure to high concentrations and death. Wheezing, sneezing, difficulty breathing and deep or rapid breathing are among the symptoms. Animals that survived twenty four hours after exposure recovered with no aftereffects.

Perfluoromethyl Vinyl Ether - See ***Perfluoroalkyl vinyl ether.***

$$CF_3{-}O{-}CF{=}CF_2$$

Perfluoropolymer - See ***Perfluorinated Fluoropolymer***.

Perfluoropropyl Vinyl Ether (PPVE) -



$$CF_3-\underset{\underset{\displaystyle CF_3}{|}}{CF}-O-CF=CF_2$$

Permeability - The capacity of material to allow another substance to pass through it; or the quantity of a specified gas or other substance which passes through under specified conditions.

Permittivity Loss Factor - See ***Dielectric Dissipation Factor***.

Persulfate Initiation - This is in reference to the action of persulfates such as ammonium persulfate in the free radical polymerization of tetrafluoroethylene.

PET - See ***Polyethylene Terphthalate***.

Petroleum Solvents - A solvent that is derived from processing petroleum.

PFA - See ***Perfluoroalkoxy Polymer***.

PFIB - See ***Perfluoroisobuthylene***.

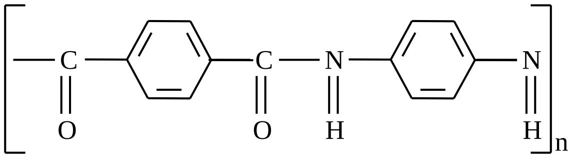
Plenum Cable - Refers to cables that are routed through the air plenums in a building. Flame resistance of perfluoropolymers such as FEP is an important consideration in plenum applications because these plastics do not increase the combustible fuel loading of the plenum.

Poisson's Ratio - This ratio is defined as the ratio of the change in the width per unit width of a material to the change in its length per unit length, as a result of strain in the length direction. At 23°C, Poisson's ratio of polytetrafluoroethylene has a value of 0.46.

Poker Chipping - Fracture of a ram extruded part such as a rod or tube at the interface of charges (weld).

Polar - In molecular structure, a molecule in which the positive and negative electrical charges are permanently separated. Polar molecules ionize in solution and impart electrical conductivity to the solution. Water, alcohol, and sulfuric acid are polar molecules; carboxyl and hydroxyl are polar functional groups.

Polyaramide - Commercial examples of these plastics include Kevlar® and Nomex®. Kevlar® has the following chemical structure:



Thermoplastics are aromatic polyamide prepared by polymerization of aromatic diamine and aromatic diacid or its derivatives (e.g., anhydride). These plastics are characterized by high heat resistance, good retention of mechanical and dielectric properties at elevated temperatures, good dielectric properties, chemical resistance, high stiffness, and low flammability. High crystallinity results in good mechanical properties such as impact strength. Resistance to light is somewhat low. Processing is difficult because of the high melting point. Processed by solution casting, molding, and extrusion. Uses include film, fibers, and molded parts requiring good surface finish. Also called *PARA, aromatic polyamide, aramid.*

Polyarylene Plastics - Examples of these plastics include polyetherketone, polyetheretherketone, polyetherketoneketone, polyphenylenesulfide, and others.

Polyarylsulfone - Polyarylsulfone is a thermoplastic containing repeating sulfone and ether groups in its wholly aromatic backbone. It has excellent resistance to high and low temperatures, good impact strength, improved resistance to environmental stress cracking, good dielectric properties, rigidity, and resistance to acids and alkalies. Polyarylsulfone is nonflammable, but is attacked by some organic solvents. Processed by injection molding, compression molding, and extrusion. Used in high temperature electrical and electronic applications such as circuit boards, lamp housings, piping, and auto parts.

Polycarbonate - Polycarbonates are thermoplastics prepared by either phosgenation of dihydric phenols such as bisphenol A or by ester exchange between diaryl carbonate, usually diphenyl carbonate, and dihydric phenol. They are characterized by the presence of repeating carbonyldioxy groups in the backbone, but classified by some as polyesters. They have very good mechanical properties, especially impact strength, low moisture absorption, and good thermal and oxidative stability. They are self-extinguishing and some grades are transparent, but they are attacked by strong acids and bases, soluble in organic solvents, and subject to stress cracking. Processed by injection and blow molding, extrusion, thermoforming, but require high processing temperatures. Used in telephone parts, dentures, business machine housings, safety equipment, nonstaining dinnerware, and food packaging. Also called *PC.*

Polychlorotrifluoroethylene (PCTFE) -

$$[—CF_2—CFCl—]_n$$

Thermoplastic prepared by radical polymerization of chlorotrifluoroethylene. It has good transparency and great barrier properties. Dielectric properties and resistance to solvents, especially chlorinated, of PCTFE are somewhat lower than those of perfluoropolymers, but tensile strength and creep resistance are higher. Processing is difficult because of high melt viscosity but is possible by extrusion, injection molding, compression molding, and coating. Uses include chemical apparatus, cryogenic seals, films, and coatings. Also, PCTFE spheres are used as fillers and PCTFE oil is used as a lubricant in various plastics.

Polyetheretherketone (PEEK) - Polyetheretherketone is a partially crystalline thermoplastic containing repeating ether and keto groups in the backbone. Its systematic name is poly(oxy-1,4-phenyleneoxy-1,4-phenylenecarbonyl-1,4-phenylene). PEEK has superb chemical resistance, toughness, rigidity, load-bearing properties, thermal stability, radiation resistance, and very low flammability. Processed readily by injection molding, spinning, cold forming, and extrusion. Used in fibers, films, automotive engine parts, aerospace composites, and wire and cable insulation.

Polyetherketone (PEK) - Thermoplastic with excellent high-temperature properties and thermal stability. Used in advanced composites, wire coating, chemical-resistant filters, integrated circuit wafer carriers, and bearings. Synthesized by polyarolyation or polyetherization.

Polyethersulfone - Polyethersulfone is a thermoplastic containing repeating sulfone and ether groups in its wholly aromatic backbone. It has excellent thermal stability in air and water, good transparency, very low flammability and smoke emission, good dimensional stability, rigidity, and toughness. It has low mold shrinkage and is a good heat-resistant dielectric. Polyethersulfone has good resistance to acids and bases but is attacked by many organic solvents, has poor weatherability, and is subject to stress cracking. Processed by injection molding, extrusion, blow molding, and compression molding, but requires high processing temperatures. Used in high temperature electrical applications such as multipin connectors, bakery oven windows, medical devices, radomes, structural aircraft components, appliance housings, and auto parts. Also called *polyether polysulfone, PESV.*

Polyethylene (PE) - A family of polyolefins consisting of linear and branched polyethylenes. Polyethylenes are thermoplastics but can be crosslinked chemically or by irradiation, and then show improved strength and dielectric properties. All linear polyethylenes, except the high density grade, are prepared by copolymerization of ethylene with higher olefins. Branched polyethylenes are prepared from ethylene alone or together with polar comonomers such as vinyl acetate. The density, melt index, crystallinity, degree of branching, molecular weight, polydispersity, and related properties of polyethylenes vary widely depending on the catalysts and methods of polymerization and on modifying comonomers and treatments. Polyethylenes have good impact resistance at low temperatures, good chemical resistance, and good moisture resistance, but high thermal expansion, poor weatherability, poor thermal stability and resistance to stress cracking. They are readily processible by all thermoplastic methods but are flammable and difficult to bond. Food grades are available. Processed by extrusion, blow and injection molding, and thermoforming. Used very broadly as films, coatings, in containers and consumer goods, electrical insulation, and piping. Also called *expandable polyethylene bead, EPE bead.*

Polyethylene Terphthalate - A family of plastics based on polymerization of an ester of diethylene glycol and terphthalic acid.

Polymer - Polymers are high molecular weight substances with molecules resembling linear, branched, crosslinked, or otherwise shaped chains consisting of repeating molecular groups. Synthetic polymers are prepared by polymerization of one or more monomers. The monomers comprise low-molecular-weight reactive substances, often containing more than one reactive molecular bond or chemical bond. Natural polymers have molecular structures similar to synthetic polymers but are not man made, occur in nature, and have various degrees of purity. Also called *synthetic resin, synthetic polymer, resin, plastic*.

Polymer Fume Fever - A condition that occurs in humans as a result of exposure to degradation products of polytetrafluoroethylene and other fluoropolymers. The symptoms of exposure resemble those of flu and are temporary. After about twenty-four hours, the flu-like symptoms disappear.

Polyolefin - Polyolefins are a large class of carbon-chain elastomeric and thermoplastic polymers usually prepared by addition (co)polymerization of olefins or alkenes such as ethylene. The most important representatives of this class are polyethylene and polypropylene. There are branched and linear polyolefins and some contain polar pendant groups or are halogenated. Unmodified polyolefins are characterized by relatively low thermal stability and a nonporous, nonpolar surface with poor adhesive properties. Processed by extrusion, injection molding, blow molding, and rotational molding. Other thermoplastic processes are used less frequently. This class of plastics is used more and has more applications than any other. Also called *olefinic resin, olefinic plastic*.

Polyphenylene Sulfide (PPS) - PPS is a high-performance engineering thermoplastic. Its linear chains consist of benzene rings para-substituted with sulfur atom links. PPS has excellent thermal stability, good resistance to solvents and chemicals except for chlorinated hydrocarbons, good radiation resistance, excellent dimensional stability, low water absorption, and good dielectric properties, but somewhat low impact strength. PPS is nonburning. Processing of PPS is hampered by its high melting point and is achieved at elevated temperatures by injection molding, compression molding, transfer molding, and extrusion. Used in hydraulic components, bearings, valves, electronic parts, small appliances such as hair dryers, and under-the-hood automotive parts. Also, PPS spheres are used as fillers in various plastics. Also called *polythiophenylene*.

Polyphenylene Sulfide Sulfone - Thermoplastic with good thermal stability, chemical resistance, and dielectric properties, and low flammability and creep. Processed by injection molding. Used in electrical components. Also called *polyphenylene sulfide sulfone*.

Polypropylene (PP) - PP is a carbon chain thermoplastic comprised of propylene homopolymer prepared by stereospecific polymerization in the presence of Ziegler Natta catalysts. The majority of PP is isostatic. PP has low density and good flexibility and resistance to chemicals, abrasion, moisture, and stress cracking, but decreased dimensional stability, mechanical strength, and resistance to UV light and heat. PP is flammable. Processed by injection molding, spinning, extrusion, and film techniques. Used as films for pressure-sensitive tapes, packaging, liners, and shrink films, and as fibers in textiles. Also called *PP homopolymer, polypropylene homopolymer, expandable polypropylene bead, EPP bead.*

Polysulfone - Polysulfones are a class of thermoplastics characterized by the presence of sulfone linkages in their repeating units. Most polysulfones are aromatic and also contain ether linkages to enhance oxidation resistance. The most important of those are polyarylsulfone and polyethersulfone. As a class, polysulfones show excellent thermal stability, low creep, good dielectric properties, transparency, self-extinguishing properties, and resistance to chemicals, but are attacked by many solvents, have poor weatherability, are subject to stress cracking, and require high processing temperatures. Processed by injection molding, compression molding, blow molding, and extrusion. Used in appliances, electronics, automotive parts, and electric insulators. A high-performance engineering thermoplastic, called polysulfone in the trade, consists of diaryl sulfone groups linked by oxygen atoms and shares many properties typical for its class. It has good rigidity at elevated temperatures, good impact strength, and resists alkalies and acids, but is attacked by polar solvents. Used for medical devices, and in food processing equipment, electronics, chemical apparatus, and battery cells. Also called *PSU, PSO.*

Polytetrafluoroethylene (PTFE) - Thermoplastic prepared by radical polymerization of tetrafluoroethylene. It has low dielectric constant, superior chemical resistance, very high thermal stability, low friction coefficient, excellent anti-adhesive properties, low flammability, and high weatherability. Impact resistance of PTFE is high, but permeability is also high whereas strength and creep resistance are relatively low. The very high melt viscosity of PTFE restricts its processing to sinter molding and powder coating. Uses include coatings for cooking utensils, chemical apparatus, electrical and nonstick items, bearings, and containers. Also, PTFE spheres are used as fillers and PTFE oil is used as a lubricant in various plastics. Also called *TFE, modified PTFE.*

Polytetrafluoroethylene Compounds - Material obtained by intimate mixing of fillers (metallic and nonmetallic) with polytetrafluoroethylene. One or more of polymer properties such as cold flow, wear, and surface hardness are altered by the addition of fillers.

Polyvinyl Chloride (PVC) - PVC is a thermoplastic prepared by free-radical polymerization of vinyl chloride in dispersion (emulsion), bulk, or suspension processes. A small amount of comonomer is sometimes added to enhance adhesion or other properties. Unmodified PVC is rigid and requires plasticizers to make it more flexible. The main end forms of PVC are rigid and flexible. The flexible form is often made from plastisols, suspensions of PVC in liquid plasticizers. PVC can be chlorinated to increase its heat deflection temperature and tensile strength and to reduce flammability and smoke generation. PVC is dimensionally stable, largely nonflammable, and resistant to weathering, but has limited thermal stability, high density, and is attacked by many solvents. Processed by injection molding, calendaring, extrusion, powder coating, blow molding, extrusion coating, and film techniques. Used very widely as films, fabric coatings, wire coatings, toys, bottles, and pipes.

Polyvinyl Fluoride (PVF) -

$$[\text{—CHF—CF}_2\text{—}]_n$$

Thermoplastic prepared by free radical polymerization of vinyl fluoride. It is extruded into thin (<100 µm) films as a plastisol (dispersion in a polar solvent). PVF is known for its weather resistance, release, adherability, and mechanical strength.

Polyvinylidene Fluoride (PVDF) -

$$[\text{—CF}_2\text{—CH}_2\text{—}]_n$$

Thermoplastic prepared from vinylidene fluoride. It has substantially higher strength, wear resistance, and creep resistance than other fluoropolymers but relatively high dielectric constant and loss factor. PVDF is nonflammable, resists most solvents, and has excellent weatherability. Its service temperature limit and chemical resistance are lower than those of perfluoropolymers. PVDF is processed readily by extrusion, injection molding, transfer molding, and powder or dispersion coating. Uses include electrical insulation, pipes, chemical apparatus, coatings, films, containers, and fibers. Also called *VF2, PVF2.*

Porosity - Porosity is defined as the volume of voids per unit volume of a material or as the volume of voids per unit weight of material.

Preform - A shape produced by the compaction of a polymer powder (or its filled compounds) below the melting point of the polymer (e.g., PTFE). The preform is subsequently sintered in a separate step to produce a useful part. See also ***Preforming.***

Preforming - The process of producing a preform which consists of filling a mold with the polymer powder, compaction of the resin by pressing it down in a press and, finally, removal of the preform from the mold. The mold is usually operated at the room temperature and is designed to allow easy escape of the air during the resin compaction. See also ***Preform***.

Pressure Hoses - Reinforced polytetrafluoroethylene (PTFE) hoses comprised of a PTFE tube and reinforcement, usually in the form of single ply or multi-plies of metal wire braiding, for super atmospheric pressure end uses.

Pressure-Sensitive Adhesive - An adhesive that requires applied pressure on the parts for bonding to occur. Usually composed of a rubbery elastomer and modifying tackifier, pressure-sensitive adhesives are applied to the parts as solvent-based adhesives or hot melts; curing does not usually occur. They adhere tenaciously under slight pressure and are highly thixotropic. Disadvantages include limited temperature capability and susceptibility to oxidative degradation. These adhesives do not undergo progressive viscosity increase like other adhesives but instead they are in a permanent tacky stage. They are usually coated on paper, plastic films, foam, or cloth, and applied with pressure to the adherend, as their name implies. Most pressure-sensitive adhesives contain a blend of elastomers like SBR or natural rubber with low or medium tacky fibers. See also ***Contact Adhesive.***

Primer - In adhesive bonding, a reactive chemical species dispersed in a solvent that is applied to the part surface by spraying or brushing. After the solvent is flashed off, the part surface may be bonded immediately, as in polyolefin primers for cyanoacrylates, or may require time to react with atmospheric moisture, as in silane and isocyanate-based primers used for silicone and polyurethane-based adhesives, respectively. Primers generally contain a multifunctional chemically reactive species capable of acting as a chemical bridge between the substrate and the adhesive. Primers are commonly used with acetals, fluoropolymers, polybutylene terephthalate, silicone, polyurethane, and polyolefins. As coatings, they are applied on a substrates prior to subsequent coatings or topcoat in order to seal the pores, improve adhesion of the topcoat, improve corrosion protection, hide surface imperfections or color, etc. Usually based on polymers with functional additives. Applied by the same techniques as coatings. Also called *primer coating.*

PTFE - See ***Polytetrafluoroethylene.***

PTFE Fiber - This is a polytetrafluoroethylene (PTFE) yarn produced by spinning of a blend of PTFE and viscose followed by chemical conversion, drying, and sintering.

PVC - See ***Polyvinyl Chloride.***

PVDF - See ***Polyvinylidene Fluoride.***

PVF - See ***Polyvinyl Fluoride***.

PV Limit - Wear of plastics is proportional to load (or pressure *P*) and velocity (*V*). Combinations of pressure and velocity are defined where the material can be used, thus a *PV* limit is defined.

Radiation Dosage - See ***Radiation Dose.***

Radiation Dose - Amount of ionizing radiation energy received or absorbed by a material during exposure. Also called *radiation dosage, ionizing radiation dose.*

Radiation Resistant Materials - Materials that resist degradation on long- and medium-term or repeated exposure to ionizing radiation, e.g., steel grades designed for nuclear reactors. Radiation damage to materials includes swelling, radiolysis, blistering, changes in electrical and mechanical properties, etc. There are different mechanisms of radiation damage but most can be linked to free-radical reactions. The resistance of materials to radiation can be improved by stabilizing them with agents that can neutralize free radicals such as dimethyl sulfoxide, carbohydrates, and various reducing agents. Also called *radiation stabilized material.*

Radicals - See ***Free Radicals.***

Radiography - An x-ray based technique used for detecting flaws in materials, for example, voids and cracks in metals.

Ram Extrusion - Ram extrusion is the only continuous process for fabrication of parts from suspension polymerized (granular) polytetrafluoroethylene. All three required steps of processing are performed in one machine called *ram extruder.* The most common shapes are solid rods and tubes. The basic steps of ram extrusion are compaction, sintering, and cooling. Free flow powder is fed into a die and compacted against the previous charge by the action of a reciprocating ram which also advances the charge into the heated section of the die. After sintering, the charge advances into the cooling zone of the die and finally exits.

Reduction Ratio - This factor is the ratio of cross-sectional surface areas of the preform and the extrudate in paste extrusion. Different dispersion polymerized polytetrafluoroethylene powders accommodate different reduction ratio ranges. In general, reduction ratio of the resin decreases as molecular weight increases. Melt fracture and defects appear in the extrudate if it is processed at above its maximum reduction ratio.

Relaxation Time - Maxwell proposed a model in the 19^{th} century to describe the time-dependent behavior of viscous materials such as pitch or tar. This model has also been applied to plastics and polymers. A parameter has been defined in this model called *relaxation time* that is a characteristic of the plastic material. Relaxation time is the ratio of viscosity to the Young's modulus of elasticity.

Repro - This is short for "reprocessed" and is applicable to a great variety of scrap generated during processing of fluoropolymers. Scrap materials are treated in multiple step processes using acids and heat for purification. Afterwards they are ground, sized, and consumed. A number of key properties of fluoropolymers decline as a result of purification process.

Rheology - A science that studies and characterizes flow of polymers, resins, gums, and other materials.

Rietz Mill - A type of hammer mill supplied by Bepex Corp., Santa Rosa, CA. See also ***Hammer Mill.***

Rotational Lining - Rotational lining is a process by which a hollow object is lined with a plastic. The surface of the part, contrary to rotational molding process, is prepared to adhere the liner to the mold wall. See also ***Rotational Molding.***

Rotational Molding - Also known as rotocasting or rotomolding; it's a process for manufacturing hollow plastic parts. A typical procedure for rotational molding is as follows: Very fine plastic powder is placed in a mold and the closed mold is heated above the melting point of the powder while the mold is rotated in two planes at right angle to each other. The heating continues until the polymer powder fuses and melts to form a homogeneous layer of uniform thickness. The mold is rotated while it is cooled down to the removal temperature. At the end, mold rotation is stopped and the part is removed.

Rotolining - See ***Rotational Lining.***

Rotomolding - See ***Rotational Molding.***

Semicrystalline Plastic - A plastic (polymeric) material characterized by localized regions of crystallinity. See also ***Amorphous Polymer.***

Shear - Displacement of a plane of a solid body parallel to itself, relative to other parallel planes within the body; deformation resulting from this displacement.

Shelf Life - Time during which a physical system such as material retains its storage stability under specified conditions. Also called *storage life.*

Shore A - See ***Shore Hardness.***

Shore D - See ***Shore Hardness.***

Shore Hardness - Indentation hardness of a material as determined by the depth of an indentation made with an indentor of the Shore-type durometer. The scale reading on this durometer is from 0, corresponding to 0.100" depth, to 100 for zero depth. The Shore A indenter has a sharp point, is spring-loaded to 822 gf, and is used for softer plastics. The Shore D indenter has a blunt point, is spring-loaded to 10 lbf, and is used for harder plastics. Also called *Shore A, Shore D.*.

Silicone - Silicones are polymers, the backbone of which consists of alternating silicon and oxygen atoms. Pendant organic groups are attached to silicon atoms. They are usually made by hydrolyzing chlorosilanes, followed by poly condensation and crosslinking. Depending on the degree of crosslinking and the nature of pendant groups, silicones can be liquid, elastomeric, or rigid. Liquid silicones or silicone fluids such as dimethylsiloxane have very good anti-adhesive properties, lubricity, resistance to heat and chemicals, and are used as release agents, surfactants, and lubricants in plastics. As lubricants they improve wear resistance of plastics. Silicone elastomers, or rubbers, have high adhesion, resistance to compression set, flexibility, good dielectric properties, weatherability, low flammability, good moisture barrier properties, and thermal stability, but somewhat low strength. Optically clear grades are available. Processed by coating and injection molding. Used as optical fiber coatings, electronic connector encapsulants, printed circuit board coatings, seals, diaphragms, fabric coatings, medical products, adhesives, sealants, and glazing compounds. Rigid silicone resins offer good flexibility, weatherability, dirt release properties, dimensional stability, and are stronger and harder than silicone rubbers. The resins are attacked by halogenated solvents. Processed by coating, casting, injection molding, compression molding, and transfer molding. Used as coatings, adhesives, sealants, bonding agents, and molded parts. Also called *siloxane, silicone rubber, silicone plastic, silicone fluid, SI, polysiloxane.*

Sintering - Consolidation and densification of polytetrafluoroethylene particles above its melting temperature is called *sintering*. See also ***Coalescence.***

Skiving - This is a popular method for producing films and tapes of polytetrafluoroethylene (PTFE). Skiving resembles peeling an apple where a sharp blade is used at a low angle to the surface of a billet (cylinder) of PTFE. A similar method is used in the production of wood veneer from trees.

Slide Bearing - See ***Bearing Pad.***

Sliding Velocity - The relative speed of movement of one body against the surface of another body (counterbody) without the loss of contact as in a sliding motion during wear and friction testing of materials. In the sliding motion, the velocity vectors of the body and the counterbody remain parallel, and should be unequal if they have the same direction.

Slitting - This is a process to cut film and webs into narrower widths than the starting material. A roll of the wide film is unwound and passed over sharp knives positioned to obtain the required cut widths. The narrower films are wound up on separate cores. Special machines are available for slitting films.

Sodium Etching - Sodium etching is a process by which the surface of fluoropolymers is rendered adherable. During etching, the fluoropolymer surface is brought into contact with a sodium solution (1:1) in naphthalene dissolved in tetrahydrofuran or an anhydrous solution of sodium in liquid ammonia.

Sodium Naphthalenide - See ***Sodium Etching.***

Softening Point - Temperature at which the material changes from rigid to soft or exhibits a sudden and substantial decrease in hardness.

Solubility - The solubility of a substance is the maximum concentration of a compound in a binary mixture at a given temperature forming a homogeneous solution. Also called *dissolving capacity.*

Specific Wear Rate - Also known as *wear factor*, specific wear rate is defined as the volume of material worn away per unit of sliding distance and per unit of load.

Spherulite - In plastics, a rounded aggregate of radiating lamellar crystals with amorphous material between the crystals. Has the appearance of a pom-pom. Spherulites exist in most crystalline plastics and usually impinge on one another to form polyhedrons. Range in size from a few tenths of a micron in diameter to several millimeters.

Standard Specific Gravity (SSG) - SSG or standard specific gravity is determined for polytetrafluoroethylene using a specially molded and sintered sample. SSG is used as a means of assessing molecular weight of this polymer. Molding and sintering are procedures specified by ASTM F4894.

Steric Hindrance - A spatial arrangement of the atoms of a molecule that blocks reaction of the molecule with another molecule.

Stick Slip - This is a jerking action that occurs in a moving part such as a bearing in overcoming a higher static coefficient of friction than a dynamic coefficient of friction before movement begins.

Strain - The per unit change, due to force, in the size or shape of a body referred to its original size or shape. Note: Strain is nondimensional but is often expressed in unit of length per unit of length or percent. Also called *mechanical strain.* See also ***Flexural Strain, Compressive Strain, Tensile Strain.***

Stress Cracking - Appearance of external and/or internal cracks in the material as a result of stress that is lower than its short-term strength. See also ***Environmental Stress Cracking.***

Stress Relaxation - Time-dependent decrease in stress in a solid material as a result of changes in internal or external conditions. Also called *stress decrease.*

Supercritical Carbon Dioxide - Refers to carbon dioxide that has been heated to above its *critical* temperature and pressure. Supercritical CO_2 is a potent solvent for a great many organic substances. It is also a suitable medium for polymerization of fluorinated monomers.

Surface Energy - See ***Surface Tension.***

Surface Roughening - In adhesive bonding, a commonly used surface preparation technique in which the substrate surface is mechanically abraded. The roughened surface increases bondability by dramatically increasing the number of sites available for mechanical interlocking.

Surface Roughness - The closely spaced unevenness of a solid surface (pits and projections); can be quantified by various methods, e.g., by using a profilometer in coatings.

Surface Tension - The surface tension is the cohesive force at a liquid surface measured as a force per unit length along the surface or the work which must be done to extend the area of a surface by a unit area, e.g., by a square centimeter. Also called *free surface energy.*

Surfactant - Derived from *surface active agent.* Defined as substances which aggregate or absorb at the surfaces and interfaces of materials and change their properties. These agents are used to make compatible two or more immiscible phases such as water and oil. In general, one end of a surfactant is water soluble and the other end is soluble in an organic liquid.

Suspension Polymerization - Refers to a heterogeneous polymerization regime in which the product of the reaction is a solid forming a suspension in the liquid medium of reaction. Little or no surfactant is added to the reaction medium. Characteristics of the process include high agitation rate and poor particle size control. An advantage of this reaction is high purity of the polymer product as compared to that of the dispersion method.

Taber Abrasion Resistance - The weight loss of a plastic or other material specimen after it was subjected to abrasion in a Taber abraser for a prescribed number of specimen disk rotations, usually 1000. A Taber abraser consists of an idling abrasive wheel, designated depending on the type and grit of abrasive used as CS-10F, H 22, etc., and a rotary disk with the specimen mounted on it. The load is applied to the wheel. The produced motion simulates that of rolling with slip.

Talc - Talc is a filler made by dry or wet grinding of mineral magnesium silicate. Talc improves stiffness, dimensional stability, flexural modulus, creep resistance, flow, surface smoothness, moisture resistance, tensile strength, and wear resistance of plastics. It also increases heat deflection temperature and decreases vapor permeability. Can be used as a film antiblock agent. Used mainly in polypropylene but also in thermoplastic and unsaturated polyesters and epoxy resins at low levels. Surface-modified grades are available.

Tempering - Homogeneous tempering refers to minimization of the mold surface temperature between the inlet and outlet of the cooling fluid.

Wall temperature differences could cause warping of the part.

Tensile Elongation - See ***Elongation.***

Tensile Fatigue - Progressive localized permanent structural change occurring in a material subjected to cyclic tensile stress that may culminate in cracks or complete fracture after a sufficient number of cycles. See also ***Fatigue, Flexural Fatigue.***

Tensile Heat Distortion Temperature - See ***Heat Deflection Temperature.***

Tensile Properties - Properties describing the reaction of physical systems to tensile stress and strain.

Tensile Strain - The relative length deformation exhibited by a specimen subjected to tensile force. See also ***Flexural Strain, Strain.***

Tensile Strength - The maximum tensile stress that a specimen can sustain in a test carried to failure. Note: The maximum stress can be measured at or after the failure or reached before the fracture, depending on the viscoelastic behavior of the material. Also called *ultimate tensile strength, tensile ultimate strength, tensile strength at break.*

Tensile Strength at Break - The maximum load per original minimum cross-sectional area of the plastic specimen in tension within the gauge length when the maximum load corresponds to the break point. Measured according to ASTM D638. See also ***Tensile Strength.***

Tensile Strength at Yield - The maximum load per original minimum cross-sectional area of the plastic specimen in tension within the gauge length, when the maximum load corresponds to the yield point. Measured according to ASTM D638.

Tensile Stress - The force related to the smallest original cross-section of the specimen at any time of the test.

Tex - A metric unit used in the textile industry to measure the density of a single fiber of yarn. One tex equals a density of one gram per kilometer of length, or 1 mg/m. One tex equals 10 drex or 9 denier. See also ***Denier.***

Thermal Conductivity - The time rate of heat transfer by conduction across a unit area of substance at unit thickness and unit temperature gradient.

Thermal Expansion Coefficient - The change in volume per unit volume resulting from a change in temperature of the material. The mean coefficient of thermal expansion is commonly referenced to room temperature.

Thermal Properties - Properties related to the effects of heat on physical systems such as materials and heat transport. The effects of heat include the effects on structure, geometry, performance, aging, stress-strain behavior, etc.

Thermal Recycling - A plastics recycling method in which mixed plastic waste undergoes controlled combustion, producing heat that can be used as a substitute for oil, gas, and coal, or for the generation of energy at power plants.

Thermal Stability - The resistance of a physical system such as material to decomposition, deterioration of properties, or any type of degradation in storage under specified conditions. Also called *oven stability, heat stability.*

Thermoforming - The process of heating a thermoplastic sheet to a point at which it softens and flows, then applying differential pressure to make the sheet conform to the shape of a mold or die.

Thermoplastic - Thermoplastics are resin or plastic compounds which, after final processing, are capable of being repeatedly softened by heating and hardened by cooling by means of physical changes. There are a large number of thermoplastic polymers belonging to various classes such as polyolefins and polyamides. Also called *thermoplastic resin.*

Thermoplastic Resin - See ***Thermoplastic.***

Thermoset - Thermosets are resin and plastic compounds which, after final processing, are substantially infusible and insoluble. Thermosets are often liquids at some stage in their manufacture or processing and are cured by heat, oxidation, radiation, or other means often in the presence of curing agents and catalysts. Curing proceeds via polymerization and/or crosslinking. Cured thermosets cannot be resoftened by heat. There are a large number of thermosetting polymers belonging to various classes such as alkyd and phenolic resins. Also called *thermosetting resin, thermoset resin*.

Thermoset Resin - See ***Thermoset.***

Thermosetting Elastomer - A large class of polymers that can be stretched at room temperature to at least twice their original length and, after having been stretched and the stress removed, return with force to approximately their original length in a short time. To attain this elastic property the rubbers must be crosslinked or vulcanized, usually by heating in the presence of various crosslinking agents and catalysts. There are natural and synthetic rubbers. The most important synthetic rubber families are olefinic rubbers, dienic rubbers (nitrile, butadiene, neoprene), silicone rubbers, and urethane rubbers. Used often as impact modifiers/fillers in plastics. Also called *synthetic rubber, rubber*.

Thixotropic Liquids - These liquids exhibit lower viscosity as shear rate increases. A practical example is house paint which appears thinner when stirred.

Tornado Mill - A type of hammer mill supplied by Tornado Engineering Division of Solus Industries, Niagara Falls, New York.

Torsional Damping - One of the methods to measure the crystallinity of polytetrafluoroethylene is torsional damping. Other methods include infrared spectroscopy, x-ray diffraction, and ultrasonics.

Transition Point - See ***Transition Temperature.***

Transition Temperature - This is a temperature (19°C for 100% homopolymer of tetrafluoroethylene) at which the unit crystalline cell of polytetrafluoroethylene changes from triclinic to hexagonal.

Tribological Characteristics - These characteristics deal with friction or contact-related phenomenon in materials. Coefficient of friction and wear rate are the most important tribological characteristics of a material.

Tubular Ovens - Ovens that have cylindrical shapes.

Two-Roll Coating - Any coating technique in which two rolls are involved can be generally called two-roll coating. One roll is in contact with the liquid coating and transfers the liquid to a web that is wrapped around the second roll. The first roll is called the applicator roll and the second roll is called the back-up roll.

Ultraviolet Light - See ***Ultraviolet Radiation.***

Ultraviolet Radiation - Electromagnetic radiation in the 40– 400 nm wavelength region. Sun is the main natural source of UV radiation on the earth. Artificial sources are many, including fluorescent UV lamps. Ultraviolet radiation causes polymer photodegradation and other chemical reactions. Note: UV light comprises a significant portion of the natural sun light. Also called *UV radiation, UV light, ultraviolet light.* See also ***Ultraviolet Radiation Exposure.***

Ultraviolet Radiation Exposure - In adhesive bonding, a surface preparation technique in which the substrate is irradiated with high intensity UV light. Exposure to UV radiation results in chain scissions, crosslinking, and oxidation of the polymer surface. The effectiveness of this technique is dependent on the wavelength of radiation used. It is commonly used for polyolefins. Also called *UV exposure.*

Vacuum Forming - Vacuum forming is a type of thermoforming process consisting of preheating the plastic sheet prior to forming. The sheet is formed into the female mold by application of vacuum through holes in the mold.

VC - See ***Vinyl Chloride.***

V-Cone Blender - See ***V-Shaped Blender.***

VDF - See ***Vinylidene Fluoride***.

VF - See ***Vinyl Fluoride.***

Vinyl Chloride (VC) - Monomer for polyvinylchloride, $CH_2{=}CHCl$.

Vinyl Fluoride (VF) - Monomer for polyvinylfluoride, $CH_2{=}CF_2$.

Vinylidene Fluoride (VDF) - Monomer for polyvinylidene fluoride, $CH_2{=}CF_2$.

Vinylidene Fluoride Hexafluoropropylene Copolymer - Thermoplastic copolymer of vinylidene fluoride and hexafluoropropylene. Has better thermal stability, antistick, dielectric, and antifriction properties, and chemical resistance, but lower mechanical strength at room temperature and creep resistance, compared to incompletely fluorinated fluoropolymers. Processing by conventional thermoplastic techniques is difficult due to its high melt viscosity. Uses include chemical apparatus, containers, films, and coatings. Also called *FKM.*

Vinylidene Fluoride Hexafluoropropylene Tetrafluoroethylene Terpolymer - Thermosetting elastomeric polymer of vinylidene fluoride, hexafluoropropylene, and tetrafluoroethylene having good chemical and heat resistance and flexibility. Used in auto parts. Also called *FKM/TFE.*

Viscoelasticity - A property of a material that exhibits both elastic and viscous behavior. Viscoelastic materials have both solid-like characteristics—elasticity, strength, and stability of form—and liquid-like characteristics, such as flow that depends on time, temperature, and stress. All plastics exhibit some degree of viscoelasticity.

Viscosity - The internal resistance to flow exhibited by a fluid, the ratio of shearing stress to rate of shear. A viscosity of one poise is equal to a force of one dyne per square centimeter that causes two parallel liquid surfaces, one square centimeter in area and one centimeter apart, to move past one another at a velocity of one cm/second.

Voids - See ***Porosity.***

V-Shaped Blender - A v-shaped blender consists, in general, of two cylindrical halves that are attached at one end, thus the name v-shaped. The blender can rotate around an axis that is horizontal and allows tumbling of the material inside the blender. Some of these blenders are equipped with an attrition bar to intensify the mixing action. See also ***Attrition Bar***.

Wafer Carrier - A basket, often made from fluoropolymers, for transportation of silicon wafers during the processing and shipping.

Warpage - See ***Warping.***

Warping - Dimensional distortion or deviation from the intended shape of a plastic or rubber article as a result of nonuniform internal stress, e.g., caused by uneven heat shrinkage. Also called *warpage*.

Wear - Deterioration of a surface due to material removal caused by any of various physical processes, mainly friction against another body.

Wear Factor - See ***Specific Wear Rate.***

Wear Rate - See ***Tribological Characteristics.***

Weep Test - This is a test to determine the integrity of a high pressure hose. In this procedure (MIL-S-3136, type III and MIL-H-25579) unbraided samples of the tube are pressurized by filling with a specified fuel (70% i-octane + 30% toluene) to a calculated initial pressure. Pressure is incrementally (0.035 MPa) increased until seepage occurs. This pressure is recorded as weep pressure.

Weld Factor - The ratio of weld strength to the strength outside the welded zone, typically determined by tensile stress tests.

Welding - A method used for joining thermoplastic parts without an adhesive. Heat, pressure, and time are variables used to weld together plastic parts. A simple method consists of clamping the parts together and heating the joint with a heater band. Also see ***Heated Tool Welding.***

Welding by Distance - A form of heated tool welding in which mechanical stops on the hot tool and holding fixtures are used to control the dimensions of the welded parts. See also ***Welding by Pressure, Heated Tool Welding.***

Welding by Pressure - A form of heated tool welding in which flow of the molten plastic after heating is regulated by application of specific pressures to the hot tool and parts. Accurate pressure control is necessary, and final part dimensions may vary due to variations in melt thickness and melt viscosity. See also ***Welding by Distance, Heated Tool Welding.***

Welding Pressure - The pressure applied to the parts during welding to hold the parts in place and provide intimate contact for bonding. Welding pressure varies depending on the welding process used and the composition of the parts being joined.

Welding Time - A processing parameter in welding. Definition varies depending on the welding process—can refer to the time vibrations are applied to the parts being joined (ultrasonic welding), the amount of time parts are held together under pressure for cooling and solidification (heated tool welding), or both the spin time and cooling time (spin welding). Welding time is dependent on other processing parameters such as weld amplitude, weld frequency, weld pressure, power level, temperature, etc.

Weld Strength - Strength of a welded plastic part at the seam that has been welded is called weld strength. It is measured by methods similar to those for measuring the strength of adhesive bonds. See also ***Adhesive Bond Strength.***

Wet Bag Isostatic Molding - A method of isostatic molding in which polytetrafluoroethylene (PTFE) powder is compressed between a hard part and an elastic bag. The compaction is achieved by submerging the filled mold in fluid inside a high pressure vessel and pressurizing the vessel. See also ***Dry Bag Isostatic Molding, Isostatic Molding.***

Wettability - The rate at which a substance (particle, fiber) can be made wet under specified conditions. See also ***Wetting.***

Wetting - The spreading out (and sometimes absorption) of a fluid onto (or into) a surface. In adhesive bonding, wetting occurs when the surface tension of the liquid adhesive is lower than the critical surface tension of the substrates being bonded. Good surface wetting is essential for high strength adhesive bonds; poor wetting is evident when the liquid beads up on the part surface. Wetting can be increased by preparation of the part surface prior to adhesive bonding.

Yellowing - Developing of yellow color in near-white or near-transparent materials such as plastics or coatings as a result of degradation on exposure to light, heat aging, weathering, etc. Usually is measured in terms of yellow index.

Yield Deformation - The strain at which the elastic behavior begins, while the plastic is being strained. Deformation beyond the yield deformation is not reversible.

Young's Modulus of Elasticity - In the elastic region, the relationship between stress and strain of a polymer, undergoing tensile or compressional strain, is linear (Hooke's Law). In this relationship, stress is proportional to strain. The coefficient of proportionality in this stress-strain relationship is called *Young's Modulus of Elasticity.*

Zero Strength Time - Zero strength time is defined as the time required to hold a sample of polychlorotrifluoroethylene at 250°C, under conditions specified by ASTM D1430, until the sample loses its strength.

ZST - See ***Zero Strength Time.***

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Index