Properties Handbook

Teflon® PTFE

fluoropolymer resin

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Introduction

Teflon® is a registered trademark of the DuPont Company for its fluoropolymer resins. *Teflon*® PTFE fluoropolymer resins are part of the DuPont family of fluorine-based products that also includes *Teflon*® FEP and *Teflon*® PFA fluoropolymer resins and *Tefzel*® fluoropolymers. These materials can be used to make a variety of articles having a combination of mechanical, electrical, chemical, temperature, and friction-resisting properties unmatched by articles made of any other material. Commercial use of these and other valuable properties combined in one material has established *Teflon*® resins as outstanding engineering materials for use in many industrial and military applications. *Teflon*® resins may also be compounded with fillers or reinforcing agents to modify their performance in use.

The design and engineering data presented in this handbook are intended to assist the design engineer in determining where and how *Teflon*® resins may best be used. It is recommended that the design engineer work closely with an experienced fabricator because the method of fabrication may markedly affect not only production costs, but also the properties of the finished article.

Typical Properties

Table 1 lists physical property data relating to the *Teflon*® PTFE resins. All properties presented in this handbook should be considered as typical values and are not to be used for specification purposes. The age of this data varies greatly, ranging in origin from the 1950s to the 1990s.

Patents

A large number of existing patents relate to various *Teflon*® resins, but no attempt has been made in this publication to refer to any of these patents by number, title, or ownership. The descriptions of a process, an apparatus, a composition, or any article may fall within a claim of an existing patent, but we do not intend that such a description should induce anyone to infringe any existing patent. It is the responsibility of the prospective user of fluoropolymer resins to determine whether his/her use constitutes infringement or noninfringement of any patent.

Effects of Processing

Teflon® PTFE fluoropolymer resins are tetrafluoroethylene polymers, usually fabricated into parts by cold-forming and sintering techniques. *Teflon*® PTFE resins have a continuous service temperature of 260°C (500°F). Much higher temperatures can be satisfactorily sustained for shorter exposures.

Various physical properties can be obtained with *Teflon*® PTFE resins by varying the processing technique. *Teflon*® PTFE resins are versatile and can, within limits, be “tailored” to provide fabricated parts with particular physical properties.

Processing can have more impact on the performance of parts made from *Teflon*® PTFE than for those made from other types of polymers. For example, preforming pressure, sintering time, cooling rate, void content, and crystallinity level can have a significant effect on certain end-use physical properties, such as tensile properties, permeability, and dielectric strength. **Table 2** lists features of *Teflon*® resins that are relatively independent of fabrication conditions.

Table 2
Properties Relatively Independent of Fabrication Conditions

Chemical Properties
Chemical resistance to corrosive reagents
Nonsolubility
Long-term weatherability
Nonadhesiveness
Nonflammability
Electrical Properties
Low dielectric constant
Low dissipation factor
High arc-resistance
High surface resistivity
High volume resistivity
Mechanical Properties
Flexibility at low temperatures
Low coefficient of friction
Stability at high temperatures

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Table 1
Typical Properties of *Teflon*® PTFE Fluoropolymer Resins

Property	ASTM Method	Unit	*Teflon*® PTFE Granular Resin	Fine Powder
Tensile Strength, 23°C (73°F)	D4894/4895	MPa (psi)	31.0 (4,500)	20.7 min. (3,000 min.)
Elongation, 23°C (73°F)	D4894/4895	%	400	200 min.
MIT Flex, 2 kg load, 10 mil	D2176		Did not break at 10^6 cycles	
Flex Modulus, 23°C (73°F)	D790	MPa (psi)	345–620 (50,000–90,000)	275–620 (40,000–90,000)
Stretching Void Index	D4895		—	15–200+
Impact Strength, Izod	D256	J/m (ft·lb/in)		
–40°C (–40°F)			80 (1.5)	133–267 (2.5–5)
21°C (70°F)			106 (2)	—
24°C (75°F)			160 (3)	—
77°C (170°F)			>320 (>6)	—
204°C (400°F)			No break	No break
Hardness, Durometer	D2240	Shore D	55	50–65
Coefficient of Linear Thermal Expansion per °C (°F), 23–60°C (73–140°F)	E228	mm/mm·°C (in/in·°F)	10 x 10^{-5} (7 x 10^{-5})	—
Thermal Conductivity, 4.6 mm (0.18 in)	D435[a]	W/m·K (Btu·in/h·ft^2·°F)	0.25 (1.7)	—
Specific Heat	D4591	kJ/kg·K (Btu/lb·°F)		
20°C (68°F)			1.4 (0.33)	1.5 (0.35)
40°C (104°F)			1.2 (0.29)	1.2 (0.29)
150°C (302°F)			1.3 (0.31)	1.3 (0.31)
260°C (500°F)			1.5 (0.37)	1.4 (0.33)
Thermal Instability Index	D4894/4895		50 max.	50 max.
Deformation Under Load, 23°C (73°F)	D621	%		
3.4 MPa (500 psi)			<0.5	<0.5
6.9 MPa (1000 psi)			2	2
14 MPa (2000 psi)			10	5
Heat Deflection Temperature	D648	°C (°F)		
450 kPa (66 psi)			73 (160)	140 (280)
1800 kPa (264 psi)			45 (115)	55 (130)
Dielectric Strength, Short Time, 2.03 mm (0.080 in)	D149	kV/mm (V/mil)	24 (600)	24 (600)
Surface Arc-Resistance[b]	D495	sec	>300	>300
Volume Resistivity	D257	ohm·cm	>10^{18}	>10^{18}
Surface Resistivity	D257	ohm·sq	>10^{18}	—
Dielectric Constant, 60 to 2 x 109 Hz	D150		2.1	2.1
Dissipation Factor, 60 to 2 x 109 Hz	D150		<0.0001	—
Water Absorption, 24 hr	D570	%	<0.01	<0.01
UL 94 Flame Rating[c]			94 V-0	94 V-0
Resistance to Weathering			Excellent	Excellent
Static Coefficient of Friction Against Polished Steel[d]			0.05–0.08	—
Specific Gravity	D4894/4895		2.16	2.1–2.3

[a] This standard is no longer in use.

[b] Does not track

[c] These numerical flame spread ratings are not intended to reflect hazards presented by this or any other material under actual fire conditions.

[d] Various methods used

Teflon® PTFE resins are fabricated to form parts by a number of techniques, including ram extrusion, screw extrusion, compression molding, and paste extrusion with an extrusion aid. Although different, these techniques have three basic steps in common: cold forming, sintering, and cooling. These fabricating steps refer to operations that involve, respectively: compacting molding powder to shape by pressing, bonding adjacent surfaces of particles by heating, and controlling crystallinity content of the article by cooling.

Previous work has pointed out that about 15 mechanical properties plus several electrical and chemical properties of *Teflon*® PTFE resins are influenced by molding and sintering conditions. Most notably affected are flex life, permeability, stiffness, resiliency, and impact strength. The five basic factors that influence these end-product properties are:

- **Presence of Macroscopic Flaws**—Internal bubbles, tears, foreign impurities, shear planes, or poor charge-to-charge bonds.
- **Extent of Microporosity**—Number and size of microscopically visible voids created by imperfect particle fusion.
- **Percent Crystallinity**—A percentage based on the weight fraction of a sample consisting of polymer chains fitted in a close-packed, ordered arrangement.
- **Molecular Weight**—A measure of the average length of polymer chains.
- **Degree of Orientation**—A measure of the extent of alignment of polymer chains in a given direction.

While, ideally, a quality control system should be based on direct measurements of these basic factors, simple and direct measuring methods suitable for routine use are not usually available. Instead, a number of highly sensitive, indirect tests have been devised. They are based on measurement of *dielectric strength, tensile strength, ultimate elongation, specific gravity, and heat of fusion*. Simple, applicable to a variety of shapes, reproducible, and sensitive, the tests and their relation to the five basic quality factors are explained in the following text.

Dielectric Strength

Dielectric strength is a function of the degree of microporosity. **Table 3** shows that it correlates well with size and number of microvoids visible with a microscope. On the other hand, dielectric strength is independent of molecular weight and crystallinity.

Table 3
***Teflon*® PTFE Granular Resin: Relation of Dielectric Strength to Degree of Microporosity**

Sample	Appearance of Cross Section in Microscope	Dielectric Strength, V/mil*
A	No visible voids at 100x magnification	760
B	Scattered 0.001-in voids between particles	575
C	Scattered 0.005-in voids	445
D	Numerous 0.005-in voids	250

* 1/16-in sheets immersed in A-80 transformer oil per ASTM D149

Tensile Strength and Ultimate Elongation

Tensile strength and ultimate elongation depend to some degree on all five quality factors. **Table 4**, for example, points out the effect of microvoids on the samples described in **Table 3**. Limited data indicate that this reduction of tensile properties by microvoids is influenced to some extent by crystallinity. While definite evidence indicates that tensile strength falls with rise of percent crystallinity, ultimate elongation increases at first, and then drops. Microvoids have their greatest effect in low-crystallinity products.

Table 4
***Teflon*® PTFE Granular Resin: Effect of Microporosity on Tensile Strength and Elongation**

Sample*	Extent of Microporosity	Tensile Strength, MPa (psi)	Ultimate Elongation, %
A	Negligible	24.8 (3,600)	390
B	Slight	17.4 (2,520)	350
C	Moderate	13.9 (2,020)	300
D	Severe	12.4 (1,800)	170

* Free-cooled 1/16-in specimens with relative crystallinity of 65–68% tested by ASTM D4894/4895

Degree of orientation also affects tensile properties. In general, tensile strength is greater in the direction of orientation, but ultimate elongation is lower.

While all flaws can reduce tensile strength to some degree, imperfect fusion between successive charges during extrusion of rod and heavy-wall tubing are probably the defects of most common concern.

Specific Gravity

Specific gravity can be readily measured by water-displacement and gradient-tube techniques, such as those described in ASTM D792 or D1505. These tests do not necessarily give the inherent or precise specific gravity, however, because microvoids introduce a disparity between the measured and the inherent specific gravity. In effect, the displaced water, from which the measured value is derived, accounts for both the resin sample and its contained voids. The void content, as described later on, although not easy to determine, should be known or accounted for in the following manner:

$$\text{Measured S.G.} = \text{Inherent S.G.} - (\text{Inherent S.G.} \times 0.01 \times [\%\ \text{Void Content}])$$

Without this correction, such as shown in the lower portion of the equation, the precise conversion of the inherent specific gravity to percent crystallinity as shown in **Figure 1** will be in error by the amount shown in the two lines representing, by way of example, two arbitrarily chosen void levels, namely 0.5 and 1%.

Table 5 indicates the relative effect of three of the basic factors on a number of properties, many of which depend upon the level of crystallinity. Relatively few properties depend directly upon molecular weight. However, crystallization rates, and therefore final levels of crystallinity, do depend upon molecular weight. Molecular weight thus exerts its greatest influence on properties through crystallinity.

To supplement standard quality control methods, a number of laboratory techniques have been developed to check directly the presence of macroflaws, extent of microporosity, percent crystallinity, and molecular weight. Because of their complexity, these methods are not ordinarily suited to routine product testing. As research tools, however, they do aid interpretation of reasons for quality variations.

Macroscopic Flaws

For detection of macroscopic flaws, X-ray radiographic examinations may be employed. Sufficient views are taken to give complete coverage of the piece. In parts more than 2 in thick, at least two views, 90° apart, are required. ASTM method E94 is a useful guide in establishing testing procedures.

Table 5
Effect on *Teflon*® PTFE Resin Properties Caused by Change in Basic Factor

Physical Property	Increasing Molecular Weight	Increasing Crystallinity	Increasing Void Content
Flex Fatigue Life	+100 fold	–100 fold	–1,000 fold
Compressive Stress at 1% Deformation	0	+50%	0
Compressibility	0	–50%	—
Recovery	0	–70%	—
Permeability to Carbon Dioxide	0	–30%	+1,000 fold
Flexural Modulus	0	+5 fold	–30%
Hardness: Durometer	0	+20%	—
Rockwell	0	–20%	–30%
Scleroscope	0	–70%	–10%
Tensile Impact Strength	0	–15 fold	–80%
Dielectric Strength	0	0	–70%
Proportional Limit	0	+80%	–20%
Yield Stress	0	+15%	–20%
Yield Strain	0	–15 fold	0
Tensile Strength	+25%	–50%	–50%
Ultimate Strength	+50%	–70%	–50%
Ultimate Elongation	–20%	+100%*	–30%

*Reaches a maximum at 85% crystallinity

Microscopic Voids

While X-ray radiographic methods are satisfactory for detecting macroscopic flaws, they are not sensitive enough for detection of microscopic voids. There are, however, a number of methods developed specifically for this purpose, as discussed below.

Visual Inspection

Visual inspection by a trained observer without a microscope can be of real value in detecting excessive microporosity and other gross quality defects. While it is difficult to convey in words the experience that enables one to judge varying degrees of microporosity, some worthwhile hints are:

- Prepare a comparison series of samples having varying degrees of microporosity. It is best to collect samples that have been processed by the same sintering and cooling conditions. These will have the same inherent specific gravity.
- It is easier to inspect for porosity by transmitted, rather than reflected, light.
- Use a powerful light source directly behind the sample. A large illuminated panel with a ground-glass surface is best for inspecting sheet stock.
- Small cracks are often more readily seen by viewing at an angle of 45°.
- If permissible, cut off a thin section with a sharp knife and inspect it.

Dye Penetrants

Vividly colored penetrants are valuable as an aid in detecting microporosity or gross defects when:

- The part to be tested is less than 1/2-in thick.
- Comparison standards of both acceptable and nonacceptable quality are available.

Both end user and fabricator should agree on the significance of occasional structural flaws, such as edge cracks and adhered flakes of resin, or saw marks.

Specific Gravity Comparisons

As has been previously discussed, void content provides a measure of degree of microporosity. It follows, then, that void content* can be defined by rearrangement of the specific gravity equation, as follows:

$$\%\ \text{Void Content} = \frac{(\text{Inherent S.G.} - \text{Measured S.G.})}{\text{Inherent S.G.}} \times 100$$

A number of techniques have been investigated for determining data for this equation. These methods include: torsional damping[3] (torsion pendulum), infrared spectroscopy,[4] ultrasonics,[7] rebound resiliency,[7] and X-ray diffraction.[5] Infrared and torsional damping techniques appear to be the most sensitive methods.

While it is beyond the scope of this article to cover the details and theory behind these two methods, their comparative precision and limitations can be pointed out. Inherent specific gravity based on an average of two infrared determinations is usually precise within ±0.003 specific gravity units (95% confidence limits). Inherent specific gravity for an average of two torsion pendulum determinations is usually precise to within ±0.002 specific gravity units.

While the torsion pendulum gives slightly better reproducibility than the infrared method, it is considerably less versatile, because it requires a fixed-size specimen. However, its cost is considerably less than that of a suitable spectrometer.

With both methods, degree of orientation introduces errors. Because means of correcting these errors are currently unknown, inherent specific gravity of paste-extruded wire coatings, tubing, film, and coined sheeting cannot yet be accurately measured. With paste-extruded products, however, apparent specific gravity measurements may be used to estimate degree of crystallinity, because void contents are normally low.

Crystallinity and Molecular Weight

Degree of crystallinity is controlled by molecular weight and by the length of time during fabrication that a part is maintained within the temperature range for rapid crystallization (307–327°C [585–620°F]). By reheating fabricated parts according to a standard thermal cycle (ASTM D4894/4895), relative molecular weights may be estimated through crystallinity or inherent specific gravity measurements. In parts with low void contents, relative molecular weights may be approximated from apparent specific gravity measurements.

Practical Crystallinity Limits

Technical papers[8, 10] have discussed at length the influence of degree of crystallinity and voids on properties of parts fabricated from *Teflon*® PTFE fluoropolymer resins. A number of questions have arisen, however, pointing to the need for further clarification of normal limits for these basic variables. While, theoretically, fabricators can control percent crystallinity or inherent specific gravity over wide ranges, there are certain practical limits.

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* Because of combined errors in inherent and measured specific gravity determinations, it is difficult to distinguish between samples having less than 0.5% voids. Precision of measurement is as good as ±0.2% in homogeneous samples, but may be no better than ±0.5% in nonuniform samples.

For instance, in parts thicker than 1/4 in, it is not practical for fabricators to cool the interior fast enough to reduce crystallinity below about 55%. Even in thin films rapidly cooled in water, it is difficult to reduce crystallinity below about 46% (inherent specific gravity 2.135). An important point to keep in mind, then, is that measured specific gravities below 2.135 generally reflect some voids in any specimen.

Often, it is also impractical for fabricators to obtain high crystallinity levels, because certain parts must be cooled against cold metal surfaces to obtain close tolerances.

How to Specify Typical Fabricated Parts

When setting property and tolerance specifications, the needs of the application must be balanced against the capabilities of both resin and method of fabrication. If needs are considered and designs frozen before any suppliers of fabricated parts are consulted, confusion, inefficiency, and often unnecessary costs may result.

As an aid in tailoring specifications to wed design needs with capabilities of fabricated parts of *Teflon*® resins, the following suggestions are offered:

- At the inception of a design program, engineers should acquaint themselves with the properties of *Teflon*® resins as given in texts such as the *Modern Plastics Encyclopedia*.
- As soon as the preliminary design is on paper, mechanical properties and dimensions for the application should be reviewed. A number of articles on designing have appeared in the literature and may be consulted.[10]

Also at this point, competent suppliers of fabricated parts should be consulted. Usually, there are several quality grades of a given fabricated form. By having a supplier point out what is available at an early stage, it is often possible to adjust design to accommodate most economic usage of materials.

Once design is frozen, there are several routes toward setting specifications. In many cases, suitable specifications are already available from such sources as ASTM, SAE, SPI, NIST, and MIL specifications.

In special situations, the previously cited specification sources may not be satisfactory. In such instances, the following guides on test methods may be useful.

Suggested Test Methods for Various Shapes

Table 6 summarizes specific tests for quality checks on extruded rod, molded sheet, molded parts, and tapes or films made from *Teflon*® PTFE resins. The significance of most of these tests has already been discussed.

In the case of extruded rod, tensile strength and ultimate elongation are standard methods for quantitatively determining the strength of charge-to-charge bonds. There are also three qualitative methods sometimes used for the purpose: X-ray radiographic inspection (previously discussed), mandrel bend tests for rods smaller than 1 in, and resintering.

In the latter, an unconfined section of rod is resintered at 371–382°C (700–720°F) for a period of 1 to 4 hr, depending on rod diameter. Extruded rods with poor charge-to-charge bonds develop distinctly visible cracks as a result of this heat-aging cycle.

With extruded rods, determination of dielectric strength and measured specific gravity may be used to check for excessive microporosity.

For testing sheet, dielectric strength and dye penetrant methods give an indication of microporosity. Measured specific gravities also relate to microporosity. The usual purpose of measured specific gravity determinations, however, is to provide an approximate indication of the sheet's percent crystallinity. Tensile strength and elongation are indicative of overall quality.

With molded parts, X-ray and dye penetrant methods are suggested for detection of surface and internal flaws. Measured specific gravities detect variations in degree of microporosity and percent crystallinity, although again, these effects are not separated in this test. Dimensional stability at elevated temperatures is usually checked by measurements after annealing a part at 288°C (550°F).

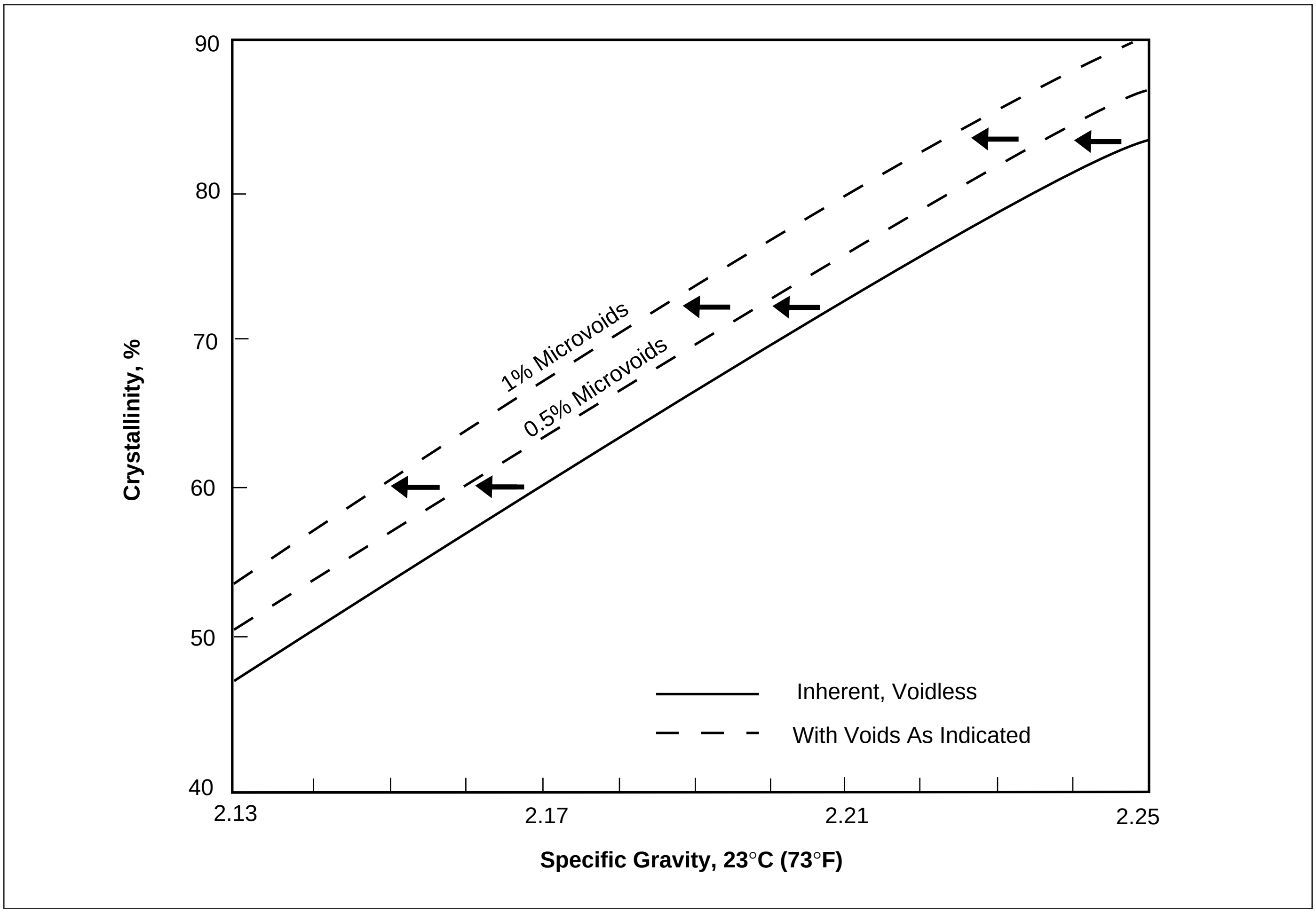
For films and tapes, pinhole counts and dielectric strength indicate degree of microporosity and the incidence of localized flaws. Measured specific gravity is used as an index of percent crystallinity. Tensile measurements, as in the case of sheeting, are used as an all-around index of quality.

Table 6
***Teflon*® PTFE Resins: ASTM Tests Applicable to Fabricated Parts**

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	D1710	—	D3294	—	—
Melting Point	D4894	D3293 D4895	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 2 in/min crosshead speed

Figure 1. Relation of Percent Crystallinity to Specific Gravity



Strength and Stiffness

General Characteristics

Fabricated shapes of *Teflon*® PTFE fluoropolymer resins are tough, flexible in thin sections, and fairly rigid in thick sections. Useful but varying mechanical properties are maintained from –268 to 260°C (–450 to 500°F) for *Teflon*® PTFE. Surfaces of fabricated parts have an extremely low coefficient of friction. Almost nothing sticks to them. However, specially treated surfaces will accept conventional industrial adhesives. *Teflon*® PTFE resins are almost completely inert to chemical attack, but, under special conditions, are affected by such substances as alkali metals and halogens. Low-loss electrical characteristics remain essentially constant, regardless of frequency, over a wide temperature range.

Teflon® PTFE resins tend to be opaque, crystalline, and malleable.

Teflon® PTFE resins can be aggregated into dense, coherent shapes at normal temperatures by various "preforming techniques," which apply uniform pressure to the unheated *Teflon*® PTFE resin. Preformed products are strengthened by heating above 327°C (620°F), generally 371–382°C (700–720°F), until the resin particles coalesce, and then cooling below 327°C (620°F). Products sintered in this manner may be further shaped by various postforming techniques that are preformed most readily at temperatures approaching but below the 327°C (620°F) transition temperature. Because *Teflon*® PTFE resins enter into a gel state at 327°C (621°F), which is not conducive to melt flow, preforming, sintering, and postforming are the processing techniques most commonly used.

Design Considerations

Parts to be made of *Teflon*® may be designed in exactly the same manner as parts made of other materials, such as steel, brass, lead, concrete, etc. Even the same formulas may be used if careful attention is paid to special characteristics of the resin. A *Teflon*® resin may be chosen in preference to other materials because of its better chemical resistance, heat resistance, friction coefficient, dielectric strength, toughness, weather resistance, or combination of such properties. Most materials are affected to some extent by temperature, moisture, and environment. Because *Teflon*® resins exhibit zero moisture absorption and are unaffected by almost all environmental conditions, designers will be interested mainly in property changes resulting from temperature variation.

When load is applied over a period of time, creep and cold flow must be considered. Consequently, data are presented for long-term loading as well as short-term loading. Information for the tables and charts was obtained from samples described in **Table 7**. These samples are representative of commercially available moldings.

Strength and Stiffness

Teflon® resins are engineering materials whose performance in any particular application may be predicted by calculation in the same manner as for other engineering materials. However, just as properties of woods are different from those of metals, the properties of *Teflon*® resins are different from those of other engineering materials. From the following data, strength and stiffness values can be selected which, with appropriate safety factors, will allow standard engineering formulas to be used in designing parts.

Table 7
***Teflon*® PTFE Granular Resin: Description of Samples Used in Tests**

Fabricated Form	Average Specific Gravity	Void Content	Crystallinity	Preform Pressure, MPa (psi)
Rod, 6 in long x 0.6 in diameter (molded)	2.17	<0.3%	60% ± 2%	17.2 (2,500)
Sheet, 14 in x 14 in, 1/8 in and 1/16 in thick	2.17	<0.3%	60% ± 2%	17.2 (2,500)

Tensile Stress

Stress-strain curves for temperatures in the usual design range (see **Figure 2a**) show that yield occurs at high deformations. Elastic response begins to deviate from linearity at strains of only a few percent, as with most plastics. Therefore, in designing with *Teflon*®, it is often best to work with acceptable strain and determine the corresponding stress. Curves that show ultimate tensile strength, the point at which fracture occurs, are given in **Figure 2b**.

Figure 3 shows strain at corresponding stresses for various temperatures. The percent strain selected for design calculations should take into account the highest temperature at which the part will operate. Because it is not always possible to work with an acceptable strain, **Table 8** gives the yield strength in psi as a function of temperature.

Table 8
Yield Strength at Various Temperatures

Temperature, °C (°F)	*Teflon*® PTFE Yield Strength, MPa (psi)
–251 (–420)	131 (19,000)
–196 (–320)	110 (16,000)
–129 (–200)	79.3 (11,500)
–73 (–100)	53.1 (7,700)
–56 (–68)	26.2 (3,800)
0 (32)	12.4 (1,800)
23 (73)	9.0 (1,300)
70 (158)	5.5 (800)
121 (250)	3.4 (500)

Compressive Stress

Compression and strain are indicated at three temperatures for *Teflon*® PTFE resins (see **Figure 4**). Stress-strain curves for compression are similar to those for tension at low values of strain (see **Figure 5**). However, as strain increases, the curves become less similar. Yield points for compression and tension occur at about the same stress values. For compression, the lower strains at higher stress may be a result of analyzing test data on the basis of original cross sections.

Shear Stress

Figure 6 is a plot of shear stress against shear strain. In a part subject to shear, a specified strain should be selected and the corresponding stress used for design calculations as mentioned previously.

Poisson's Ratio

Poisson's ratio is 0.46 at 23°C (73°F) and approaches a limiting value of 0.50 with increasing temperature.

Modulus of Elasticity

No attempt has been made to include data on modulus of elasticity. Because modulus of elasticity E is

$$E = \frac{\text{Stress (psi)}}{\text{Strain (in/in)}}$$

the preceding stress-strain curves permit substitution, when working at a specified strain, of the corresponding stress so that modulus of elasticity can be determined.

Figure 2a. Tensile Stress, Based on Original Cross Section

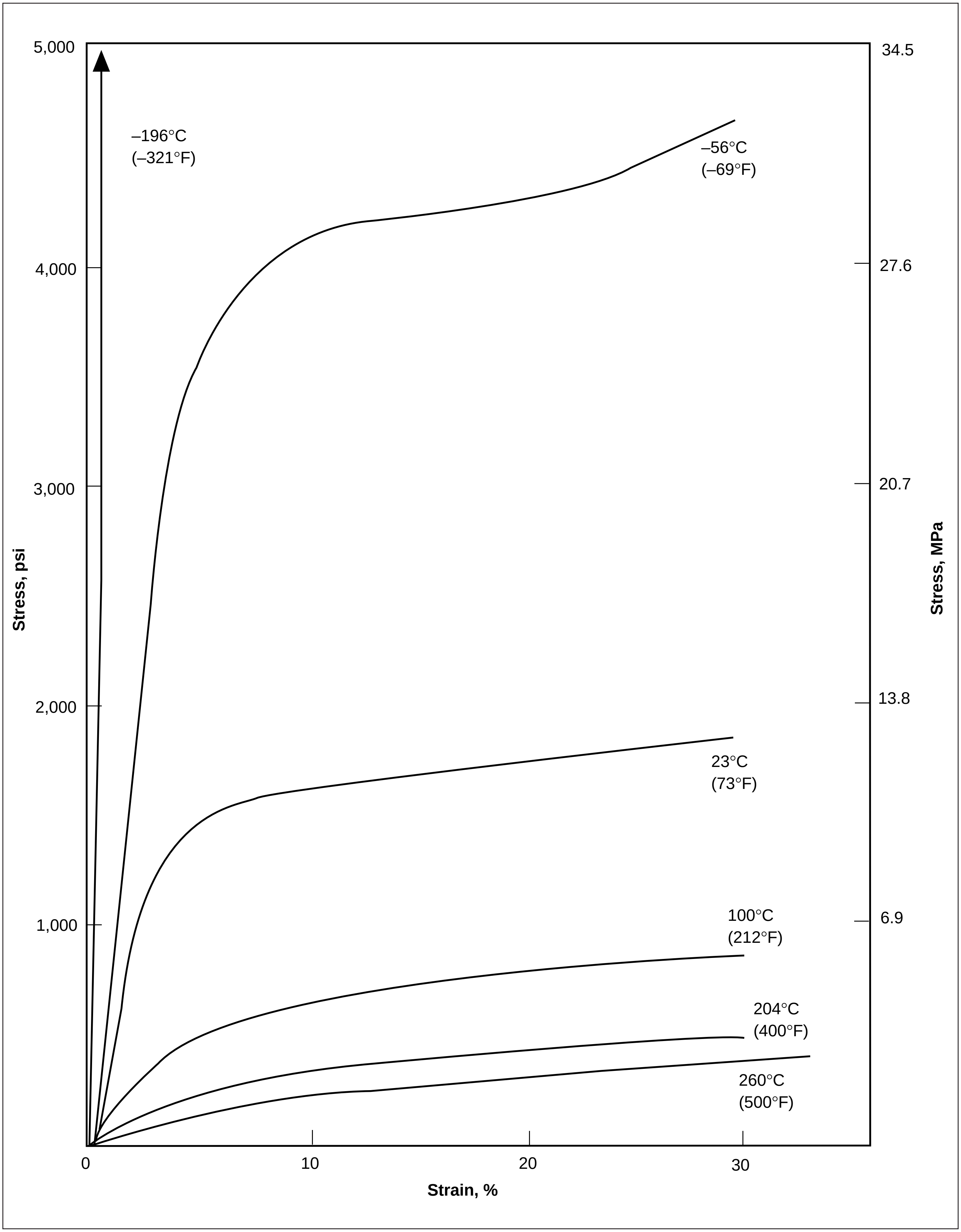


Figure 2b. Stress vs. Strain in Tension

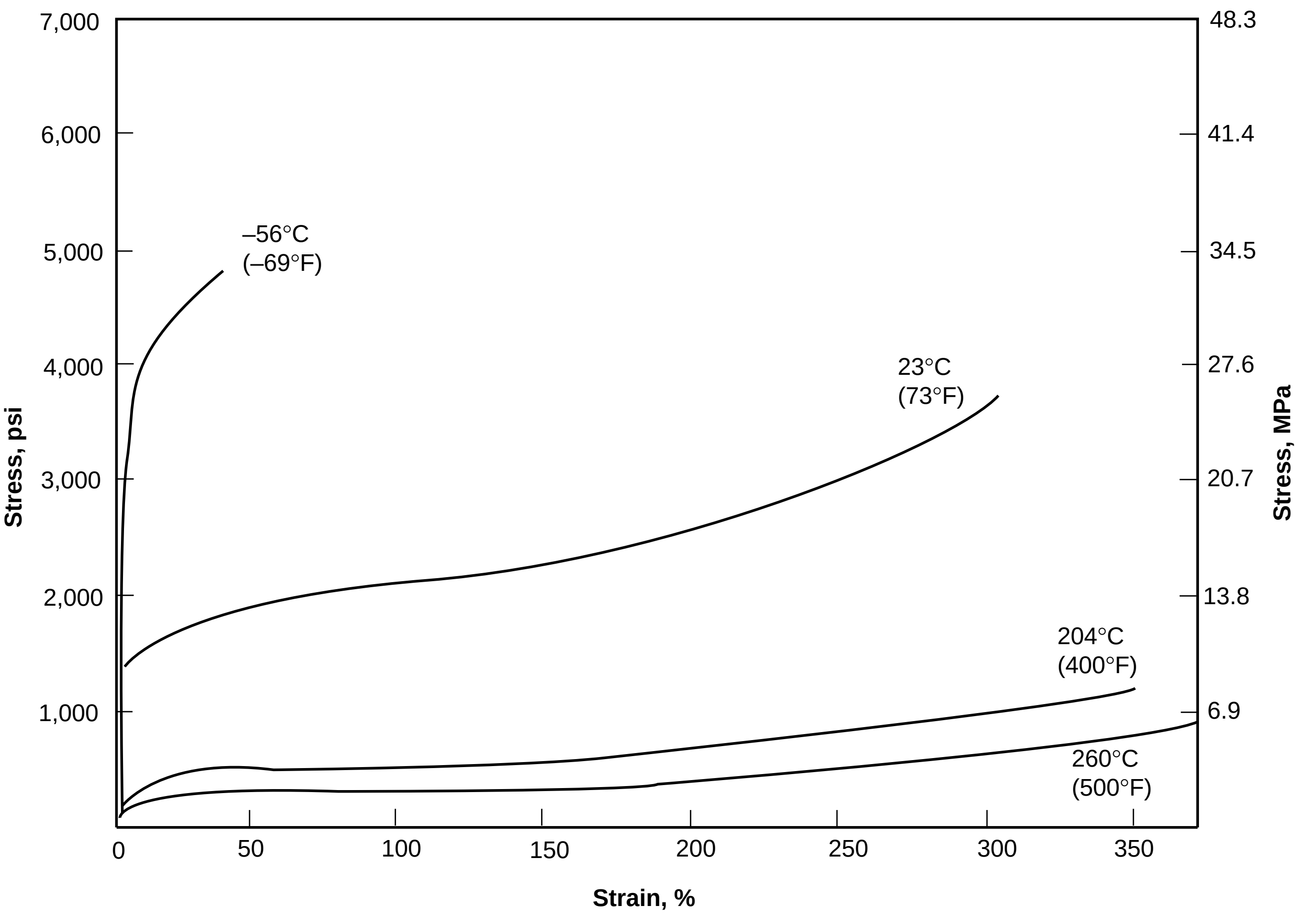


Figure 3. Tensile Stress vs. Temperature at Constant Strain

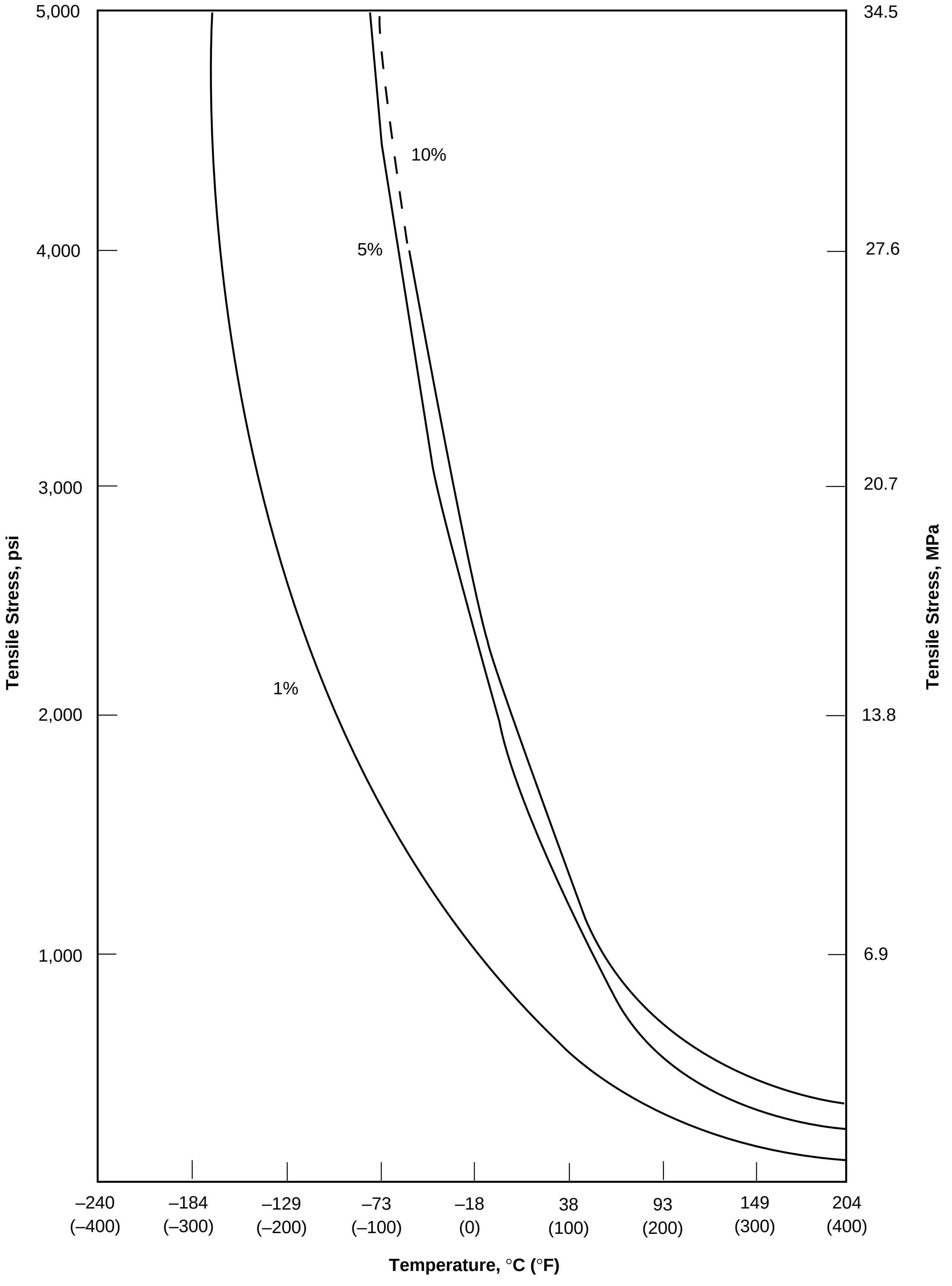


Figure 4. Stress vs. Strain in Compression (ASTM D695)

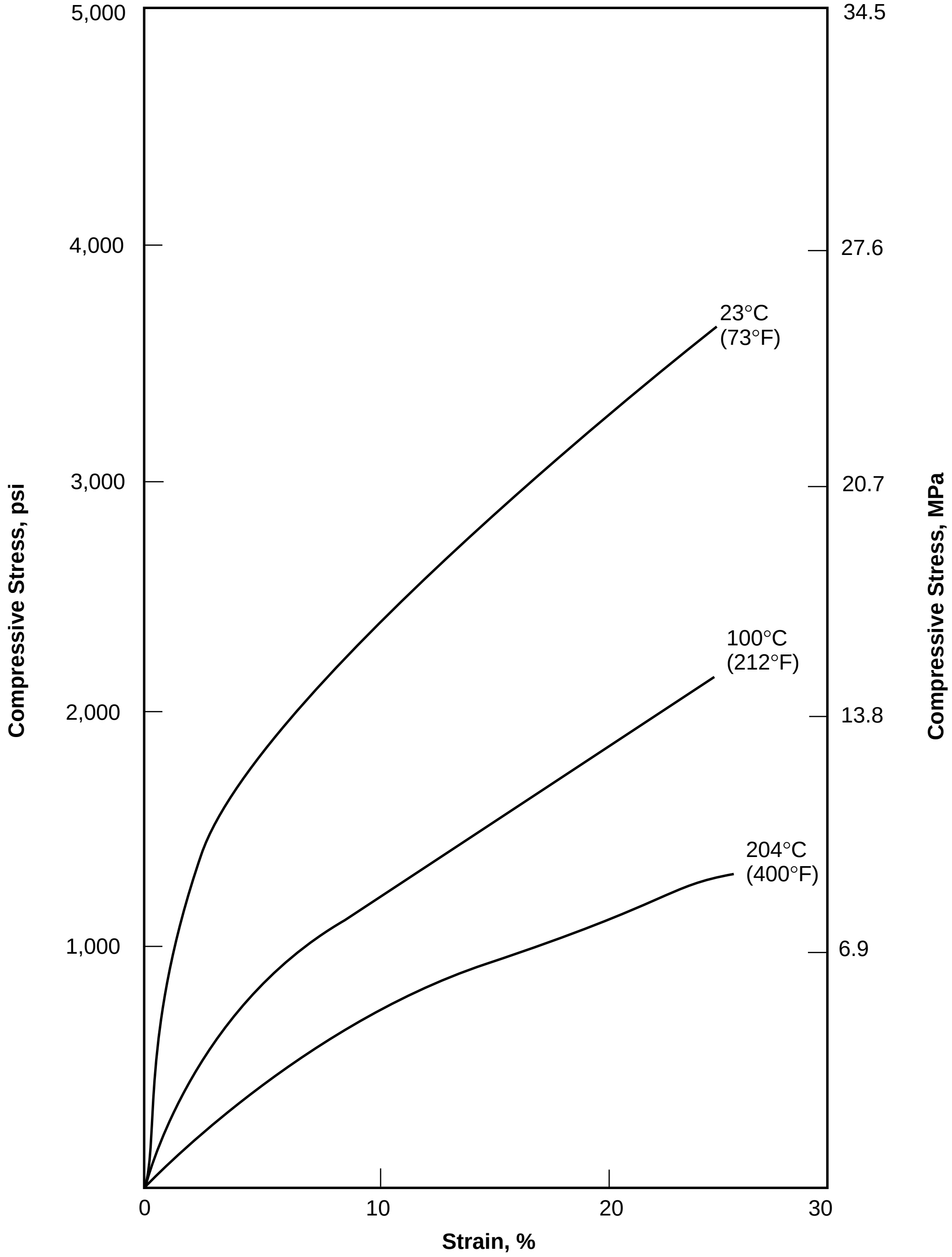


Figure 5. Stress vs. Strain in Tension and Compression (ASTM D695)

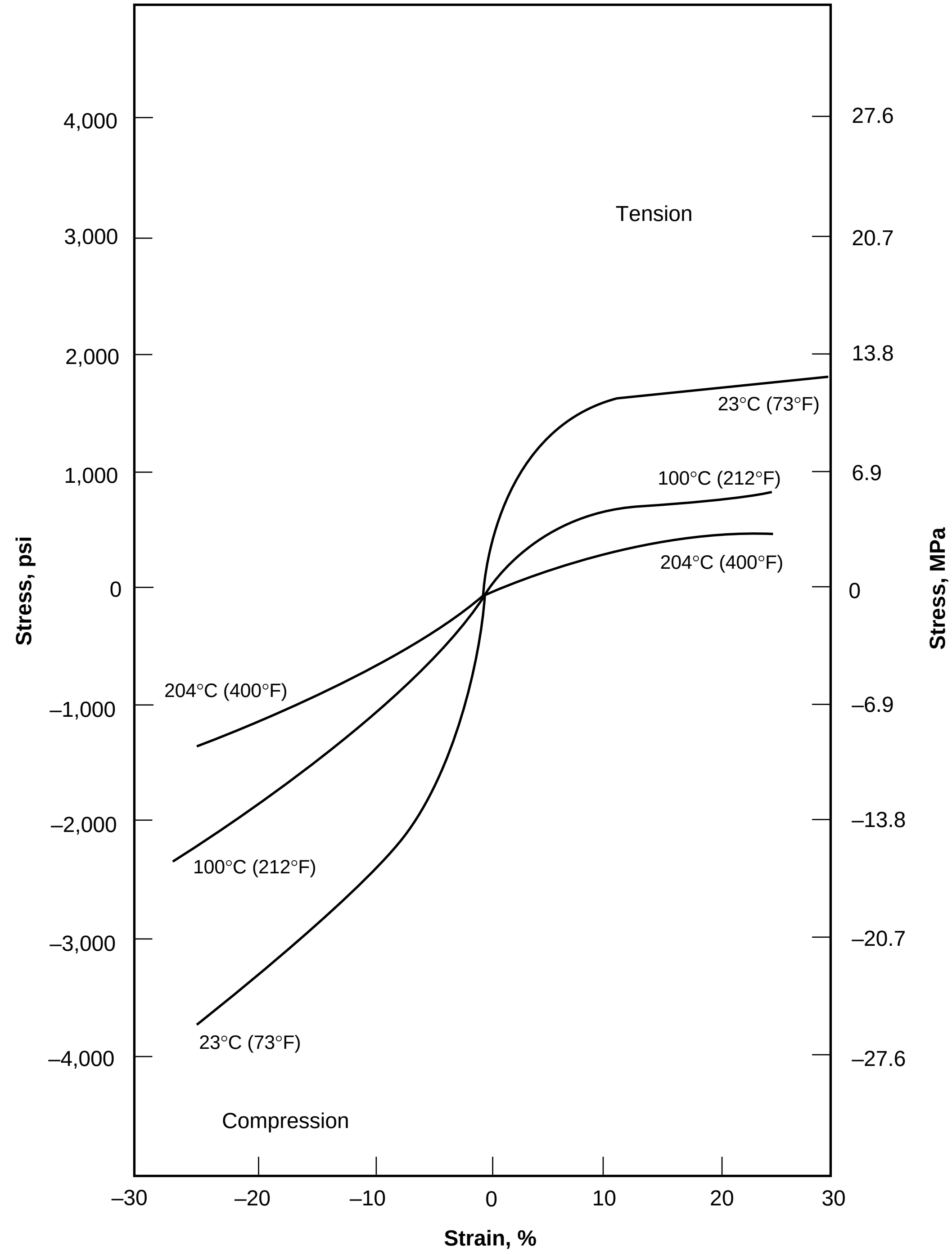
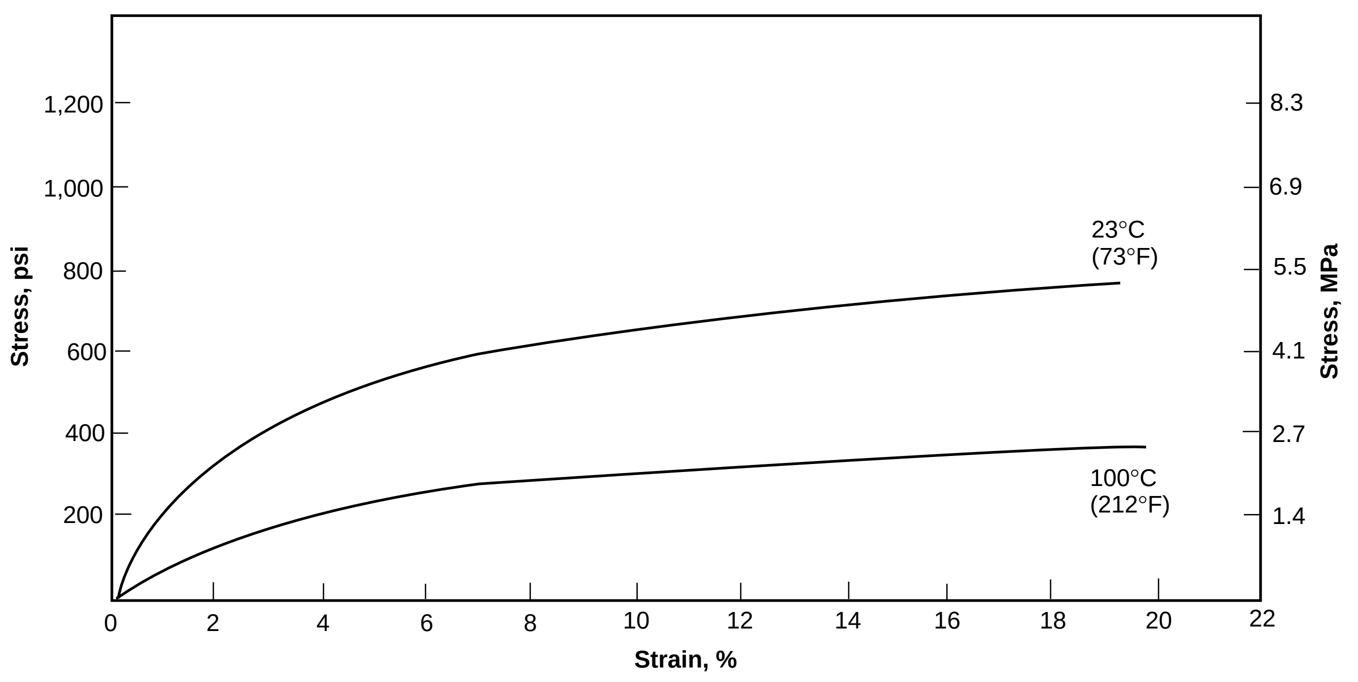


Figure 6. Stress vs. Strain in Shear to 20%



Creep and Cold Flow

A plastic material subjected to continuous load experiences a continued deformation with time that is called creep or cold flow. A similar phenomenon occurs with metals at elevated temperatures. With most plastics, however, deformation can be significant even at room temperature or below; thus, the name “cold flow.”

Creep is the total deformation under stress after a specified time in a given environment beyond that instantaneous strain that occurs immediately upon loading. Independent variables that affect creep are time under load, temperature, and load or stress level.

Initial strain or deformation occurs instantaneously as a load is applied to *Teflon*® resins. Following this initial strain is a period during which the part continues to deform but at a decreasing rate. Creep data over a wide range of temperatures are plotted for tensile loading in **Figures 7a** through **7d**, for compressive loading in **Figures 8a** and **8b**, and for torsional loading in **Figures 9a** and **9b**.

Apparent Modulus of Elasticity

The concept of “apparent modulus” is a convenient method for expressing creep because it takes into account initial strain for an applied stress plus the amount of deformation or strain that occurs with time. Thus, apparent modulus EA is

$$E_A = \frac{\text{Stress (psi)}}{\text{Initial Strain + Creep}}$$

Because parts tend to deform in time at a decreasing rate, the acceptable strain based on service life of the part must be determined—the shorter the duration of load, the higher the apparent modulus and the higher the allowable stress. Apparent modulus is most easily explained with an example.

As long as the stress level is below the elastic limit of the material, modulus of elasticity E is obtained from the above equation. For a compressive stress of 1,000 psi, **Figure 4** gives a strain of 0.015 in/in for *Teflon*® PTFE resin at 23°C (73°F). Then,

$$E = \frac{1{,}000}{0.015} = 66{,}700 \text{ psi}$$

If the same stress level prevails for 200 hr, total strain will be the sum of initial strain plus strain due to time. This total strain is obtained from **Figure 8a** where total deformation under compressive load for 200 hr is 0.02 in/in for *Teflon*® PTFE resin. Therefore,

$$E_A = \frac{1{,}000}{0.02} = 50{,}000 \text{ psi}$$

Similarly, E_A can be determined for 1 yr. Extrapolation of the curve in **Figure 8a** gives a deformation of 0.025 in/in, and

$$E_A = \frac{1{,}000}{0.025} = 40{,}000 \text{ psi}$$

When plotted against time, these calculated values for “apparent” modulus provide an excellent means for predicting creep at various stress levels. For all practical purposes, curves of deformation versus time eventually tend to level off. Beyond a certain point, creep is small and may be neglected for many applications.

Stress Relaxation

When materials that creep or cold flow are used as gaskets in flanged joints, the phenomenon of stress relaxation is generally encountered. In flanged, bolted connections, parts of *Teflon*® will cold flow between the flange faces with a resultant decrease in bolt pressure. Such relaxation in gasket stock may result in a leaky joint. Tightening the flange bolts during the first day after installation will usually maintain bolting pressure and prevent leakage; thereafter, stress relaxation will be negligible.

Typical curves for tensile stress relaxation illustrate the rates at which tensile stress decays when the specimen is maintained at constant strain (see **Figures 10a** and **10b**).

Compressive Recovery

Specimens that were successively compressed and allowed to recover from various percentages of strain indicate that they experience no work hardening. Recovery of the specimen is nearly complete, provided the original strain does not exceed the yield strain.

Recommendation for Gasket Design

To minimize creep and stress relaxation in gaskets, the following rules are recommended:

- Use bolting loads less than 6.9 MPa (1,000 psi) for unconfined gaskets.
- Specify the thinnest possible gasket that will accommodate flange roughness. Gaskets thicker than approximately 1.6 mm (1/16 in) increase the amount and rate of stress relaxation.
- Use reinforced compositions made with *Teflon*® resin, such as 60% *Teflon*® resin and 40% fiber, for temperatures higher than 149°C (300°F).
- Design a "self-contained" joint with captive gasket when such construction is desirable.

It is advisable to check the torque on a gasket made from *Teflon*® PTFE and to retighten once, if needed, following the first 24 hr in service.

The three forces that act on a gasket that is bolted securely in position are: bolt load, hydrostatic end force, and internal pressure. The procedure in the 1959 ASME Boiler and Pressure Vessel Code, Section VIII, Appendix II, may be used to calculate required bolt loadings for solid gaskets of *Teflon*® PTFE resins. The method requires knowledge of the "yield stress" and the "gasket factor." Yield stress is the stress required to seal the gasket or the minimum stress that will effect a seal against even slight fluid pressure. As internal pressure is applied to the vessel, the flanges tend to separate, thus lowering the effective stress on the gasket. Obviously, to maintain the seal requires that resultant stress on the gasket exceed the internal pressure. The minimum required ratio of these pressures is called the gasket factor.

Proved values for yield stress and gasket factor are listed in **Table 9** for solid *Teflon*® PTFE resins. With these values, the necessary gasket load can be calculated from Formula UA-47-2 given in the above ASME reference. Required gasket load can then be converted to bolt load by standard mechanical engineering calculations (see Mechanical Engineers' Handbook, Marks, Sixth Edition, Section 3, page 48).

Table 9
Values for Calculations of Required Gasket Loads

***Teflon*® PTFE Thickness, mm (in)**	**Yield Stress, MPa (psi)**	**Gasket Factor**
3.1 (1/8)	8.3 (1,200)	2.00
2.4 (3/32)	9.3 (1,350)	2.50
1.6 (1/16)	11.0 (1,600)	2.75
0.8 (1/32)	22.1 (3,200)	3.50

Gaskets made by enveloping fillers or rubber in molded *Teflon*® PTFE resin are widely used for flanged connections to glass-lined reaction vessels and to glass-lined pipe. Spiral-wound gaskets of stainless steel and sheet stock of *Teflon*® resin have been used successfully in both large and small flanged joints requiring high bolting pressures. Molded *Teflon*® PTFE resins, either alone or in combination with other gasket materials, also give excellent service under the most corrosive conditions encountered in the chemical industry.

The performance of *Teflon*® PTFE resins is improved considerably by use of fillers. Such modification affects certain mechanical properties and permits resin filler compositions to be tailored to the requirements of a wide variety of mechanical, electrical, and chemical applications.

In general, *Teflon*® PTFE resins can be compounded to increase:

- Resistance to initial deformation under load by approximately 25%
- Resistance to rotating shaft wear by as much as 500×
- Stiffness by a factor of two or three
- Thermal conductivity by a factor of five
- Resistance to creep approximately twofold
- Thermal dimensional stability by a factor of two
- Hardness by approximately 10%

Further, modified compositions retain the desirable properties of uncompounded *Teflon*®.

Figure 7a. Total Deformation vs. Time Under Load at –54°C (–65°F)

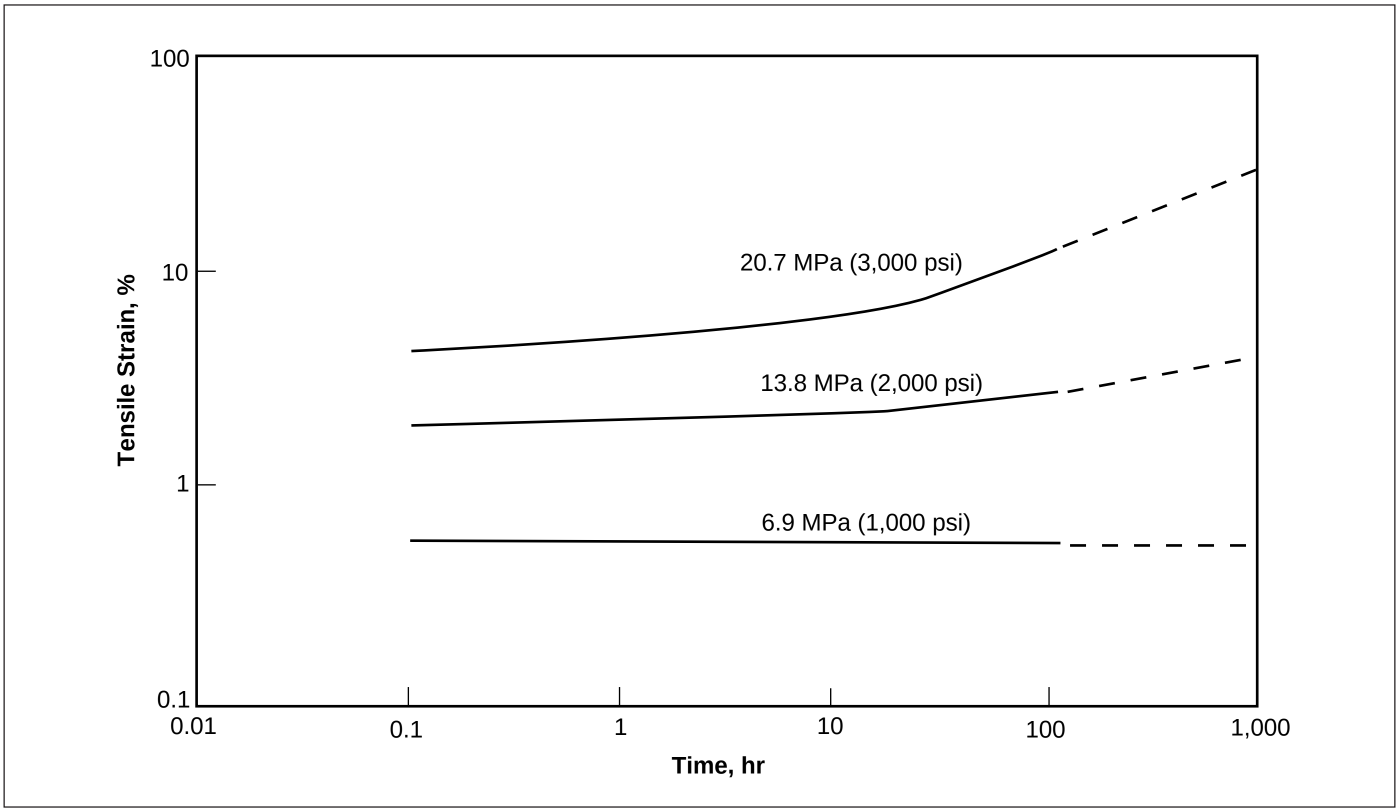


Figure 7b. Total Deformation vs. Time Under Load at 23°C (73°F)

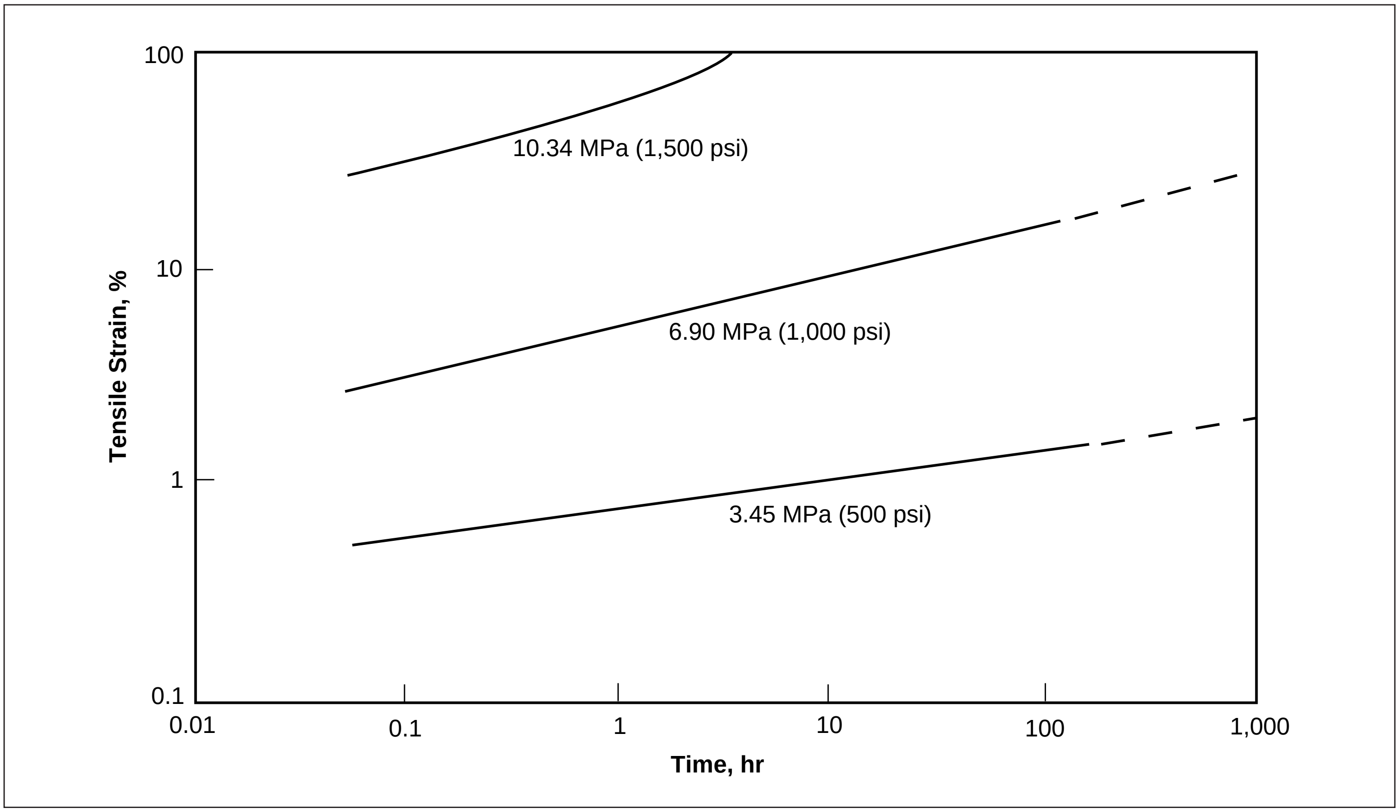


Figure 7c. Total Deformation vs. Time Under Tensile Load at 100°C (212°F)

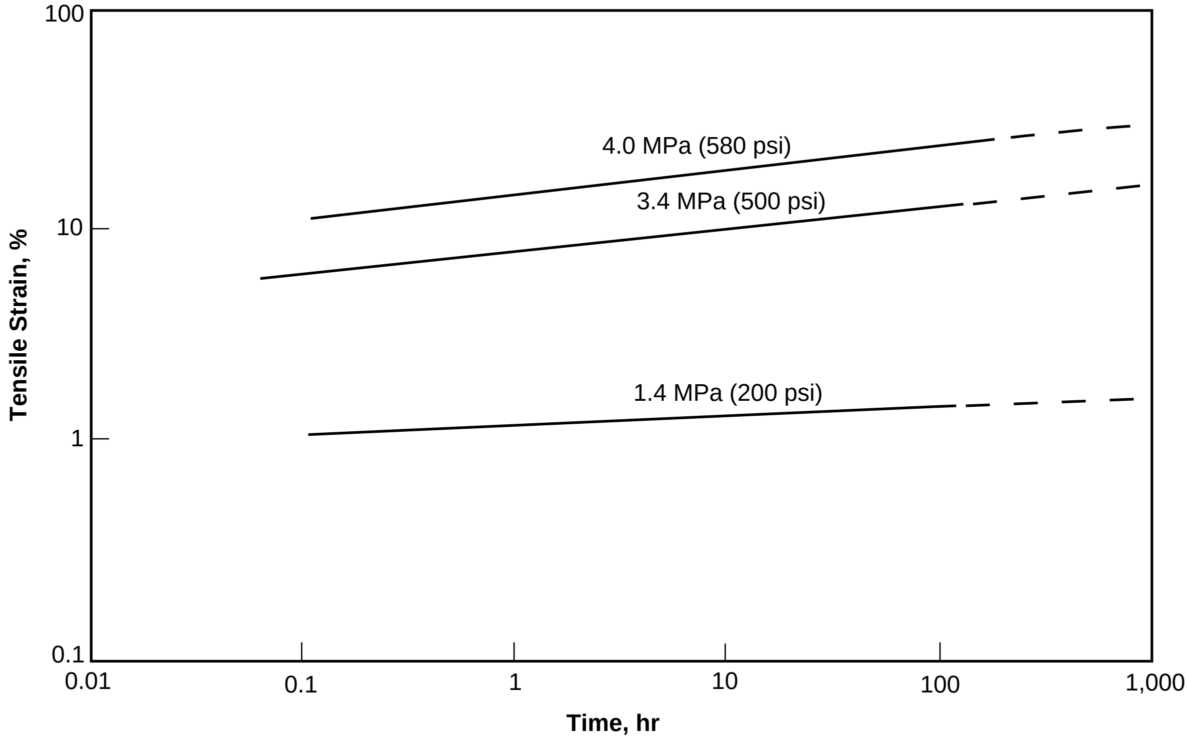


Figure 7d. Total Deformation vs. Time Under Tensile Load at 200°C (392°F)

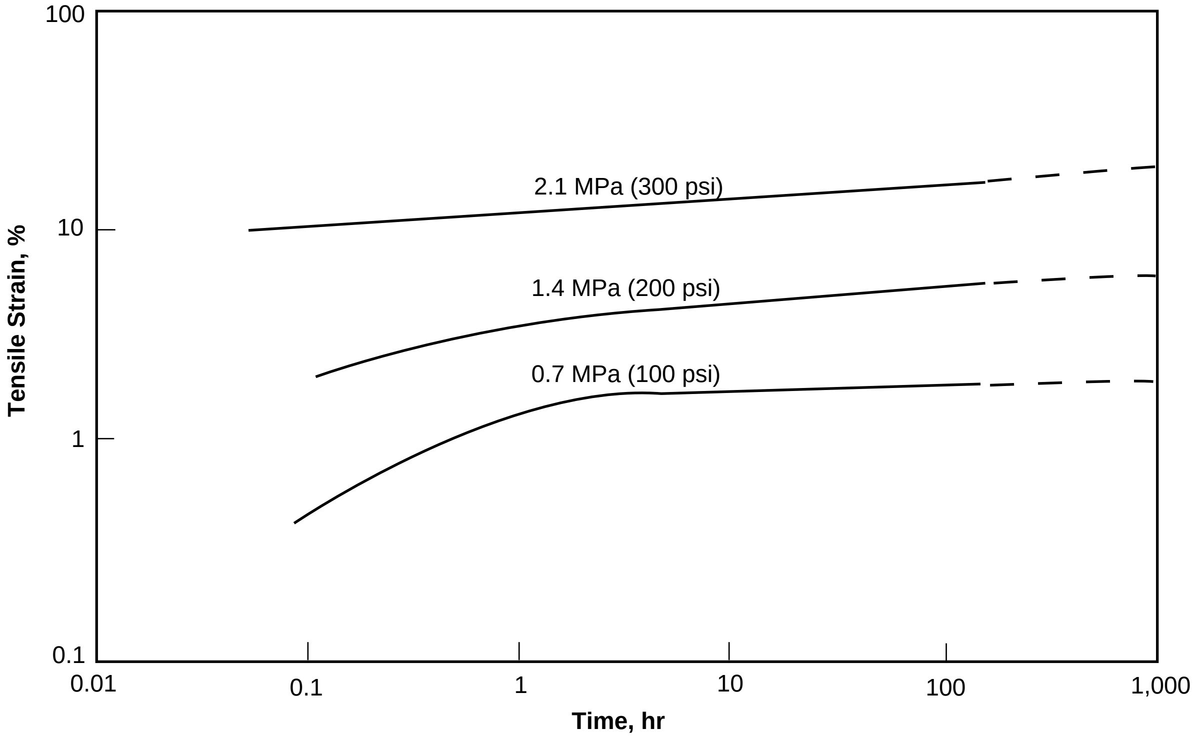


Figure 8a. Total Deformation vs. Time Under Compressive Load at 23°C (73°F)

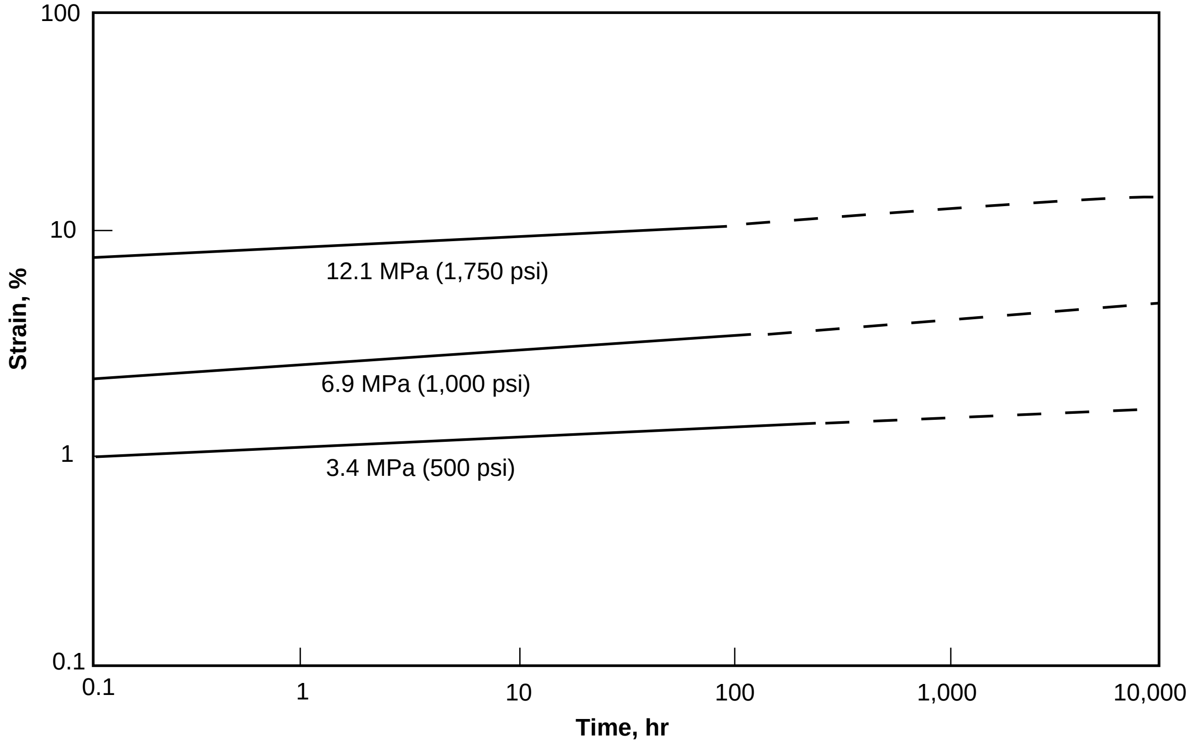


Figure 8b. Total Deformation vs. Time Under Compressive Load at 100°C (212°F)

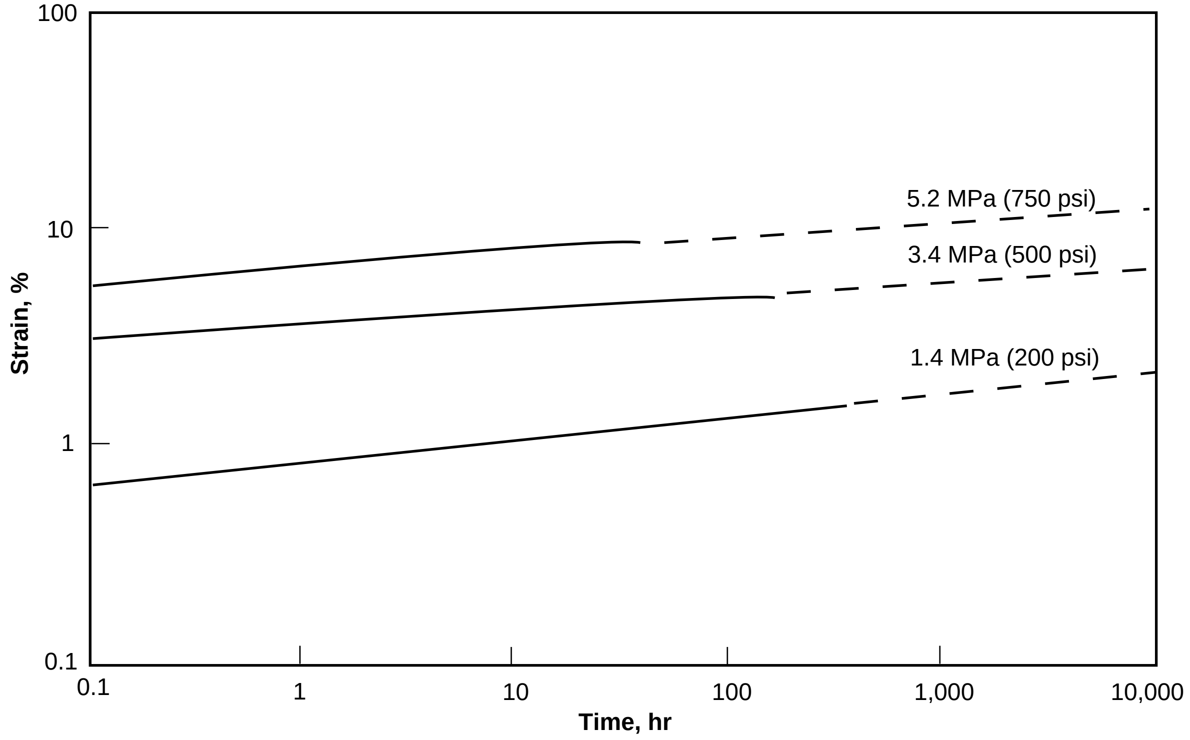


Figure 9a. Total Deformation vs. Time Under Torsional Load at 23°C (73°F)

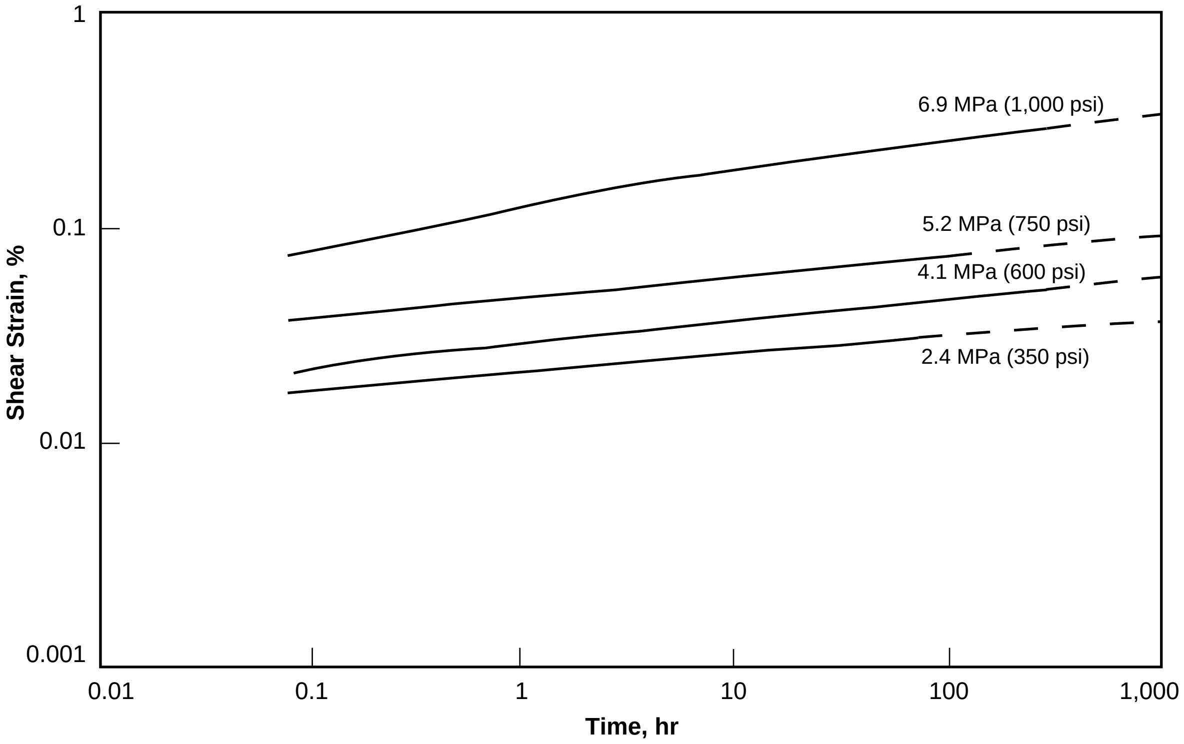


Figure 9b. Total Deformation vs. Time Under Torsional Load at 100°C (212°F)

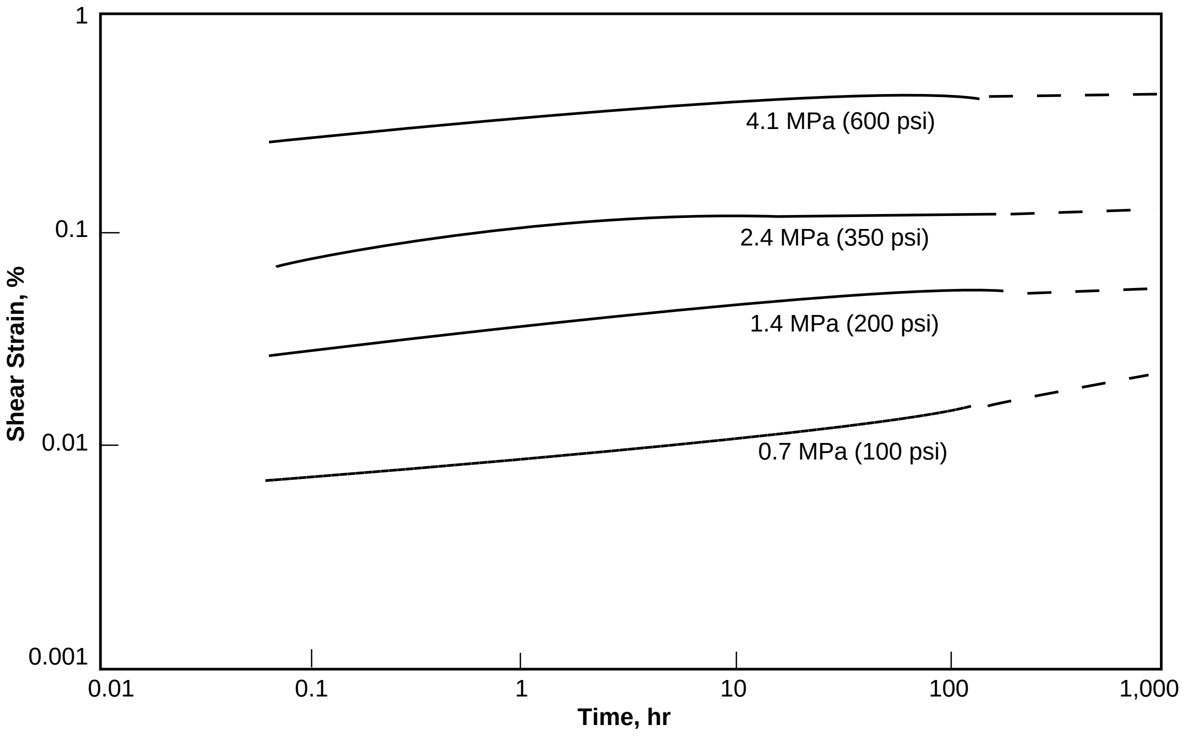


Figure 10a. Tensile Strength Relaxation at 23°C (73°F)

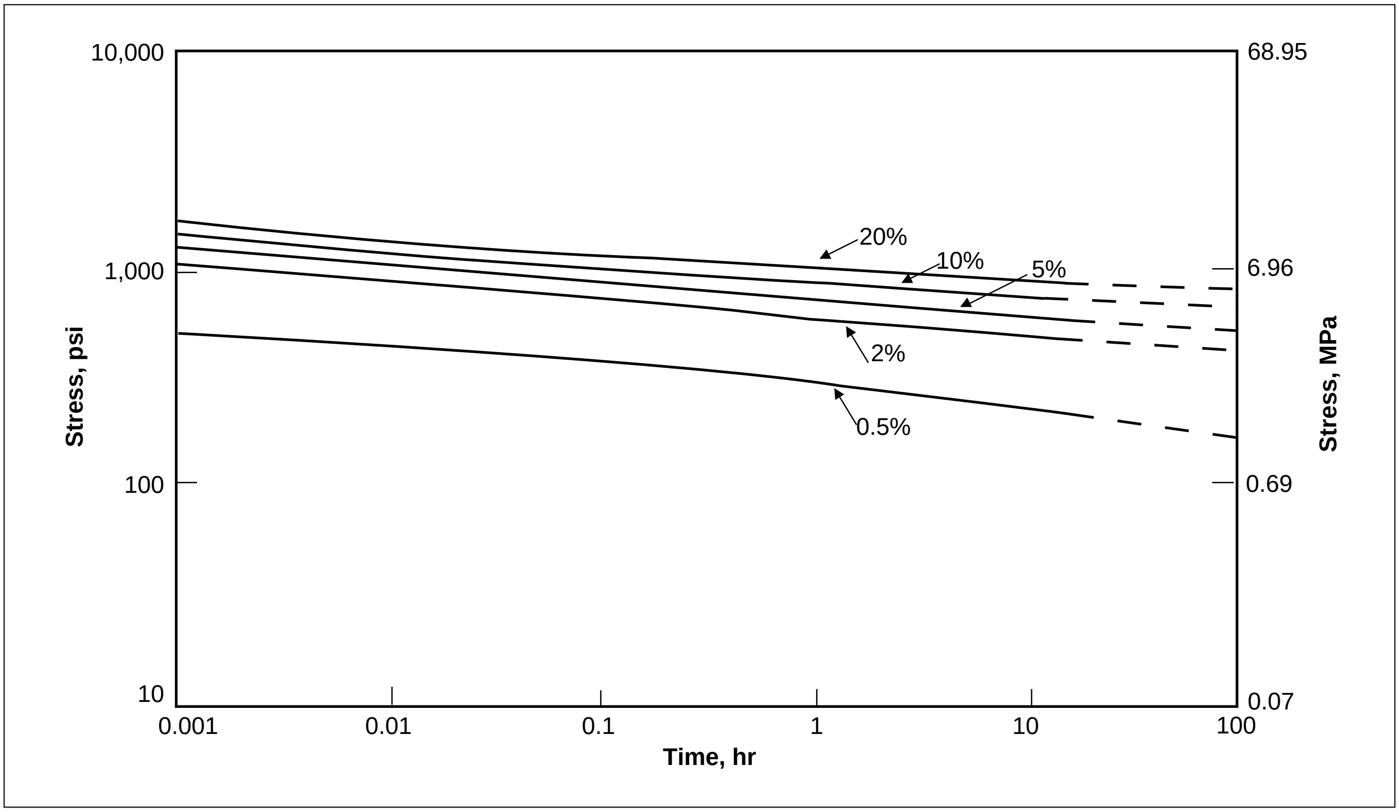
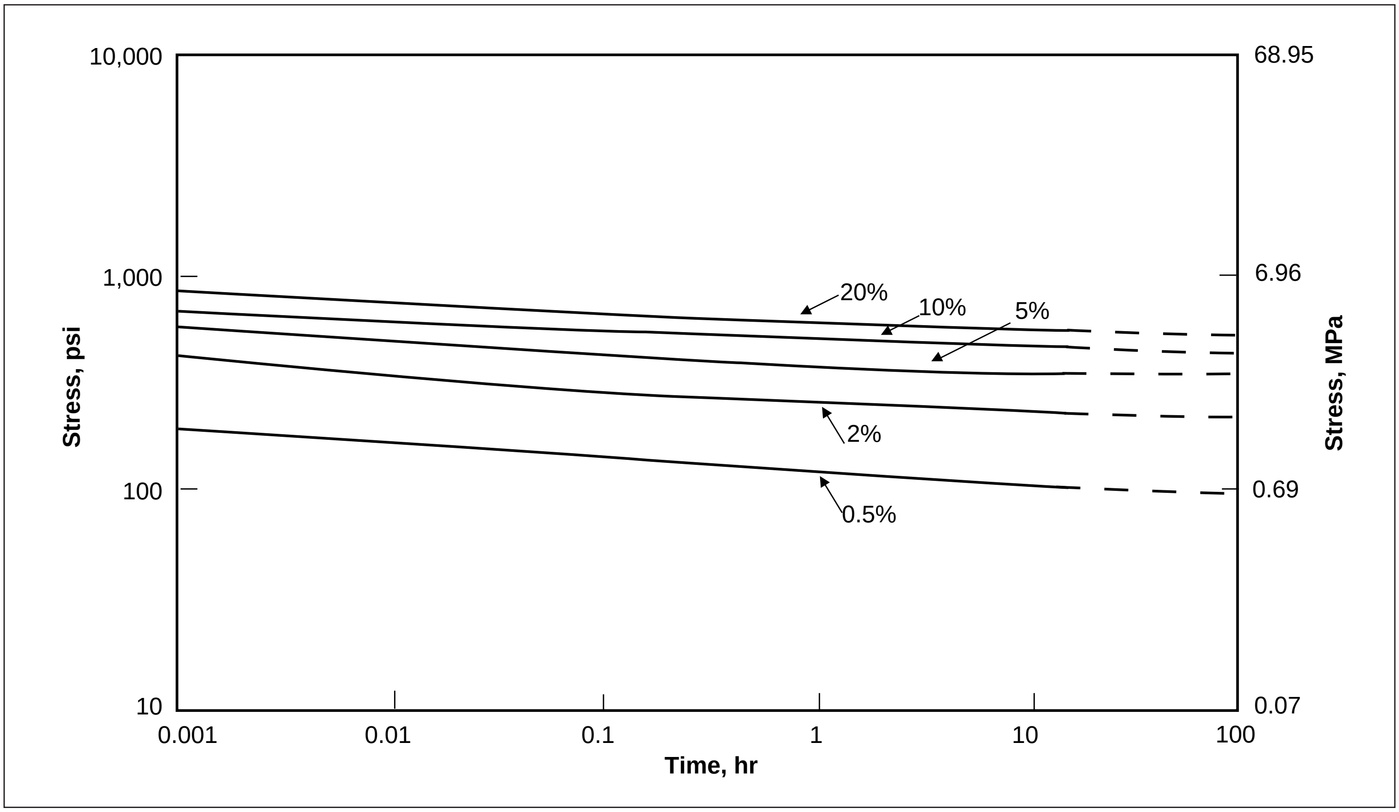


Figure 10b. Tensile Strength Relaxation at 100°C (212°F)



Effect of Temperature, Fatigue, and Impact

Thermal Expansion

Linear expansion of *Teflon*® PTFE fluoropolymer resins is shown in **Figure 11** and **Table 10**. A marked change in volume of 1.0 to 1.8% is evident for *Teflon*® PTFE resins in the transition zone from 18–25°C (65–77°F). A part that has been machined on either side of this zone will obviously change dimensions if permitted to go through the zone. Thus, final operating temperature of a precision part must be accurately determined. Measurement on a production basis must allow for this volume change if the transition zone is traversed in either manufacture or operation of the part. **Table 11** gives the coefficient of cubical expansion for various temperature ranges.

Table 10
***Teflon*® PTFE Resins**
Linear Coefficients of Expansion

Temperature Range, °C (°F)	Linear Coefficient of Expansion, 10^{-5} mm/mm·°C	(10^{-5} in/in·°F)
25 to –190 (77 to –310)	8.6	4.8
25 to –150 (77 to –238)	9.6	5.3
25 to –100 (77 to –148)	11.2	6.2
25 to –50 (77 to –58)	13.5	7.5
25 to 0 (77 to 32)	20	11.1
10 to 20 (50 to 68)	16	8.9
20 to 25 (68 to 77)	79	43.9
25 to 30 (77 to 86)	16	8.9
25 to 50 (77 to 122)	12.4	6.9
25 to 100 (77 to 212)	12.4	6.9
25 to 150 (77 to 302)	13.5	7.5
25 to 200 (77 to 392)	15.1	8.4
25 to 250 (77 to 482)	17.5	9.7
25 to 300 (77 to 572)	22	12.1

Table 11
***Teflon*® PTFE Resins**
Cubical Coefficients of Expansion

Temperature Range, °C (°F)	$cm^3/cm^3 \cdot °C$	$in^3/in^3 \cdot °F$
–40 to 15(–40 to 59)	2.6×10^{-4}	1.5×10^{-4}
15 to 35 (59* to 95)	1.7%	
35 to 140 (95 to 284)	3.1×10^{-4}	1.7×10^{-4}
140 to 200 (284 to 392)	6.3×10^{-4}	3.5×10^{-4}
200 to 250 (392 to 482)	8.0×10^{-4}	4.4×10^{-4}
250 to 300 (482 to 572)	1.0×10^{-3}	5.7×10^{-4}

*Quinn et al., *J. Applied Phys. 2*2, 1085 (1951)

Low Temperature Properties

Parts fabricated of *Teflon*® PTFE resins exhibit high strength, toughness, and self-lubrication at low temperatures. *Teflon*® PTFE resins are useful from –268°C (–450°F) and are highly flexible from –79°C (–110°F).

Thermal Conductivity and Specific Heat

The average thermal conductivity of *Teflon*® PTFE is 1.7 ± 0.3 Btu·in/h·ft^2·°F. The average heat capacity is 0.3 Btu/lb·°F for *Teflon*® PTFE. These data were obtained at temperatures ranging from 20–260°C (68–500°F).

Heat Distortion

Temperatures obtained for heat distortion of *Teflon*® PTFE are (ASTM D648) 122°C (252°F) for a stress of 66 psi and 56°C (132°F) for a stress of 264 psi.

Elastic Memory

Parts made from *Teflon*® PTFE resins tend to return to their original dimensions after a deformation, but the process of recovery may require a long time. A fabricated part that creeps or deforms over a period of time under stress will recover its original shape when stress is removed and the part is raised to sintering temperature. However, partial recovery will occur at lower temperatures. At any given temperature, recovery to be expected at that temperature is substantially complete in 15 min or less, but extent of recovery increases with increased temperature.

For example, a filament of *Teflon*® PTFE 4 in long, stretched to a length of 12 in and heated at 100°C (212°F), recovers to approximately 11 in within 15 min and then remains substantially unchanged. A similar piece heated to 200°C (392°F) recovers to 10 in. The first piece, after additional heating to 200°C (392°F), undergoes further recovery until it is 10 in long. When heated to 350°C (662°F), both pieces return to their original length of 4 in.

Figure 11. Linear Thermal Expansion vs. Temperature

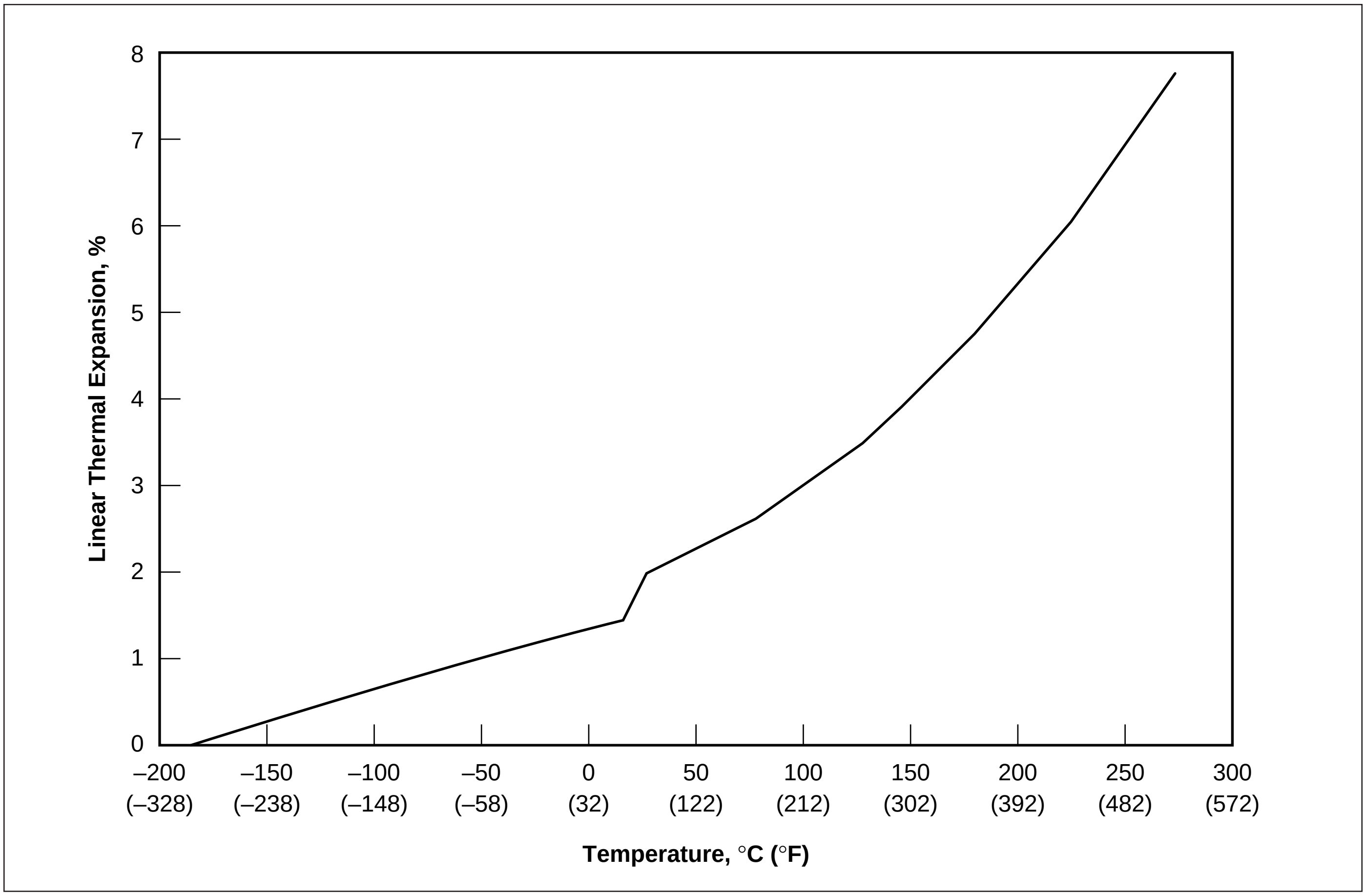


Table 12
***Teflon*® PTFE Resins: Decomposition Rates at Elevated Temperatures**

	Rate of Decomposition, %/hr		
	Fine Powder	Granular Resin	
Temperature, °C (°F)	Initial	Initial	Steady State
232 (450)	0.0001–0.0002	0.00001–0.00005	1×10^{-11}
260 (500)	0.0006	0.0001–0.0002	100×10^{-11}
316 (600)	0.005	0.0005	0.000002
371 (700)	0.03	0.004	0.0009

Decomposition at Elevated Temperatures

Rate of decomposition of a part of *Teflon*® PTFE depends on the particular resin, temperature, heat-exposure time, and, to a lesser extent, pressure and nature of the environment. In designs where the rate of outgassing is important, as in high-vacuum work or for safety considerations, initial rates of decomposition in **Table 12** may be used. For most applications these decomposition rates are small enough below the maximum service temperature (260°C [500°F] for *Teflon*® PTFE resins), and no special precautions are necessary. Where temperatures run above 343°C (650°F) during fabrication, proper ventilation is required.

Experience indicates that in many instances the rate of decomposition of an article fabricated from *Teflon*® PTFE resin decreases after continual exposure. For example, when parts made of *Teflon*® PTFE are used, a very low, fairly steady decomposition rate is established after less than 1% of the resins have decomposed.

Impact

Ability to absorb impact energy, or impact toughness, is difficult to predict in a part because shape has a major effect on performance. Understanding how a part resists impact, however, helps in selecting a good design.

The energy of an impact has to be absorbed by a force developed within the part multiplied by the distance the part can deform. Designing flexibility into the part to lengthen the distance over which the energy is absorbed greatly reduces the internal force required to resist the impact. For example, a rigid base made from spring steel would not have as high a capacity for absorbing energy as a coil spring made from the same material. The same factors that affect metals also affect plastics. As more and more flexibility is designed into a part subject to impact load, the better the part will perform.

Teflon® PTFE resins have excellent impact strength over a wide range of temperatures. Average values for specimens subjected to the tensile and Izod impact tests are given in **Table 13**.

There is no exact method for relating impact test data to actual design calculations or performance. Generally, in addition to incorporating flexibility, the most important method for obtaining toughness or impact resistance is to eliminate all sharp corners and other features subject to high stress concentration. For exact design, prototype models must be tested under actual loads.

Table 13
Tensile and Izod Impact Strength

		Impact Strength	
Resin	Temperature, °C (°F)	Tensile, ft•lb/in³	Izod,* ft•lb/in
Teflon® PTFE	23 (73)	320	2.9
	–54 (–65)	105	2.3

*ASTM D256

Hardness and Friction

Hardness

Table 14 lists the hardness of *Teflon*® PTFE resins as determined by various tests. Fillers elevate the hardness of *Teflon*® PTFE resins by 10 to 15% and much of the improvement is retained over a wide temperature range. In general, the greater the filler loading, the harder the compound. Spherical or flake fillers impart the best hardness.

Table 14
Hardness

Resin	Rockwell R Scale*[11]	Durometer D Scale**	Durometer A Scale**
Teflon® PTFE	58	52	98

*ASTM D785 or D2240
**23°C (73°F)

Friction (Granular)

Teflon® PTFE has a smooth surface with a slippery feel. Because of the low coefficient of friction of *Teflon*® PTFE (see **Table 15**), there have been many practical nonlubricated and minimally lubricated mechanical systems developed.

Table 15
Coefficient of Friction

Property	***Teflon*® PTFE**
Static Load, 500 psi	0.05–0.08
Dynamic PV, 8,000 to 10,000,	
at 10 fpm	0.10
at 100 fpm	0.13
at 1,000 fpm	Unstable Operation

Teflon® PTFE resins exhibit exceptionally low friction in nonlubricated applications, especially at low surface velocities and pressures higher than 5 psi. The coefficient of friction increases rapidly with sliding speeds up to about 100 ft/min, under all pressure conditions. This pattern of behavior (see **Figure 12**) prevents “stick-slip” tendencies. Moreover, no “squeaking” or noise occurs, even at the slowest speeds. Above 150 ft/min, sliding velocity has relatively little effect at combinations of pressure and velocity below the composition’s PV limit. **Figure 13** indicates that static friction of *Teflon*® PTFE resins decreases with increases in pressure.

PV limits presented in **Table 16** define the maximum combinations of pressure and velocity at which these materials will operate continuously without lubrication. They are based on operation in air at ambient temperatures of 21–27°C (70–80°F). The PV limits of all *Teflon*® PTFE resin matrix compositions approach zero at 288–315°C (550–600°F) ambient temperature. In other words, the limiting surface temperature for operation of *Teflon*® PTFE compositions is 288–315°C (550–600°F), regardless of the cause of the temperature. Reduced ambient temperatures, below 21°C (70°F), and/or cooling will provide increased PV limits.

PV limit does not necessarily define useful combinations of pressure and velocity because wear is not considered in its determination. The useful PV limit of a material cannot exceed the PV limit and must take into account the composition’s wear characteristics and the allowable wear for the application.

Wear factor, K, is a proportionality factor relating to the wear of a nonlubricated surface (operating against a specific mating surface at combinations of pressure and velocity below the material’s PV limit). The wear factors listed in **Table 16** can be used to predict wear against specific mating surfaces, using the following expression:

$$t = KPVT$$

where t = wear, in

K = wear factor, $\dfrac{\mathrm{in}^3\cdot\mathrm{min}}{\mathrm{lb}\cdot\mathrm{ft}\cdot\mathrm{h}}$

P = pressure, psi

V = velocity, fpm

T = time, h

Table 16
PV and Wear Performance

Property	***Teflon*® PTFE**
PV Limit (lb/in² x fpm)*	
at 10 fpm	1,200
at 100 fpm	1,800
at 1,000 fpm	2,500
PV for 0.005 in radial wear in 1,000 hr** (nonlubricated)	20
Wear Factor, K (x 10^{-10}) (in³·min/ft·lb·hr)***	2,500

* Ambient temperature 21–27°C (70–80°F)

** Based on (1) unidirectional load on fixed bushing or (2) thrust washer

*** At PV values below the composition’s PV limit when operating unlubricated against soft carbon steels (R_c20 to 25) finished to 12–20 µin (AA). Factor is also applicable for operation against most stainless steels and cast irons.

Abrasion and Wear (Granular)

Parts fabricated from *Teflon*® PTFE resins have good wear properties as previously shown in **Table 16**. **Tables 17, 18,** and **19** indicate the abrasion resistance of unfilled fluoropolymer resins for various types of tests. These three tests do not represent typical bearing wear because in each a new abrading surface is being continuously presented versus a repeating surface.

Figure 12. Coefficient of Friction vs. Sliding Speed

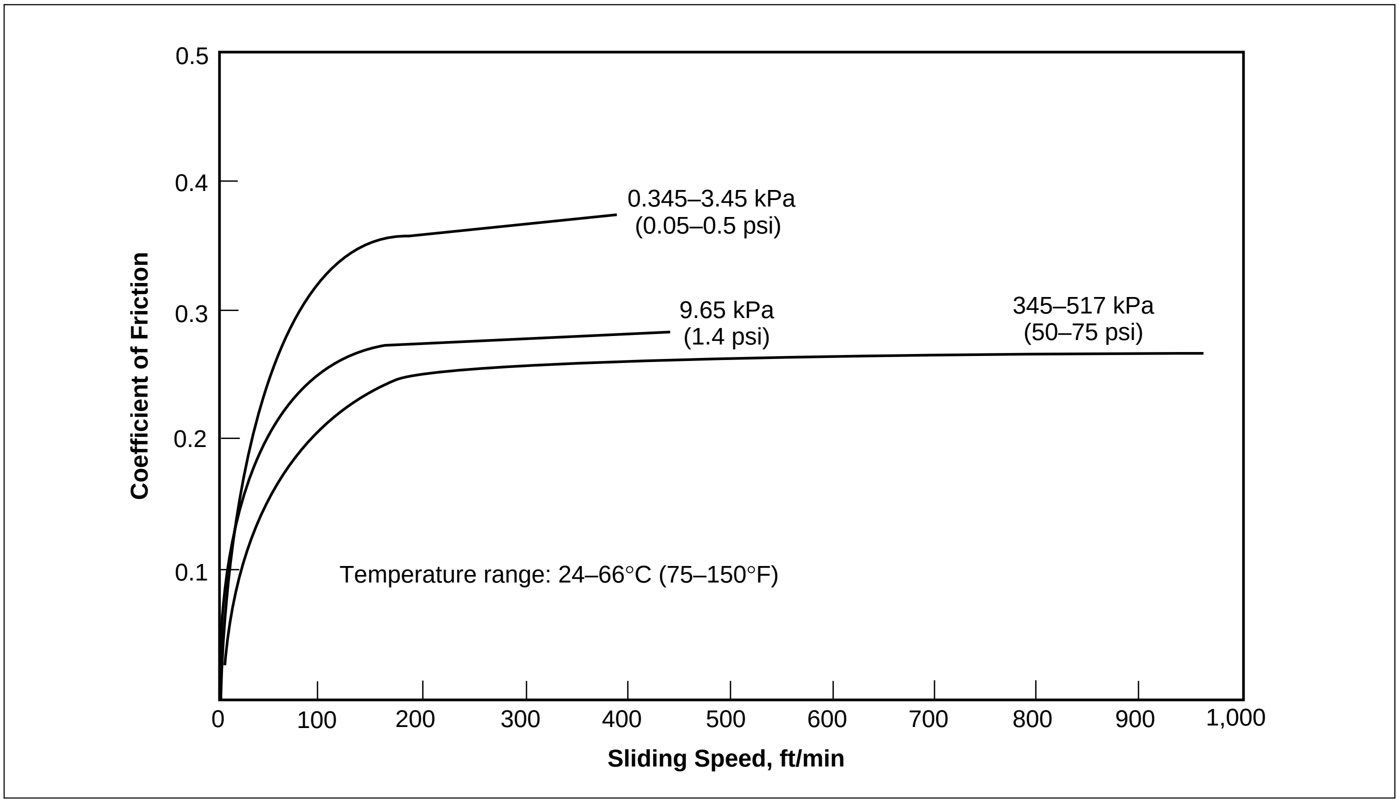


Figure 13. Coefficient of Friction vs. Load (at <2 ft/min and room temperature)

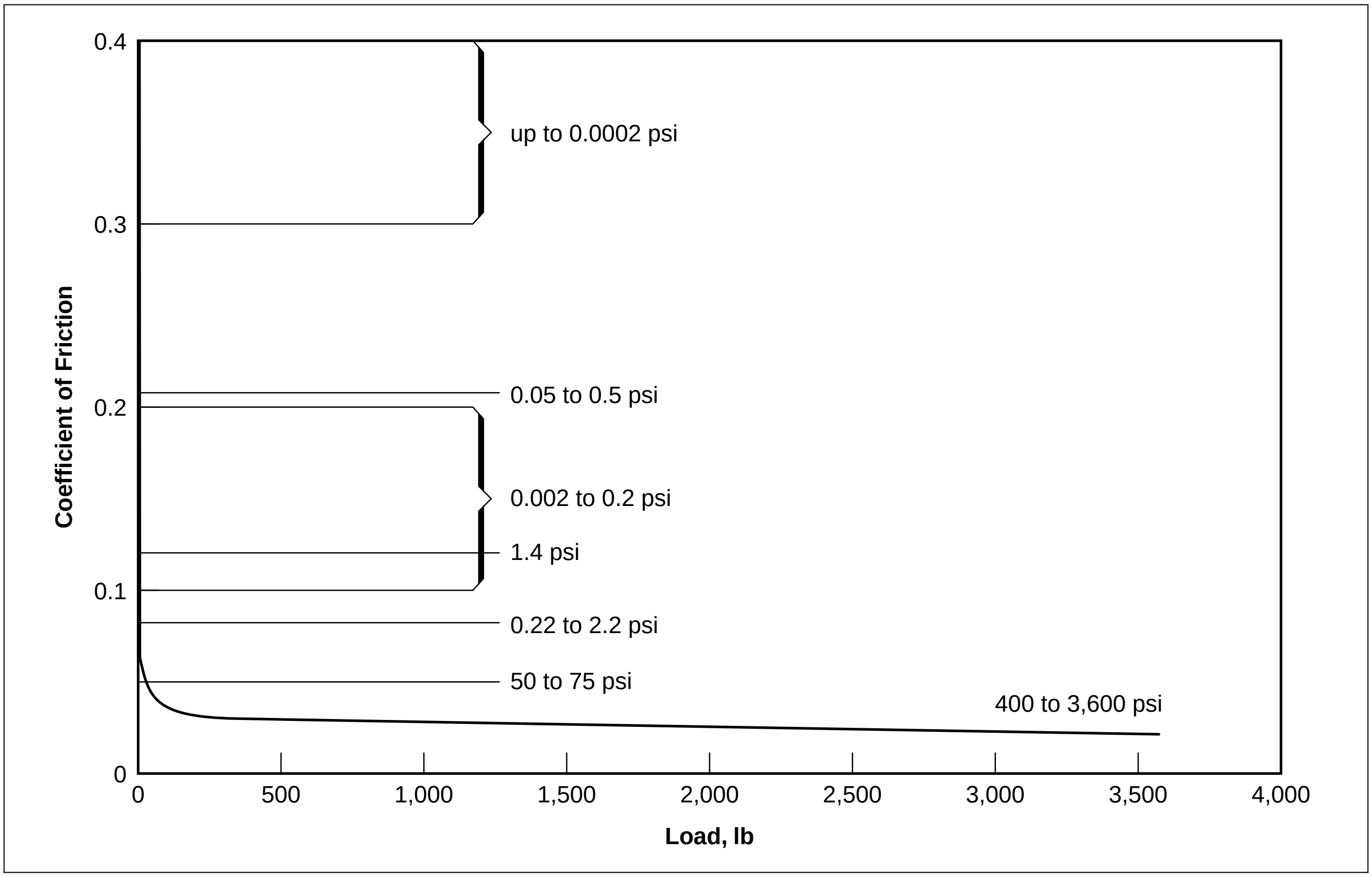


Table 17
Weight Loss Caused by Sliding Tape*

Resin	Average Weight Loss, g/in^2
Teflon® PTFE	0.337

*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 100 g/in^2. With No. 320 abrasive under a 15-lb load, weight loss was measured after 200 revolutions (1 hr, 40 min).

Table 18
Weight Lost from Revolving Disk*
(Cumulative weight loss in milligrams)

	Test Cycles					
Resin	10	50	100	500	1,000	2,000
Teflon® PTFE	0.35	1.65	2.2	5.7	8.9	13.4

*Taber Abrasion Test: This test measures abrasion resistance of a flat surface by rotating a 4-in diameter specimen disk beneath an abrasive under load. A 1,000 g load was used on a Calibrase wheel No. CS-17F.

Table 19
Tape Length Required to Abrade through Wire Coating*
(Average tape length in inches)

	Heat Aging			
Resin	None	96 hr at 150°C (302°F)	500 hr at 150°C (302°F)	96 hr at 200°C (392°F)
Teflon® PTFE	76	78	98	84

*Tape Abrasion Test (MIL-T-5438): This test measures abrasion resistance of wire coatings by drawing, under load, a clean abrasive cloth tape of continuous length across the test wire until the coating is worn through. A 1-lb load on No. 400 grit tape was used on a coating thickness of 0.015 in.

Electrical Properties

Teflon® PTFE fluoropolymer resins offer remarkable electrical stability over a wide range of frequency and environmental conditions. In this respect, they differ markedly from other insulating materials.

Dielectric Constant

The dielectric constant of *Teflon*® PTFE resins shows less change over a wide range of temperatures and frequencies than any other solid material. This value remains essentially constant at 2.1 over the entire frequency spectrum.

Teflon® PTFE specimens have been heat-aged at 300°C (572°F) for six months, and then cooled to room temperature for measurement, with no change in dielectric constant. Nonfluoropolymer insulating materials do not show these properties.

Dissipation Factor

The dissipation factor of *Teflon*® PTFE resins remains below 0.0004 over a frequency range up to 10^8 Hz.

The dissipation factor of *Teflon*® PTFE resins remains quite constant. For *Teflon*® PTFE at room temperature, it reaches a peak at about 10^9 Hz. This peak value is 0.0004 for *Teflon*® PTFE resins. Theoretical analysis of this phenomenon and spot checks indicate that as temperature increases, the peak will occur at higher frequencies.

Dielectric Strength

The dielectric strength of *Teflon*® PTFE resins is high and does not vary with temperature and thermal aging. Initial dielectric strength is very high (600 V/mil for 1.5 mm [0.06 in] thickness) as measured by the ASTM short-time test. As with any material, the value drops as thickness of specimen increases.

Life at high dielectric stresses is dependent on corona discharge. The absence of corona, as in special wire constructions, permits very high voltage stress without damage to *Teflon*® PTFE resins. Changes in relative humidity or physical stress imposed upon the material do not diminish life at these voltage stresses.

Surface Arc-Resistance

Surface arc-resistance of *Teflon*® PTFE resins is high and is not affected by heat-aging. When *Teflon*® PTFE resins are subjected to a surface arc in air, they do not track or form a carbonized conducting path. When tested by the procedure of ASTM D495, *Teflon*® PTFE resins pass the maximum time of 300 sec without failure.

The unique nonstick surface of these resins helps reduce surface arc phenomena in two ways:

- It helps prevent formation of surface contamination, thereby reducing the possibility of arcing.
- If an arc is produced, the discharge frequently cleans the surface of the resin, increasing the time before another arc.

Volume and Surface Resistivity

Volume resistivity (>10^{18} ohm·cm) and surface resistivity (>10^{16} ohm·sq) for *Teflon*® PTFE resins are at the top of the measurable range. Neither resistivity is affected by heat-aging or temperatures up to recommended service limits.

Other Properties

Weathering

Parts fabricated of *Teflon*® PTFE fluoropolymer resins are virtually unaffected by weather. Conclusive tests on samples exposed for 15 yr to practically all climatic conditions confirm these weather-resistant properties. Thus, where applications demand the ultimate in dependability under these conditions, these resins are the answer. Resistance to extreme heat, cold, and ultraviolet light encountered in radar and other electronic components, such as antenna bushings, are excellent examples of the value of this material to the industrial designer.

Miscellaneous

Molded *Teflon*® PTFE fluoropolymer resins have excellent vibration dampening properties both at sonic and ultrasonic frequencies. Installations for this purpose have been very successful. The thickness of material required must be sufficient to absorb the energy produced and is usually determined experimentally.

Chemical Properties

Resistance to Chemical Attack

Teflon® PTFE fluoropolymer resins are essentially chemically inert. Up to the upper use temperature (260°C [500°F]) for *Teflon*® PTFE, only very few chemicals are known to chemically react with these resins, i.e., molten alkali metals, turbulent liquid, or gaseous fluorine; and a few fluorochemicals, such as chlorine trifluoride, ClF_3, or oxygen difluoride, OF_2, which readily liberate free fluorine at elevated temperatures.

The unique degree of inertness of *Teflon*® PTFE resins reflects their chemical structure. Molecules of *Teflon*® PTFE resin are formed simply from strong carbon-carbon and super-strong carbon-fluorine inter-atomic bonds; moreover, the fluorine atoms form a protective sheath around the carbon core of each molecule. This structure also produces other special properties, such as insolubility and low-surface adherability and friction.

To a minor degree, halogenated organic chemicals may be absorbed by fluoropolymer resins. This will cause a very small weight change and in some cases slight swelling. If absorption is very high, it usually indicates a fabricated part of high porosity.

Permeability

Fluoropolymer resins may be permeated to a limited extent by some substances. Permeation rates are generally comparable to those observed for other thermoplastics.

For more detailed data on exposure of *Teflon*® PTFE resins to chemical media, please contact your DuPont representative or call the appropriate sales office listed on the back cover.

Forming and Fabrication

When extreme tolerance must be specified, or when product shapes are very complex, or when just one or two prototypes are required, the machining of *Teflon*® PTFE resins becomes a logical means of fabrication.

All standard operations—turning, facing, boring, drilling, threading, tapping, reaming, grinding, etc.—are applicable to *Teflon*® PTFE resins. Special machinery is not necessary.

When machining parts from *Teflon*® PTFE resins, either manually or automatically, the basic rule to remember is that these resins possess physical properties unlike those of any other commonly machined material. They are soft, yet springy. They are waxy, yet tough. They have the cutting "feel" of brass, yet the tool-wear effect of stainless steel. Nevertheless, any trained machinist can readily shape *Teflon*® PTFE to tolerances of ±0.001 in and, with special care, to ±0.0005 in.

Choose Correct Working Speeds

One property of *Teflon*® PTFE resins strongly influencing machining techniques is their exceptionally low thermal conductivity. They do not rapidly absorb and dissipate heat generated at a cutting edge. If too much generated heat is retained in the cutting zone, it will tend to dull the tool and overheat the resin. Coolants, then, are desirable during machining operations, particularly above a surface speed of 150 m/min (500 fpm).

Coupled with low conductivity, the high thermal expansion of *Teflon*® PTFE resins (nearly 10× that of metals) could pose supplemental problems. Any generation and localization of excess heat will cause expansion of the fluoropolymer material at that point. Depending on the thickness of the section and the operation being performed, localized expansion may result in overcuts or undercuts and in drilling a tapered hole.

Machining procedures then, especially working speeds, must take conductivity and expansion effects into account.

Surface speeds from 60–150 m/min (200–500 fpm) are most satisfactory for fine-finish turning operations; at these speeds, flood coolants are not needed. Higher speeds can be used with very low feeds or for rougher cuts, but coolants become a necessity for removal of excess generated heat. A good coolant consists of water plus water-soluble oil in a ratio of 10:1 to 20:1.

Feeds for the 60–150 m/min (200–500 fpm) speed range should run between 0.05–0.25 mm (0.002–0.010 in) per revolution. If a finishing cut is the object of a high-speed operation (e.g., an automatic screw-machine running at 240 m/min [800 fpm]), then feed must be dropped to a correspondingly lower value. Recommended depth of cut varies from 0.005–6.3 mm (0.0002–0.25 in).

In drilling operations, the forward travel of the tool should be held to 0.13–0.23 mm (0.005–0.009 in) per revolution. It may prove advantageous to drill with an in-out motion to allow dissipation of heat into the coolant.

Properly Shape and Use Tools

Along with working speeds, choice of tools is quite important to control of heat buildup. While standard tools can be used, best results come from tools specifically shaped for use with *Teflon*® PTFE resins. The table below presents shape information important to proper single-point tool design:

Top rake	0–15° positive
Side rake and side angle	0–15°
Front or end rake	0.5–10°

Boring tools normally require the higher angles listed.

The quality of a tool's cutting edge not only influences the amount of heat generated, but it also controls tolerances in a different way. A tool that is not sharp may tend to pull the stock out of line during machining, thereby resulting in excessive resin removal. On the other hand, an improperly edged tool tends to compress the resin, resulting in shallow cuts.

An extremely sharp edge is, therefore, highly desirable, especially for machining work on filled compositions. "Stellite" and carbide-tipped tools will help to minimize required resharpening frequency.

To partially compensate for tool wear, it is helpful to grind tools with a slight nose radius. All drills, either twist or half-round, should have deep, highly polished flutes.

Adequate material support is also important, especially when machining long, thin rods of *Teflon*® PTFE. If support is not provided, stock flexibility may lead to poor results.

Another characteristic of *Teflon*® PTFE resins will be noted immediately after beginning any turning operation. Rather than chips and ribbons of removed stock, as encountered during the machining of most materials, a *Teflon*® PTFE resin turns off as a long, continuous curl. If this curl is not mechanically guided away from the work, it may wrap around it, hampering the flow of coolant, or worse, forcing the work away from the tool. On an automatic screw machine, a momentary withdrawal of the tool from the stock will suffice.

Rules for Dimensioning and Finishing

Normally, *Teflon*® PTFE resins are machined to tolerances of about 0.13 mm (±0.005 in). While closer tolerances are occasionally required, they usually are not necessary. The natural resiliency of these resins allows machined parts to conform naturally to working dimensions. For example, a part with an interference can be press-fitted at much lower cost than that required for final machining to exact dimensions, and the press-fitted part will perform equally well.

Closer Tolerances

When it is necessary to produce shapes with extremely close tolerances, it is usually essential to follow a stress-relieving procedure. By heating a fluoropolymer resin stock to slightly above its expected service temperature (but below 327°C [621°F]), initial stresses are relieved.

Holding this temperature for 1 hr per 2.5 cm (1 in) of thickness, followed by slow cooling, completes the initial annealing step. (Stress-relieved stock can also be purchased from processors.) A rough cut will then bring the stock to within 0.38–0.76 mm (0.015–0.030 in) of final dimensions. Reannealing prior to a final finishing-cut will remove stresses induced by the tool.

A transition occurs in *Teflon*® PTFE resin, resulting in a 1–1.5% increase in volume as temperature is increased through the neighborhood of 19°C (66°F). This must be considered when measuring a part for a critical application.

Measuring Tolerances

Personnel should exercise caution when measuring tolerances on parts machined from *Teflon*® PTFE resins; in general, results will be better if the measuring instruments do not exert excessive pressure on the piece.

For example, a micrometer used by inexperienced personnel could easily read 0.13–0.25 mm (0.005–0.010 in) under the true dimension because of the compressibility of the *Teflon*® PTFE resin being used. Optical comparators are often useful in eliminating this type of error.

It is best to check dimensions at the expected service temperature, but temperature compensations will suffice if this is not practical. Parts machined to final size and measured at room temperatures or below will not meet specifications at higher temperatures. The reverse is also true.

Surface Finishes

Surface finishes better than 0.4 µm (16 µin) are possible on parts made with *Teflon*® PTFE resins, but rarely are needed because of the resin's compressibility and low coefficient of friction. Precision-honed and lapped cutting tools will produce a 0.4-µm (16-µin) surface when required; standard equipment yields a finish of about 0.8 µm (32 µin).

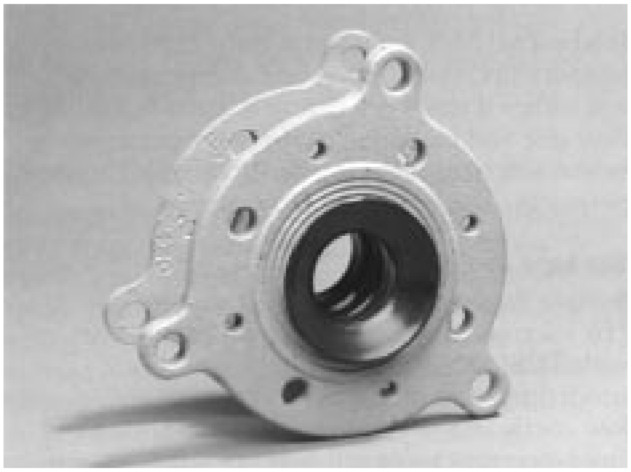
Lapping compounds may be used, but these as well as grinding compounds may become embedded in the fluoropolymer and may prove to be very difficult to remove. Contaminants from machinery not used exclusively for *Teflon*® resins can also embed in the resin surface.

Safe Handling

As with all organic polymers exposed to high temperatures, good safety practice requires the use of adequate ventilation when processing *Teflon*® PTFE fluoropolymer resins. The heated fluoropolymer should be kept enclosed, or exhaust ventilation should be used, to prevent inhalation of fumes and gases that may arise. Heating may produce fumes and gases that are irritating or toxic. Similarly, care should be taken to avoid contamination of smoking tobacco or cigarettes with fluorine-containing resins. Precautions are to be used in the handling, processing and use of *Teflon*® PTFE or other fluoropolymer resins. Before using *Teflon*®, read the Material Safety Data Sheet and the detailed information in the Society of the Plastics Industry publication, "Guide to the Safe Handling of Fluoropolymer Resins." Copies may be obtained from your DuPont representative.

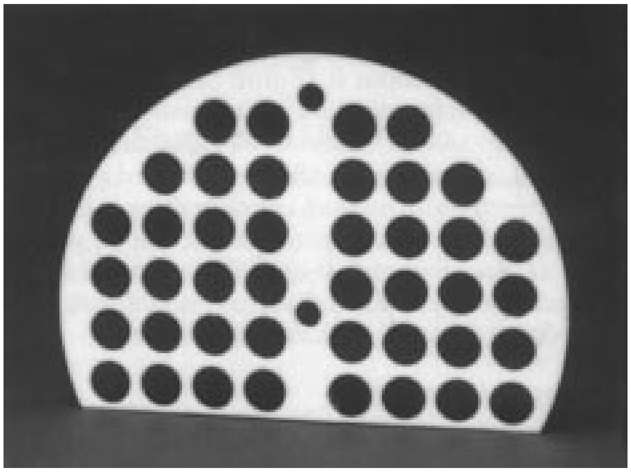
Typical Applications

Flexible Pipe Joint

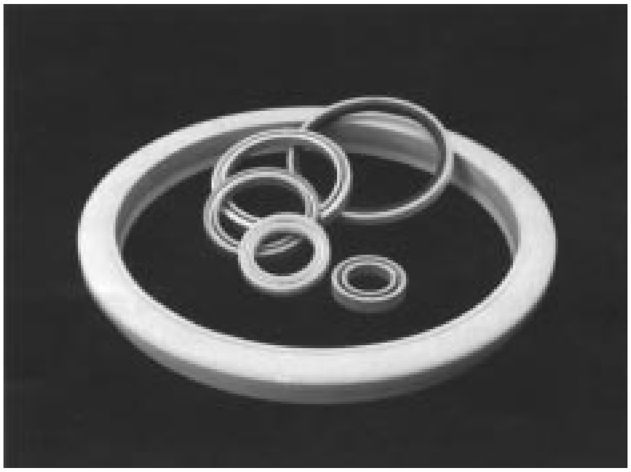


Chemical Transfer Hose

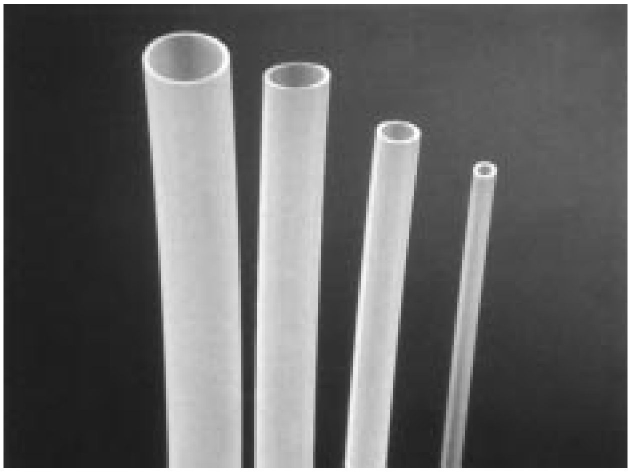
Heat Exchanger Tube Sheet



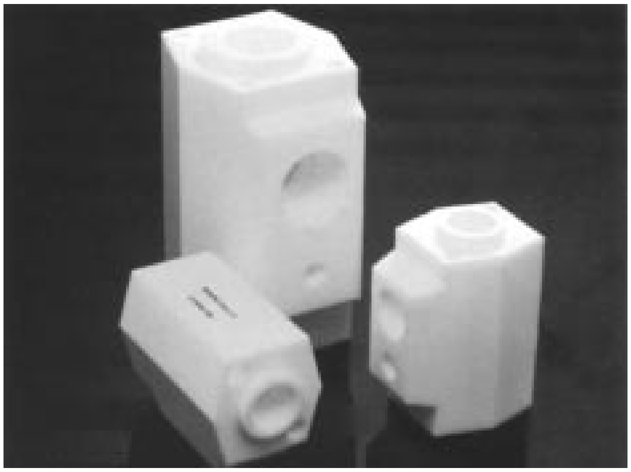
Filled Seals



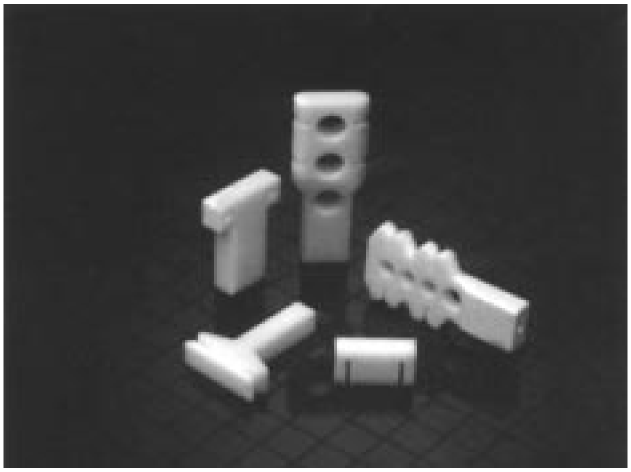
Tubing



Valve Body



Electrical Insulators



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