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Udel® PSU

Design Guide

SPECIALTY
POLYMERS

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Udel® Polysulfone (PSU)

Udel® PSU resins offer a superior combination of high-performance properties that include:

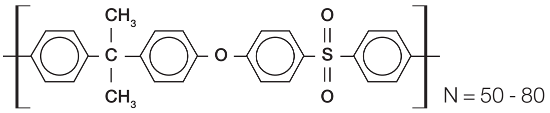
- Excellent thermal stability
- High toughness and strength
- Good environmental stress cracking resistance
- High heat deflection temperature, 174°C (345°F)
- Combustion resistance
- Transparency
- Approved for food contact and potable water
- Low creep

This manual has been compiled to provide design engineers with the necessary information to effectively use Udel® PSU. It contains the mechanical, thermal, and chemical properties of these materials and recommendations for processing and part design.

Chemical and Property Relationships

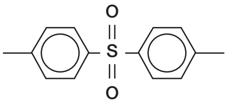
Udel® PSU is a rigid, strong, high-temperature amorphous thermoplastic that can be molded, extruded, or thermoformed into a wide variety of shapes.

Udel® PSU has the following repeating structure or basic unit:



This structural unit is composed of phenylene units linked by three different chemical groups – isopropylidene, ether, and sulfone – each contributing specific properties to the polymer. The complex repeating structure imparts inherent properties to the polymer that conventionally are gained only by the use of stabilizers or other modifiers.

The most distinctive feature of the backbone chain is the diphenylene sulfone group:



diphenylene sulfone

The influence of diphenylene sulfone on the properties of resins has been the subject of intense investigation since the early 1960's. The contributions of this group become evident upon examination of its electronic characteristics. The sulfur atom (in each group) is in its highest state of oxidation. Furthermore, the sulfone group tends to draw electrons from the adjacent benzene rings, making them electron-deficient. Thermal stability is also provided by the highly resonant structure of the diphenylene sulfone group. This high degree of resonance imparts high strength to the chemical bonds. Substances stable to oxidation strongly resist the tendency to lose their electrons to an oxidizer. It then follows that the entire diphenylene sulfone group is inherently resistant to oxidation.

Therefore, large amounts of incident energy in the form of heat or ionizing radiation can be dissipated without chain scission or crosslinking taking place. Non-aromatic-backbone polymers do not similarly resonate, cannot absorb energy by this mechanism, and are therefore less stable.

The diphenylene sulfone group thus confers on the entire polymer molecule, as inherent characteristics, thermal stability, oxidation resistance, and rigidity, even at elevated temperatures.

To take full advantage of the potentially available contributions of the diphenylene sulfone structure in a thermoplastic resin, these units must be linked with other groups, which are thermally and hydrolytically stable, and which will contribute desirable processing and end use properties.

Some flexibility in the backbone of the polymer is desired to impart toughness. This is provided by the ether linkage and moderately augmented by the isopropylidene link. These ether linkages also add to the thermal stability. Similarly, both the ether and isopropylidene linkages impart some chain flexibility, making the material more easily processable at practical temperatures.

The chemical structure of polysulfone is thus directly responsible for an excellent combination of properties that are inherent in the resins – even without the addition of modifiers. Polysulfone is rigid, strong, and tough. It is transparent in its natural form and maintains its physical and electrical properties over a broad temperature range. Its melt stability permits fabrication by conventional thermoplastic processing and fabrication techniques. It is resistant to oxidation and thermally stable, and therefore, can tolerate high use temperatures for long periods of time.

Product Data

Material Selection

Udel® PSU resins are amorphous sulfone polymers and offer many desirable characteristics, such as resistance to hydrolysis, thermal stability, retention of mechanical properties at elevated temperatures, clarity, and transparency.

This material is available in both unfilled grades and glass-reinforced grades. The unfilled grades are available in a range of melt viscosities.

Udel® PSU is indicated when higher thermal capability, inherent flame resistance, better chemical resistance, and improved mechanical properties are required. The recommended maximum service temperature shown in Table 1 may help you position polysulfone among other engineering materials.

Table 1: Temperature limits of some engineering materials

Engineering Material	Maximum Service Temperature [°C (°F)]
Phenolic – general purpose	149 – 177 (300 – 350)
Polysulfone	140 – 160 (284 – 320)
Polycarbonate	121 (250)
Zinc die casting alloy	121 (250)
Modified polyphenylene oxide	93 – 104 (200 – 220)
Polypropylene	107 (225)
Polyamides	77 – 116 (170 – 240)
Polyacetal	85 – 104 (185 – 220)

Superior thermal, mechanical, and chemical resistance properties relative to more conventional resins, have shown Udel® PSU to be the best solution in many applications. These applications include: medical devices, electronics, electrical devices, appliances, plumbing, and general processing equipment.

The glass-reinforced grades offer higher stiffness and dimensional stability, with attendant benefits in creep resistance, chemical resistance, and lower thermal expansion.

Udel® PSU can be matched to a wide range of both transparent and opaque colors.

Nomenclature

The nomenclature system for Udel® PSU resins uses the prefix **P** to designate grades without reinforcement. Glass-fiber-reinforced grades are designated with the prefix **GF**. The numerical string following the **P** is an indication of melt viscosity (molecular weight), with P-3500 LCD being the most viscous commercially available grade. P-3500 LCD is well suited for extrusion and microporous membranes. P-1700 is a mid-range viscosity material designed primarily for injection molding applications.

Regarding glass-reinforced resin nomenclature, the last two digits of the numeric string following the **GF** prefix indicate the proportion by weight of glass-fiber reinforcement in the product. Udel® GF-120, for example, represents a 20 % glass-fiber reinforced polysulfone resin.

A variety of stock and made-to-order colored Udel® PSU resins are available. Colors are designated with a suffix format of **YY XXX** where **YY** is the color indicator and **XXX** is a numeric string indicating a specific shade. For example, **BK 937** indicates a resin that is black and **937** indicates a specific formulation.

Packaging

Udel® PSU is available as free flowing pellets packaged in either 25 kg (55 lb) bags or 500 kg (1,100 lb) lined boxes.

Approvals

A number of organizations and standards have been established throughout the world to ensure that materials that are used in direct contact with drinking water and foodstuff do not result in adverse health effects. Many of these organizations, through inspection and other means of oversight, help to assure the continued compliance of listed products to the specific requirements of the standards that they were tested against. These standards include:

Drinking Water Standards

- ANSI/NSF Standard 61: Drinking Water System Components – Health Effects
- Water Regulations Advisory Scheme: Items Which Have Passed Full Test of Effect on Water Quality – BS6920
- Kunststoff Trinkwasser Empfehlungen (KTW): German Federal Health Office
- DVGW Arbeitsblatt W 270 December 1990: Micro Organism Growth in Drinking Water
- French Attestation de Conformite Sanitaire “ACS”: France Sanitary Conformity Certificate for Materials and Accessories

Food Contact

- United States Food and Drug Administration (FDA): Complies with the specifications of the FDA 21CFR177.1655 for repeated use and selected single use in contact with food under conditions of use as specified in the citation
- 3A Sanitary Standards: Plastic Materials Used in Dairy Equipment
- NSF Standard 51: Plastic Materials and Components Used in Food Equipment
- European Commission Directive 2002/72/EC: Commission Directive Relating to Plastic Materials and Articles Intended to Come in Contact with Foodstuffs

Medical

- ISO 10993: We have several grades of sulfone polymers that comply with the requirements of ISO 10993, making them suitable for use in Class II and Class III medical devices. Please consult with your sales representative for further details.

Only products designated as belonging to the Solviva® family of biomaterials may be considered candidates for medical applications implanted in the human body and devices that are in contact with bodily fluids or tissues for greater than 24 hours.

NSF International

Products approved for use under NSF standards can be found on the NSF web site.

Underwriters Laboratories

Underwriters Laboratories Inc. (UL) is an independent, not-for-profit product safety testing and certification organization. Several grades of Udel® PSU are listed by Underwriters Laboratories. A detailed listing can be found on their web site.

Specific Grade Listings

Several grades of Udel® PSU are recognized under each of these standards. Specific information on current listings for specific grades are available from your Solvay representative.

Insert Fitting

Vanguard Piping Systems chose to use Udel® PSU for its line of insert fittings for use with cross-linked polyethylene pipe. Udel® PSU was chosen because it is able to withstand long term exposure to hot chlorinated water under pressure and it is listed by NSF International for use for contact with hot potable water. Millions of fittings have been installed in homes, manufactured under the HUD code, since 1989.

Property Data

The mechanical properties of a material are of fundamental importance in component design. The designer must match the requirements of the application to the mechanical properties of the material to achieve an optimal part design.

The mechanical properties of polymeric materials are more dependent on time and temperature than those of metals. They can also be more affected by environmental factors. To design successfully with polymeric materials, the designer must not only consider the short-term mechanical properties, but also the time, temperature, and environmental demands of each application.

Mechanical Properties

The mechanical properties typically listed in a material supplier's data sheet are short-term properties. In some cases, these values may be considered an indication of the absolute maximum capability of a material.

These property values are obtained by preparing a special test specimen, then subjecting the specimen to an increasing load until failure, usually rupture, occurs. The test specimens are specifically designed to obtain reproducible results when tests are run under ideal conditions. Because the tests are run quickly, the time-related effects are minimized.

Environmental factors are eliminated by running the tests in a controlled environment, thereby avoiding any reduction in properties from chemical exposure.

Short-term mechanical properties usually include:

- Tensile strength and modulus
- Flexural strength and modulus
- Notched and unnotched izod impact
- Compressive strength
- Shear strength
- Surface hardness

Typical Property Tables

The typical short-term properties of Udel® PSU resins are shown in Tables 2 (SI units) and 3 (U.S. units).

Faucet Cartridge
Moen chose Udel® PSU for components of their PureTouch™ faucet. Requirements for the material included resistance to purified water and approvals for contact with potable water. The ability to mold very complex parts accurately and hold close tolerances was also an important consideration.

Table 2: Typical properties(1) of Udel® PSU resins (SI Units)

Property	**Units**	**P-1700**	**P-1720**	**P-3500 LCD**	**GF-110**	**GF-120**	**GF-130**	**ASTM Method**
Mechanical								
Tensile strength	MPa	70.3	70.3	70.3	77.9	96.5	107.6	D 638
Tensile modulus	GPa	2.48	2.48	2.48	3.72	6.00	8.69	D 638
Tensile elongation at break	%	50 – 100	50 – 100	50 – 100	4	3	2	D 638
Flexural strength	MPa	106	106	106	128	148	154	D 790
Flexural modulus	GPa	2.69	2.69	2.69	3.79	5.52	7.58	D 790
Izod impact strength	J/m							D 256
Notched		69	69	69	48	53	69	
Unnotched		NB(2)	NB(2)	NB(2)		477		
Tensile impact	kJ/m^2	420	337	420	100	110	109	D 1822
Compressive strength	MPa	96		96	123	152	176	D 695
Compressive modulus	GPa	2.58		2.58	4.07	5.79	8.00	D 695
Rockwell hardness		M69	M69	M69	M80	M83	M86	D 785
Thermal								
Heat deflection temperature at 264 psi	°C	174	174	174	179	180	181	D 648
Thermal expansion coefficient	ppm/°C							E 831
Flow direction		57	57	57	40	23	19	
Transverse direction		57	57	57	49	49	49	
Thermal conductivity	W/mK	0.26	0.26	0.26				C 177
Oxygen index	%	26	32	30	31	31	32	D 2863
UL-94 Flammability rating 1.5 mm (0.059 inch)		HB	V – 0		HB	HB	V – 1	UL94
Electrical								
Dielectric strength	kV/mm	17		17	19	19	19	D 149
Volume resistivity	ohm · cm	$3 \cdot 10^{16}$		$3 \cdot 10^{16}$	$3 \cdot 10^{16}$	$2 \cdot 10^{16}$	$2 \cdot 10^{16}$	D 257
Surface resistivity	ohm	$4 \cdot 10^{15}$		$4 \cdot 10^{15}$	$4 \cdot 10^{15}$	$4 \cdot 10^{15}$	$6 \cdot 10^{15}$	D 257
Dielectric constant								D 150
at 60 Hz		3.03		3.03	3.18	3.31	3.48	
at 1 kHz		3.04		3.04	3.19	3.31	3.49	
at 1 MHz		3.02		3.02	3.15	3.28	3.47	
Dissipation factor								
at 60 Hz		0.0007		0.0007	0.0007	0.0008	0.0007	
at 1 kHz		0.0010		0.0010	0.0011	0.0014	0.0014	
at 1MHz		0.0060		0.0060	0.0060	0.0060	0.0050	
General								
Specific gravity		1.24	1.24	1.24	1.33	1.40	1.49	D 792
Water absorption(3)	%							D 570
24 hours		0.30	0.30	0.30	0.29	0.26	0.22	
30 days		0.50	0.50	0.50	0.39	0.37	0.34	
Melt flow at 343 °C (650 °F), 2.16 kg	g/10 min	7	7	4.0	6.5	6.5	6.5	D 1238
Mold shrinkage	%	0.7	0.7	0.7	0.4	0.3	0.2	D 955

(1) *Actual properties of individual batches will vary within specification limits*

(2) *NB = no break*

(3) *Measured from 'dry as molded'*

Table 3: Typical properties(1) of Udel® PSU resins (US Units)

Property	Units	P-1700	P-1720	P-3500 LCD	GF-110	GF-120	GF-130	ASTM Method
Mechanical								
Tensile strength	kpsi	10.2	10.2	10.2	11.3	14.0	15.6	D 638
Tensile modulus	kpsi	360	360	360	540	870	1,260	D 638
Tensile elongation at break	%	50 – 100	50 – 100	50 – 100	4	3	2	D 638
Flexural strength	kpsi	15.4	15.4	15.4	18.5	21.5	22.4	D 790
Flexural modulus	kpsi	390	390	390	550	800	1,100	D 790
Izod impact strength								
Notched	ft·lb/inch	1.3	1.3	1.3	0.9	1.0	1.3	D 256
Unnotched	ft·lb/inch	NB(2)	NB(2)	NB(2)	–	9	–	D 256
Tensile impact	ft·lb/inch^2	200	160	200	48	52	54	D 1822
Compressive strength	kpsi	13.9	–	13.9	17.8	22.0	25.6	D 695
Compressive modulus	kpsi	374	–	374	590	840	1160	D 695
Rockwell hardness		M69	M69	M69	M80	M83	M86	D 785
Thermal								
Heat deflection temperature at 264 psi	°F	345	345	345	354	356	358	D 648
Thermal expansion coefficient	ppm/°F							E 831
Flow direction		31	31	31	22	13	10	
Transverse direction		31	31	31	27	27	27	
Thermal conductivity	BTU·inch/ft^{2}hr°F	1.8	1.8	1.8	–	–	–	C 177
Oxygen index	%	26	32	30	31	31	32	D 2863
UL-94 Flammability rating 1.5 mm (0.059 inch)		HB	V – 0	–	HB	HB	V – 1	UL94
Electrical								
Dielectric strength	V/mil	425		425	475	475	475	D 149
Volume resistivity	ohm·cm	$3 \cdot 10^{16}$		$3 \cdot 10^{16}$	$3 \cdot 10^{16}$	$2 \cdot 10^{16}$	$2 \cdot 10^{16}$	D 257
Surface resistivity	ohm	$4 \cdot 10^{15}$		$4 \cdot 10^{15}$	$4 \cdot 10^{15}$	$4 \cdot 10^{15}$	$6 \cdot 10^{15}$	D 257
Dielectric constant								D 150
at 60 Hz		3.03		3.03	3.18	3.31	3.48	
at 1 kHz		3.04		3.04	3.19	3.31	3.49	
at 1 MHz		3.02		3.02	3.15	3.28	3.47	
Dissipation factor								
at 60 Hz		0.0007		0.0007	0.0007	0.0008	0.0007	
at 1 kHz		0.0010		0.0010	0.0011	0.0014	0.0014	
at 1 MHz		0.0060		0.0060	0.0060	0.0060	0.0050	
General								
Specific gravity		1.24	1.24	1.24	1.32	1.39	1.48	D 792
Water absorption(3)	%							D 570
24 hours		0.30	0.30	0.30	0.29	0.26	0.22	
30 days		0.50	0.50	0.50	0.39	0.37	0.34	
Melt flow at 343 °C (650 °F), 2.16 kg	g/10 min	7.0	7.0	4.0	6.5	6.5	6.5	D 1238
Mold shrinkage	%	0.7	0.7	0.7	0.4	0.3	0.2	D 955

(1) *Actual properties of individual batches will vary within specification limits*

(2) *NB = no break*

(3) *Measured from 'dry as molded'*

Tensile Properties

Tensile properties are determined by clamping each end of a test specimen into the jaws of a testing machine. The testing machine applies a unidirectional axial force to the specimen at a specified rate in accordance with ASTM test method D638. The force required to separate the jaws divided by the minimum cross-sectional area is defined as the tensile stress. The test specimen elongates as a result of the stress, and the amount of elongation divided by the original specimen length is the strain.

If the applied stress is plotted against the resulting strain, a curve similar to that shown in Figure 1 is obtained for ductile polymers like polysulfones. The initial portion of the stress-strain curve, as shown in Figure 2, is of special interest because its slope in the region where strain is directly proportional to stress, defines the elastic modulus. Measuring the slope of a curved line accurately is difficult. Conventions have been developed to standardize the measurement and reduce the variability in test results. One method uses the slope of a line drawn tangent to the curve, and another method utilizes the slope of a secant drawn through the origin and some arbitrarily designated strain level. The tangent method was used for the tensile modulus data reported in this publication.

Ductile polymers undergo yield prior to rupture. At the onset of jaw separation, the stress or force required to elongate the specimen is directly proportional to the elongation or strain. As the test proceeds, the specimens exhibit greater amounts of permanent deformation until the point where additional elongation is achieved with the application of less than the proportional amount of stress. This point is called yield and the stress level is often referred to as tensile strength at yield. The elongation is called elongation at yield or yield strain. As the test proceeds, the specimen is elongated until rupture occurs. The stress level at this point is called tensile strength at break or ultimate tensile strength. The test method used for determining tensile properties, ASTM D638, defines tensile strength as the greater of the stress at yield or the stress at rupture.

Figure 1: Typical stress-strain curve

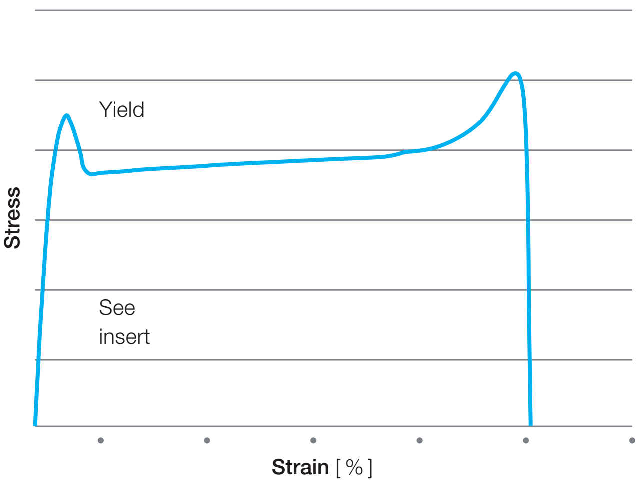
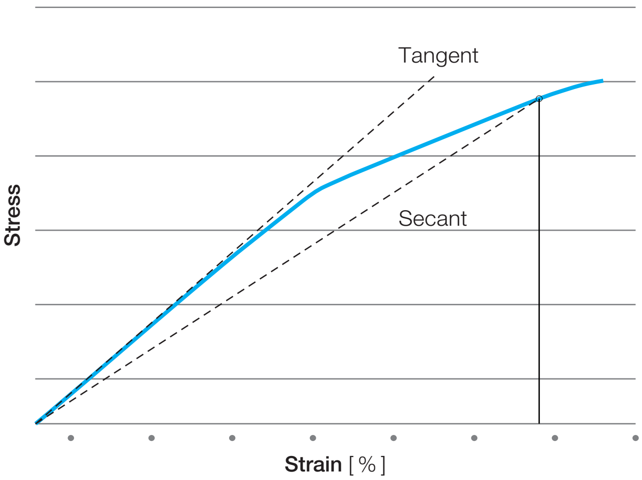


Figure 2: Stress-strain curve insert secant vs. tangent modulus



Figures 3 and 4 show the tensile strength and modulus for unfilled and glass-reinforced Udel® PSU. As expected, the addition of the glass fiber improves both the strength and stiffness.

Figure 3: Glass fiber increases tensile strength

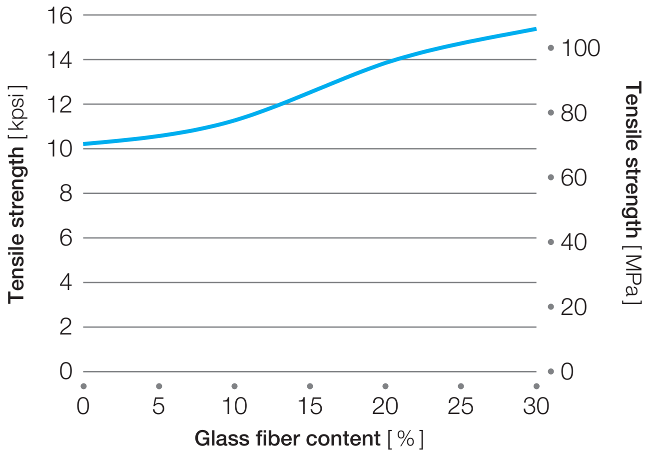
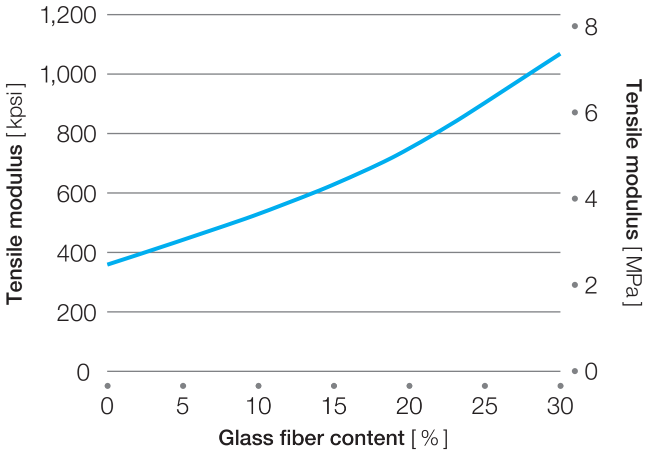


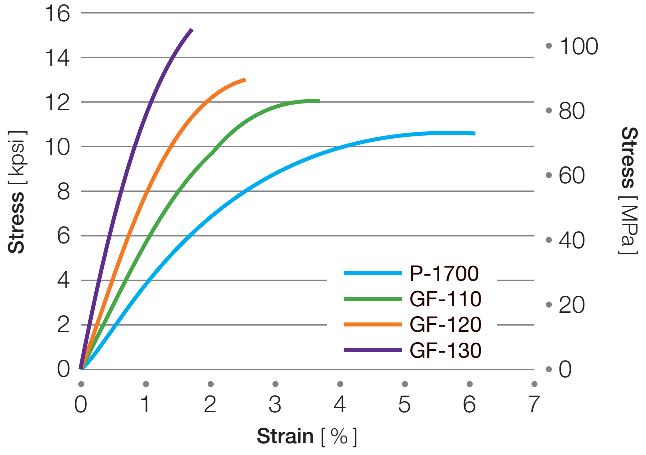
Figure 4: Glass fiber increases tensile modulus



Stress-strain curves

Tensile stress-strain curves for neat and glass-reinforced Udel® PSU are shown in Figure 5.

Figure 5: Tensile stress-strain curve for Udel® PSU resins



Flexural Properties

The flexural properties are determined in accordance with ASTM D790 Method I using the three-point loading method shown in Figure 6. In this method, the 127 × 13 × 3.2 mm (5.0 × 0.5 × 0.125 inch) test specimen is supported on two points while the load is applied to the center. The specimen is deflected until rupture occurs or the outer fiber strain reaches five percent.

Flexural testing provides information about a material's behavior in bending. In this test, the bar is simultaneously subjected to tension and compression.

Figure 6: Flexural test apparatus

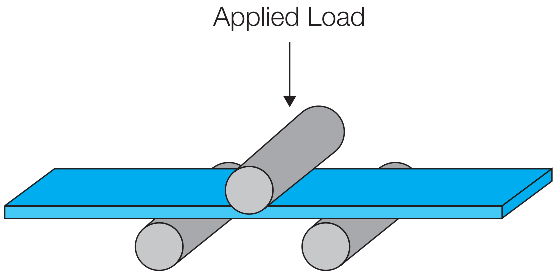


Figure 7: Glass fiber increases flexural strength

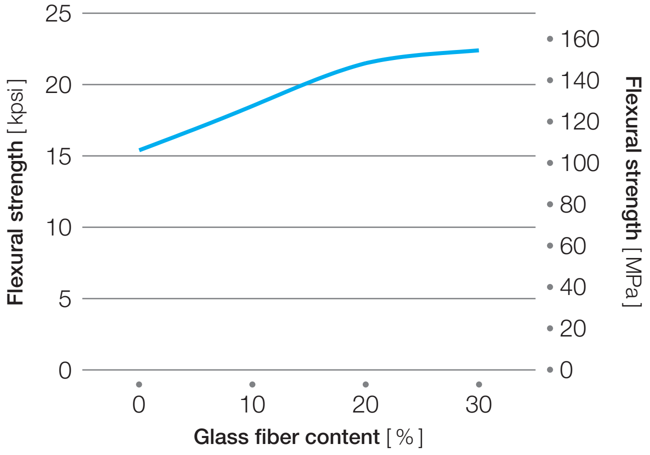


Figure 9: Compressive strength of Udel® PSU

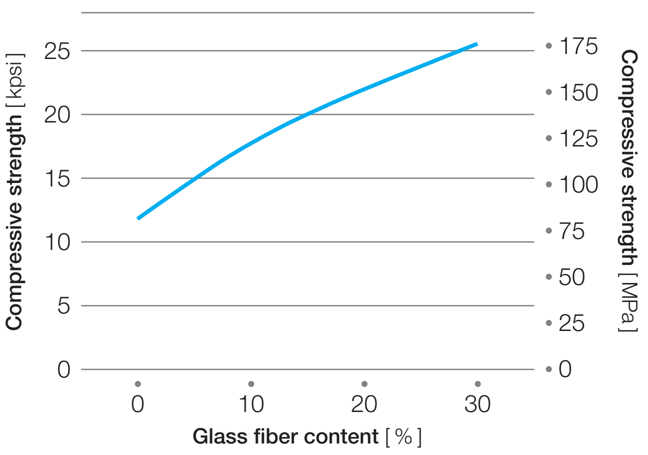


Figure 8: Glass fiber increases flexural modulus

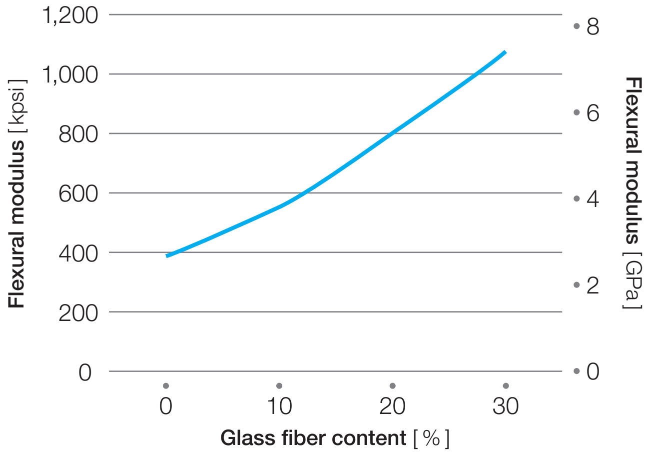
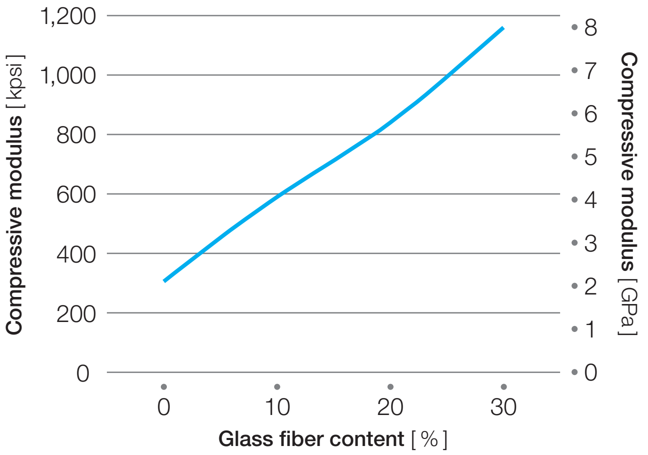


Figure 10: Compressive modulus of Udel® PSU



Compressive Properties

Compressive strength and modulus were measured in accordance with ASTM D695. In this test, the test specimen is placed between parallel plates. The distance between the plates is reduced while the load required to push the plates together and the plate-to-plate distance is monitored. The maximum stress endured by the specimen (this will usually be the load at rupture) is the compressive strength, and the slope of the stress-strain curve is the compressive modulus.

Table 4: Compressive properties of Udel® PSU

Grade	Strength [MPa (kpsi)]	Modulus [GPa (kpsi)]
P-1700 / P-3500 LCD	96 (13.9)	2.58 (374)
GF-110	123 (17.8)	4.07 (590)
GF-120	152 (22.0)	5.79 (840)
GF-130	176 (25.6)	8.00 (1160)

Shear Properties

Shear strength is determined in accordance with ASTM test method D732. In this test, a plaque is placed on a plate with a hole below the specimen. A punch with a diameter slightly smaller than the hole is pushed through the material, punching out a circular disc. The maximum stress is reported as the shear strength.

Table 5: Shear strength of Udel® PSU

Grade		Shear Strength [MPa (kpsi)]
P-1700	at yield	41 (6.0)
P-1700	at break	62 (9.0)
GF-110	at break	56 (8.1)
GF-120	at break	58 (8.4)
GF-130	at break	59 (8.6)

Impact Properties

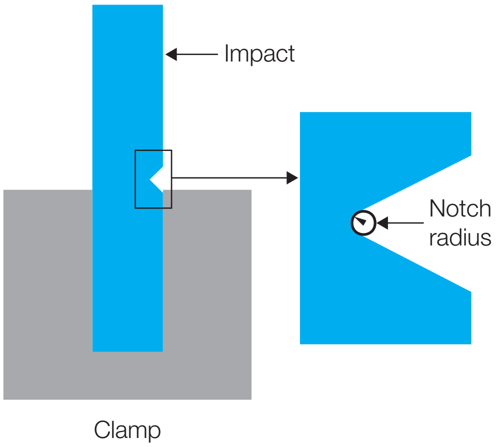
Because polymers are visco-elastic, their properties depend on the rate at which load is applied. When the loading rate is rapid, the part is said to be subjected to an impact loading.

An example of a common impact loading is a drop test, in which the plastic part is dropped from a known height onto a hard, unyielding surface, such as a concrete floor. If a plastic part is to survive the collision without damage, it must be able to absorb the energy transferred rapidly to the part as a result of the impact. The ability of a plastic part to absorb energy is a function of its shape, size, thickness, and the nature of the plastic material. The impact resistance testing methods currently in use do not provide the designer with information that can be used analytically. The tests are only useful for determining relative impact resistance and comparing the relative notch sensitivities of materials.

Notched Izod

The notched Izod test (ASTM D256) is one of the most widely employed methods for comparing polymeric materials. In this test, a test specimen is prepared by machining in a notch with a prescribed geometry. The notched specimen is then struck by a swinging pendulum, as illustrated in Figure 11.

Figure 11: Izod impact test apparatus

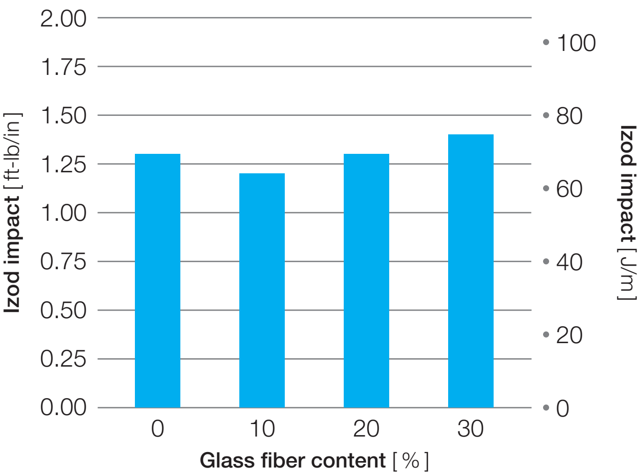


After the impact the pendulum continues to swing, but with less energy due to the collision. The amount of energy lost is reported as the Izod impact strength in units of foot-pounds per inch or Joules per meter of beam thickness.

Failure of a material under impact conditions requires that a crack form, then propagate through the specimen. In the notched Izod test, the notch acts like a crack and the test is primarily measuring crack propagation resistance. When the test is run without a notch, a crack must first be formed, then propagated.

Notched Izod impact results are shown in Figure 12.

Figure 12: Izod impact of Udel® PSU

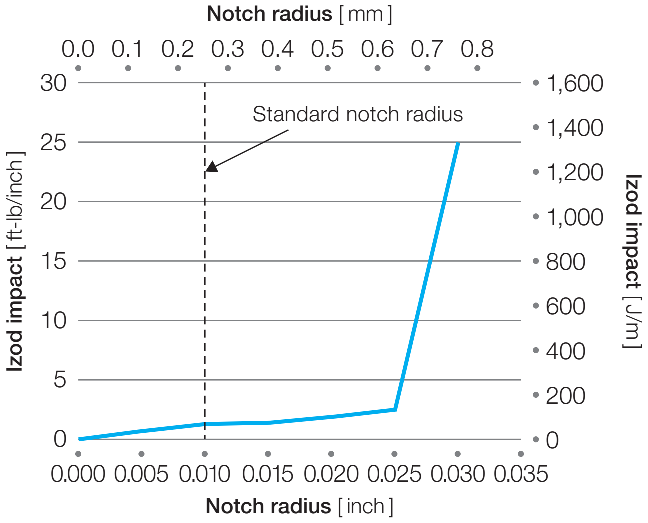


Notch sensitivity

The standard notch radius for the Izod impact test is 0.254 mm (0.010 inch). To evaluate the effect of the sharpness of the notch on the impact strength of Udel® PSU, specimens were prepared using various notch radii. These specimens were then tested according to ASTM D256. The results in Figure 13 clearly show that notch radii smaller than 0.76 mm (0.030 inch) cause brittle failure, while radii greater than 0.76 mm (0.030 inch) give ductile behavior and good toughness.

In general, whenever possible corner radii should be greater than 0.76 mm (0.030 inch) to avoid brittle failure due to high stress concentration.

Figure 13: Izod impact of Udel® P-1700 at various notch radii



Charpy

The Charpy impact test is run in conformance with ISO test method 179. This test is similar to the notched Izod in that the test specimen has a notch machined into it. The major difference is that in the Charpy test, the bar is supported at both ends and struck in the center, while in the notched Izod test, the bar is supported at one end the other end is struck. The two test arrangements are illustrated in Figures 11 and 14. Another difference is in the calculation. In the Izod test, the energy is divided by the sample thickness and the results are expressed in units of Joules per meter or foot-pounds per inch. In the Charpy test, the energy is divided by the cross-sectional area of the sample and the results are expressed in units of kilojoules per square meter or foot-pounds per square inch.

Figure 14: Charpy impact

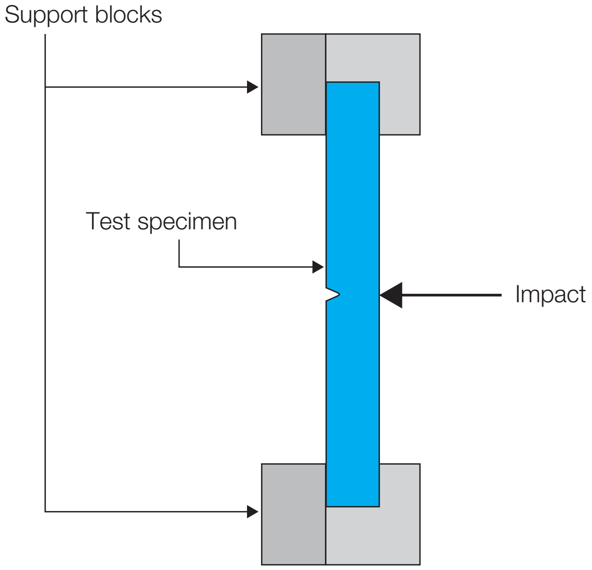
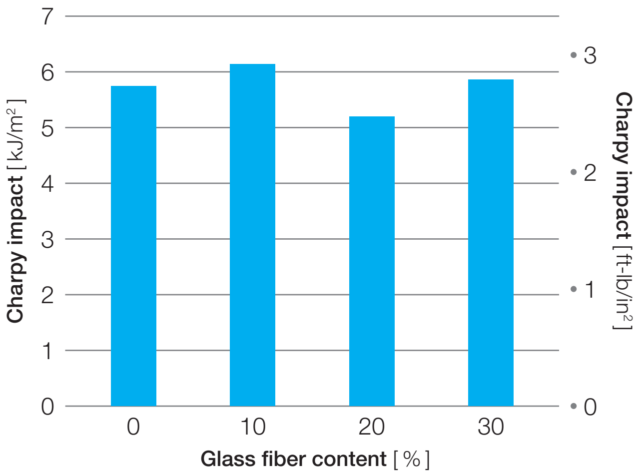


Figure 15: Charpy impact strength of Udel® PSU

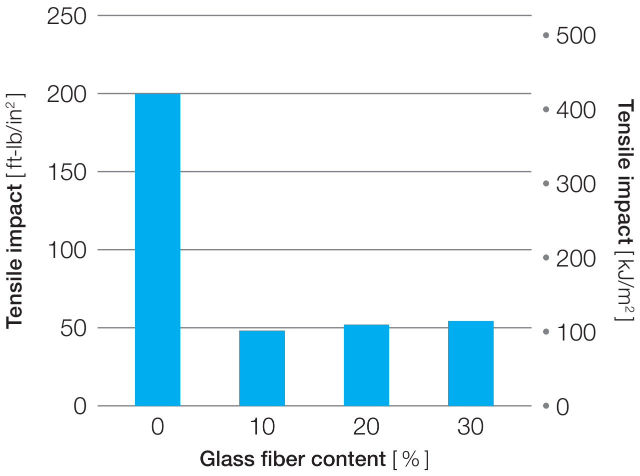


Tensile impact

Tensile impact is similar to the Izod impact test in that a pendulum is used. However, instead of holding the notched test specimen in a cantilevered beam mode and striking the free end, resulting in a high speed bending or flexural test, the specimen is subjected to a high speed tensile loading. This test measures the inherent impact resistance of a plastic. The specimen does not contain a notch or other feature to enable crack formation.

The method described in ASTM D1822 was followed and the results are shown in Figure 16.

Figure 16: Tensile impact of Udel® PSU



Falling dart impact

Another method for determining relative impact resistance involves dropping an object onto a specimen and noting whether the collision causes damage to the specimen. A number of standard test methods have evolved with different test specimen, test specimen support, and dropped object size and shape. The test method used was ASTM D5420, Impact Resistance of Flat, Rigid Plastic. Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact).

Table 6: Poisson's ratio of Udel® PSU

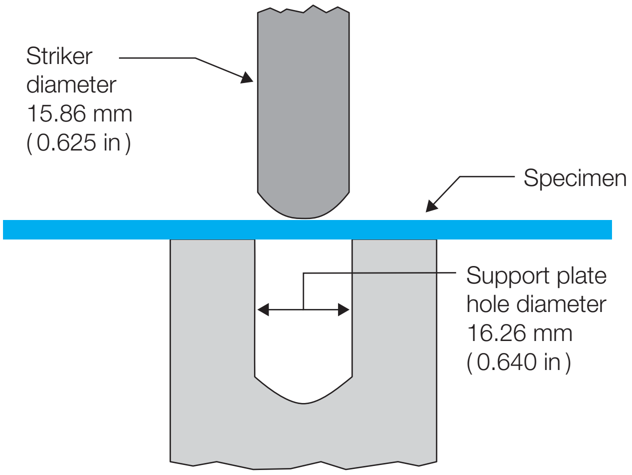
Grade	Poisson's Ratio
P-1700	0.37
GF-110	0.43
GF-120	0.42
GF-130	0.41

In this test, the specimen is placed on a support plate and the striker is placed on the specimen. A weight is then dropped onto the striker from various heights and the effect on the specimen noted. Failure is defined as a visible crack in the specimen. The mean failure energy is defined as the energy required to cause 50 % failures and it is equal to the product of the constant mass and the mean failure height.

The specimen thickness used was 3.2 mm (0.125 inch). Of the optional geometries listed in the method, GC was used. Figure 17 shows the details for Geometry GC.

The impact resistance of Udel® P-1700 by this test is > 320 inch · lb or >20 J.

Figure 17: Gardner impact detail



Poisson's Ratio

Poisson's ratio is the ratio of lateral strain to longitudinal strain within the proportional limit. To illustrate, consider a cylindrical bar subjected to tensile stress. The length (L) increases and simultaneously its diameter (D) decreases. Poisson's ratio (υ) would be calculated by:

$$\upsilon = \frac{\frac{-\Delta D}{D}}{\frac{\Delta L}{L}}$$

The value of Poisson's ratio was measured according to ASTM test method E132.

Long-Term Creep Properties

The response of materials to mechanical loading is affected by the rate of strain application and the mode of load application. Polymeric materials exhibit a more nonlinear response than most metals. The designer must be aware that constant stress results in more deformation than might be expected from the short-term modulus.

When a bar made of a polymeric material is continuously exposed to a stress, its dimensions change in response to the stress. The immediate dimensional change that occurs when the load is applied can be estimated from the elastic modulus. If the stress is maintained, the dimensions continue to change. The continual response to the stress is commonly called creep and is typically monitored by measuring the strain as a function of time.

In tensile mode, the test bar will elongate as a function of time under stress. The term strain is used for the amount of length increase or elongation divided by the initial length.

Creep can also be observed and measured in a bending or flexural mode, or in a compressive mode. In the flexural mode, the strain is the amount the surface on the outside of the bend must stretch. In the compressive mode, the test bar will actually get shorter and the strain is the amount of shortening.

When a component is being designed, the short-term properties such as strength, stiffness, and impact resistance are always considerations. Normally, the maximum deformation is also calculated because deformation impacts component function. When the component is subjected to constant or long-term stress, the deformations will be greater than those predicted from the short-term properties.

To more accurately predict deformations, the apparent or creep modulus is useful. The apparent modulus is derived by dividing the applied stress by the measured strain after exposure to load for a specified time. Using the apparent modulus gives a more accurate prediction of deformation values after long-term exposure to stress.

Tensile Creep

Figure 18 shows the tensile creep of neat polysulfone at 99 °C (210 °F) measured in air.

Figure 19 shows this property at 149 °C (300 °F).

Figure 18: Tensile creep of Udel® PSU in air at 99 °C (210 °F)

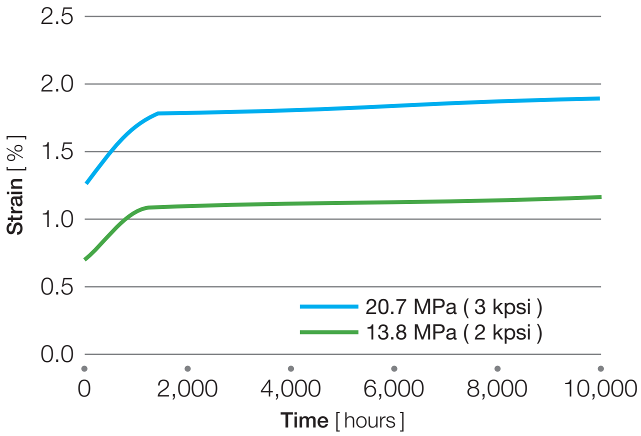
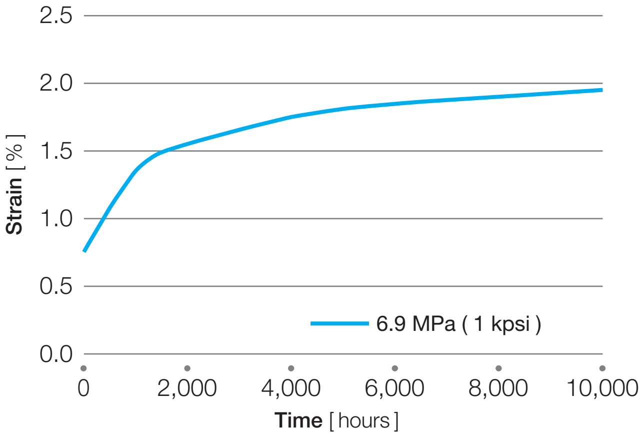


Figure 19: Tensile creep of Udel® PSU in air at 149 °C (300 °F)



Tensile Creep in Water

The creep resistance of polysulfone immersed in water is shown in Figures 20 and 21. At room temperature and a constant stress level of 13.8 MPa (2 kpsi), the strain after 20,000 hours was 1.17 %. When the stress level was increased to 20.7 MPa (3 kpsi), the strain at 20,000 hours was only 1.55 %.

This excellent creep resistance is also seen at 60 °C (140 °F), where after 10,000 hours at a stress of 10.3 MPa (1.5 kpsi) the strain was 1.19 %. The strain after 10,000 hours at 13.8 MPa (2.0 kpsi) at 60 °C (140 °F) was only 1.7 %.

Figure 20: Tensile creep of Udel® PSU in water at 23 °C (73 °F)

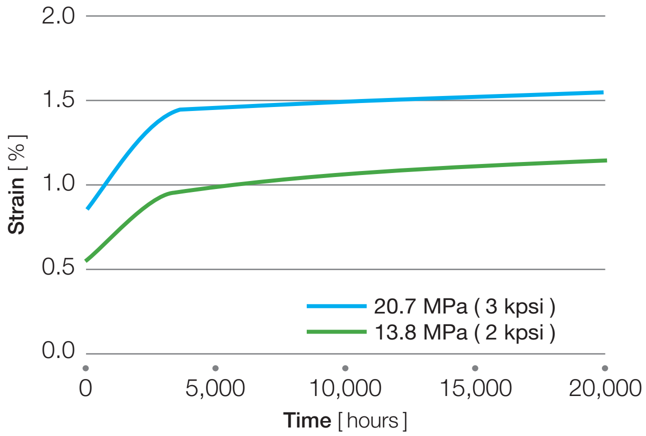
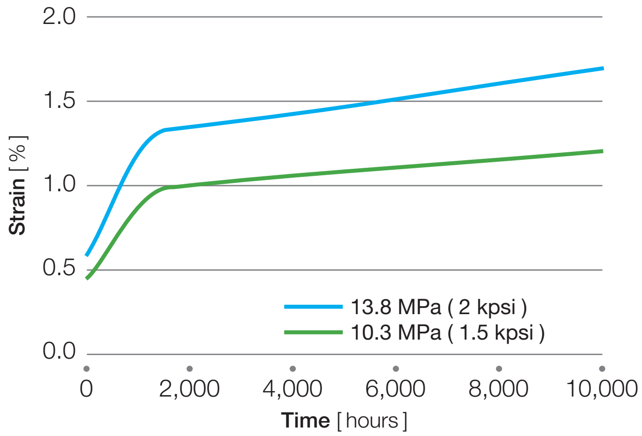


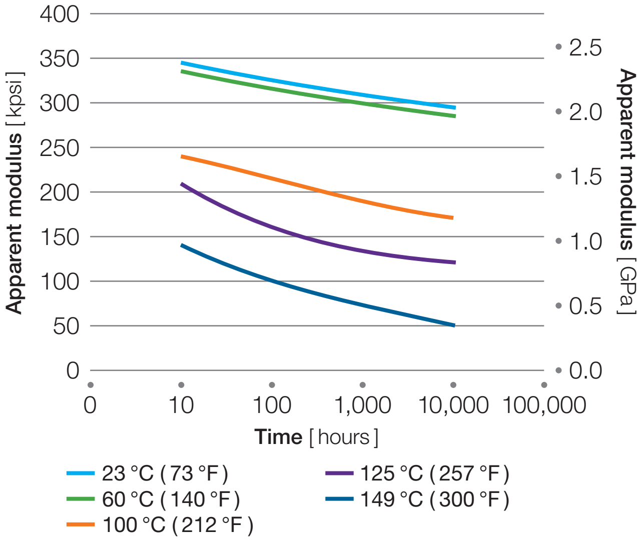
Figure 21: Tensile creep of Udel® PSU in water at 60 °C (140 °F)



Apparent or Creep Modulus

Figure 22 was prepared by calculating the modulus from the strain when polysulfone was stressed at various temperatures in both the tensile and flexural modes.

Figure 22: Creep modulus for unfilled Udel® PSU



Thermal Properties

Thermal properties measure how a material responds to changing ambient temperatures. These include changes in strength and stiffness; changes in dimensions; chemical changes due to thermal or oxidative degradation; softening, melting, or distortion; changes in morphology; and simple changes in temperature. The properties of the materials while molten are discussed in the fabrication section of this publication. The behavior of these materials while burning is discussed in the combustion properties section.

Glass Transition Temperature

Typically, when a polymer is heated it becomes progressively less stiff until it reaches a rubbery state. The temperature at which the material goes from a glassy to a rubbery state is defined as the glass transition temperature (T_g). This temperature is important because several fundamental changes occur at this temperature. These include changes in polymer free volume, refractive index, enthalpy, and specific heat.

The glass transition temperature was measured using differential scanning calorimetry (DSC). Using this method, the glass transition temperature is taken at the onset of the change in heat capacity. Typically the measured value is rounded to the nearest 5 °C. Using this method, the T_g value for Udel® PSU is 185 °C (365 °F).

Another common method reports the T_g as the mid-point of the DSC heat capacity transition. Using that convention, the T_g would be 190 °C (374 °F).

Mechanical Property Changes

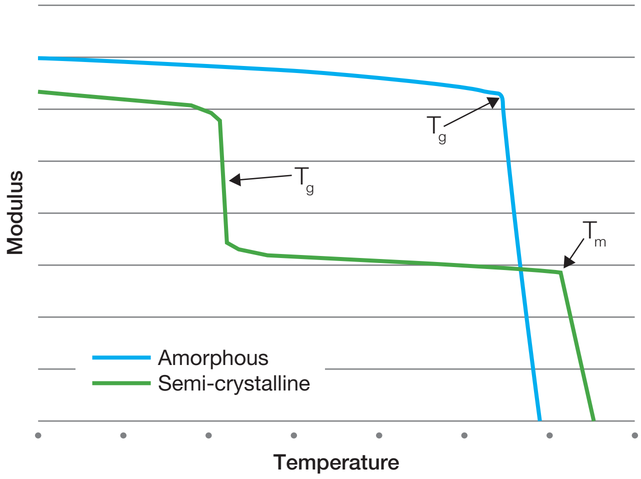
As ambient temperatures are increased, thermoplastics become softer and softer until they become fluid. Prior to this point, the softening can be monitored by plotting the elastic modulus versus the ambient temperature.

Classification of thermoplastic resins

Thermoplastic resins are often divided into two classes: amorphous and semi-crystalline. Figure 23 shows in a generalized manner, the difference in temperature response between these resin types. The modulus of amorphous resins decreases slowly with increasing temperature until the glass transition temperature (T_g) is reached. Amorphous resins are not normally used at service temperatures higher than their glass transition temperature.

The modulus of semi-crystalline resins follows the behavior of amorphous resins up to the glass transition temperature. At T_g, the modulus shows a rapid decrease to a lower level, but remains at or near the new level until the melting point T_m is reached. Semi-crystalline resins, usually reinforced grades, are often used in ambient temperatures above their glass transition temperatures, but below their melting points.

Figure 23: Typical change in modulus with temperature



Temperature effects on tensile properties

Figure 24 shows the effect of increasing ambient temperature on the tensile strength of neat and glass-reinforced polysulfone. Figure 25 shows the same information for tensile modulus.

Figure 24: Tensile strength vs. temperature

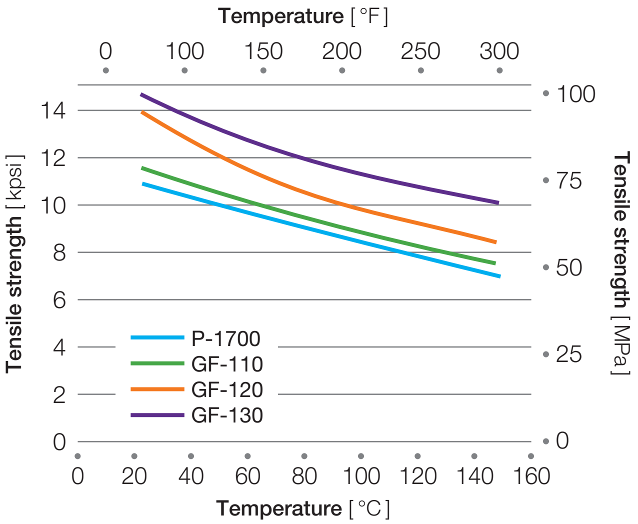
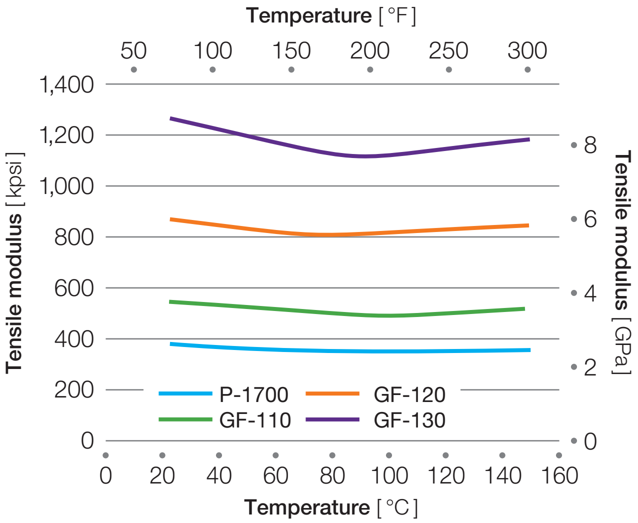


Figure 25: Tensile modulus vs. temperature



Temperature effects on flexural properties

The effect of temperature on the flexural strength of neat and glass-reinforced polysulfone is shown in Figure 26. The effect of temperature on flexural modulus is shown in Figure 27.

Figure 26: Flexural strength vs. temperature

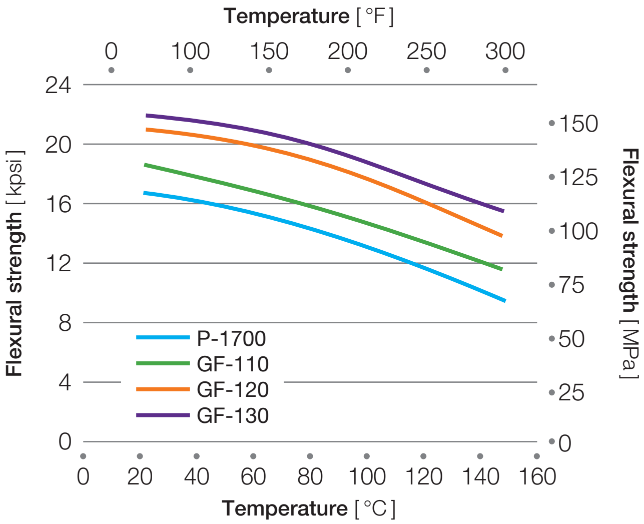
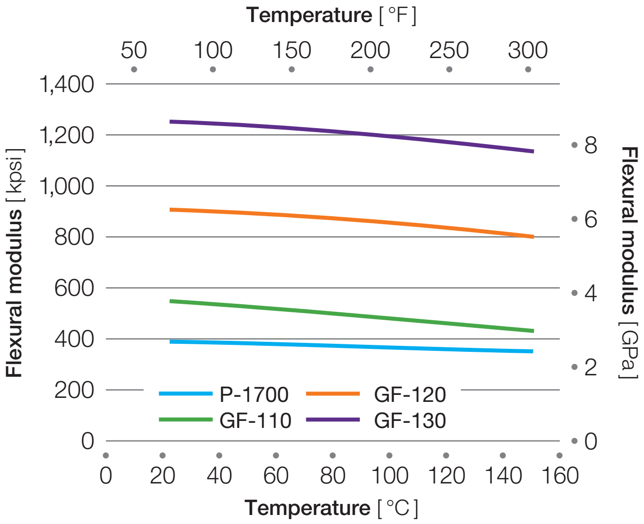


Figure 27: Flexural modulus vs. temperature



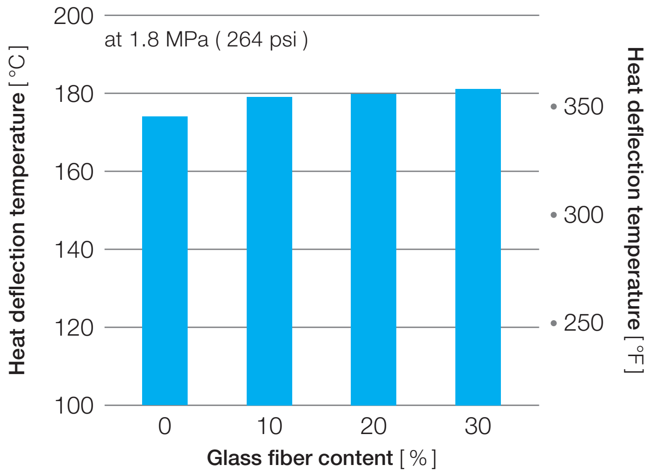
Deflection Temperature under Load

One measure of short-term thermal capability is the deflection temperature under flexural load test described in ASTM test method D648. In this test, a bar 127 mm (5 inch) long is placed on supports 102 mm (4 inch) apart. The bar is loaded to an outer fiber stress of either 0.45 MPa (66 psi) or 1.82 MPa (264 psi). The vertical deformation is monitored while the temperature is increased at a rate of 2 °C/minute. When the vertical deformation reaches the specified end point of 0.25 mm (0.010 inch), the temperature is noted and reported as the deflection temperature. The deflection temperature is also commonly referred to as the heat distortion temperature or heat deflection temperature (HDT).

This test measures the temperature at which the flexural modulus of the material being tested is approximately 240 MPa (35,000 psi) when the test stress is 0.45 MPa (66 psi), or 965 MPa (140,000 psi) when the stress is 1.8 MPa (264 psi).

The deflection temperatures of four grades of Udel® PSU at 1.8 MPa (264 psi) are shown in Figure 28.

Figure 28: Heat deflection temperatures of Udel® PSU resins



Thermal Expansion Coefficient

As temperatures rise, most materials increase in size. The magnitude of the size increase is given by the following equation.

$$\Delta L = \alpha L_0 \Delta T$$

Where L_0 is the original length, and ΔL and ΔT are the change in length and temperature respectively. The coefficient of linear thermal expansion (α) was measured in accordance with ASTM D696.

The coefficients of linear thermal expansion (CLTE) measured near room temperature for Udel® PSU and some common metals are shown in Table 7.

Table 7: Coefficient of linear thermal expansion

Material		ppm/°C (ppm/°F)
Udel® P-1700	FD*	56 (31)
	TD	56 (31)
Udel® GF-110	FD	40 (22)
	TD	49 (27)
Udel® GF-120	FD	23 (13)
	TD	49 (27)
Udel® GF-130	FD	19 (10)
	TD	49 (27)
Zinc die-casting alloy		27 (15)
Aluminum die-casting alloy		25 (14)
Stainless steel		18 (10)
Carbon steel		14 (8)

** FD = Flow Direction, TD = Transverse Direction*

The thermal expansion coefficient varies with the temperature range over which it is measured, the dimension measured, and the flow of the material when the specimen was molded. Figure 29 shows the effect of temperature and flow direction on the expansion coefficient of Udel® P-1700 resin. Because this is an unfilled, amorphous resin, the coefficient shows essentially no dependence on flow direction and only a minor dependence on temperature.

Figure 30 shows this relationship for Udel® GF-110 (10 % glass-reinforced) resin. The effect of the glass is seen primarily in the flow direction where the glass fibers aligned in that direction retard the thermal expansion and reduce the coefficient. In the direction perpendicular to flow, the transverse direction, the coefficient is essentially the same as unfilled resin.

Figure 29: CLTE vs. temperature for Udel® P-1700

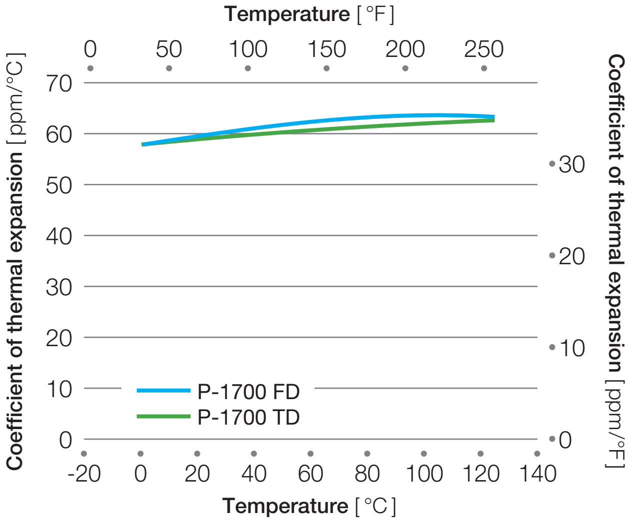


Figure 30: CLTE vs. temperature for Udel® GF-110

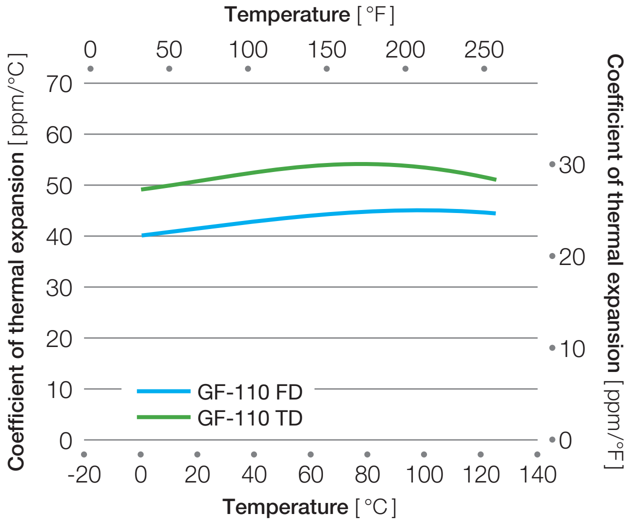


Figure 31: CLTE vs. temperature for Udel® GF-120

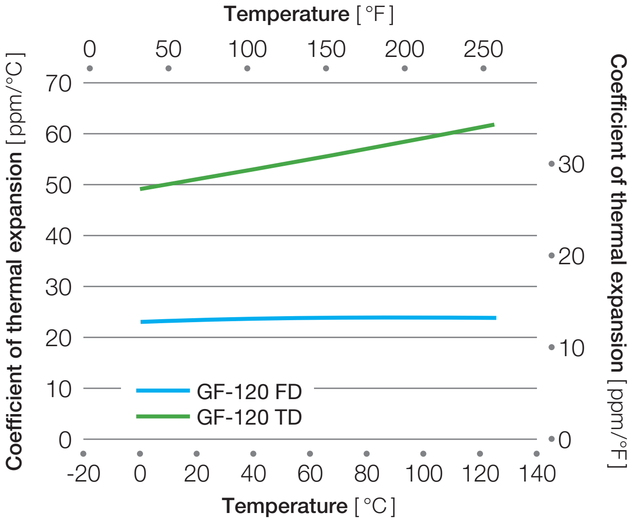
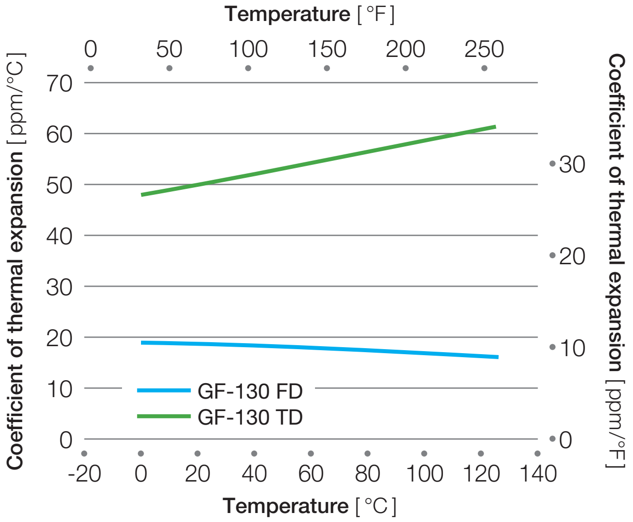


Figure 32: CLTE vs. temperature for Udel® GF-130



The coefficients for Udel® GF-120 (20 % glass-reinforced) resin are shown in Figure 31. The impact of glass fiber orientation in the flow direction is evident by the substantial reduction in the CLTE in the flow direction.

Udel® GF-130 (30 % glass-reinforced) resin coefficients are shown in Figure 32. The glass fibers essentially reduce the expansion in the flow direction to one-half that of unfilled resin. The geometry of these test specimens accentuate the tendency of the glass fibers to orient in the flow direction. In an actual component, it is likely that the flow pattern will be more complex and the actual expansion coefficient will lie between the values shown.

Thermal stresses will be induced in assemblies when materials with different expansion coefficients are joined. The values shown in Figures 29 through 32 should allow the design engineer to calculate the magnitude of any thermal stresses arising from thermal expansion.

Thermal Conductivity

Polymers in general are poor conductors of heat. For many applications, this is desirable because the polymer provides a measure of thermal isolation. Table 8 shows the relative thermal conductivities, measured by ASTM test method E1530, of Udel® PSU resins as well as some other common materials.

Table 8: Thermal conductivity

Material	Thermal Conductivity [W/mK (Btu–inch/hr–ft^2–F)]
Udel® P-1700	0.26 (1.80)
Udel® GF-110	0.19 (1.32)
Udel® GF-120	0.20 (1.38)
Udel® GF-130	0.22 (1.52)
Stainless steel	20–37 (140–250)
Carbon	5–9 (36–60)
Wood (particle board)	1.7 (12)
Rubber	0.14 (1.00)

Vicat Softening Point

This test, ASTM D1525, measures the temperature at which a flat-ended needle with a 1 mm^2 (0.00155 inch^2) circular cross section penetrates the specimen to a depth of 1 mm (0.039 inch) under a one kg (2.2 lb) load using a uniform rate of temperature increase of 50 °C (90 °F) per hour. The results for select Udel® PSU grades are shown in Table 9.

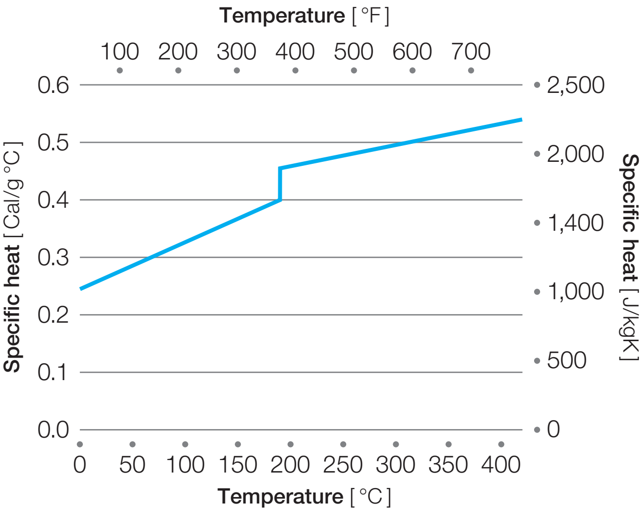
Table 9: Vicat softening point

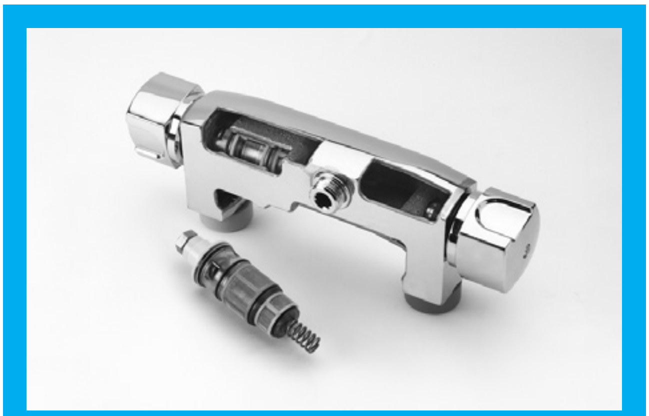
Grade	Vicat Softening Point [°C (°F)]
P-1700	188 (370)
GF-110	192 (378)
GF-120	192 (378)
GF-130	192 (378)

Specific Heat

Specific heat is defined as the amount of heat required to change the temperature of a unit mass one degree. The relationship between the specific heat of polysulfone and temperature is shown in Figure 33.

Figure 33: Specific heat of Udel® PSU





Thermostatic Faucet Cartridge
FM Mattsson chose Udel® PSU instead of brass for production of their thermostatic valve used for showers and baths. In production since the early 1980's, the valve has proven to resist problems with mineral build up and corrosion that can interfere with the operations of the valve.

Specific Volume

PVT (pressure, volume, temperature) data are equation of state thermodynamic properties that describe the compressibility and volume expansion coefficient for a material. These properties are typically employed when performing mold filling analysis with algorithms that make use of compressible flow equations.

Dilatometry is the preferred method for measuring the change in volume of a specimen subjected to different temperatures and pressures. High-pressure dilatometry equipment confines a molded material sample in a fluid on which the pressure can be varied. A bellows is used to determine the actual change in volume of the sample as the temperature and pressure are changed.

The specific volume data for Udel® PSU are shown in Table 10 and Figure 34.

Figure 34: Specific volume of Udel® PSU as a function of temperature and pressure

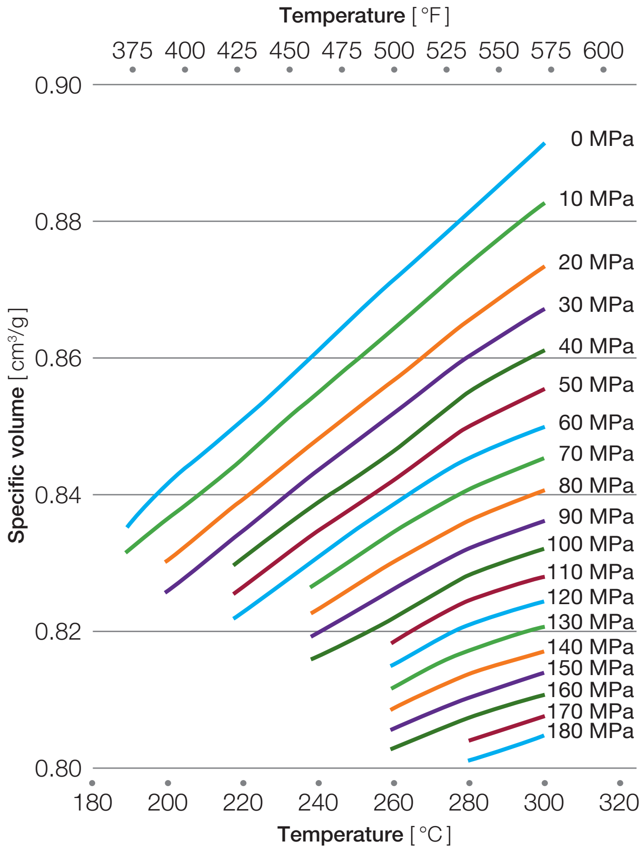


Table 10: Specific volume (cm^3/g) of Udel® PSU as a function of temperature and pressure in the liquid phase

Pressure [MPa]	**Temperature** [°C] **188.8**	**199.1**	**217.4**	**238.0**	**259.1**	**279.8**	**300.1**
0	0.8351	0.8413	0.8496	0.8601	0.8710	0.8811	0.8915
10	0.8314	0.8361	0.8440	0.8540	0.8638	0.8737	0.8827
20		0.8300	0.8382	0.8474	0.8563	0.8654	0.8735
30		0.8256	0.8336	0.8428	0.8515	0.8602	0.8672
40			0.8295	0.8382	0.8443	0.8550	0.8610
50			0.8254	0.8340	0.8417	0.8499	0.8554
60			0.8218	0.8301	0.8384	0.8453	0.8499
70				0.8263	0.8347	0.8407	0.8453
80				0.8226	0.8299	0.8362	0.8407
90				0.8192	0.8259	0.8321	0.8362
100				0.8159	0.8217	0.8282	0.8321
110					0.8182	0.8245	0.8281
120					0.8149	0.8209	0.8244
130					0.8116	0.8171	0.8207
140					0.8085	0.8138	0.8172
150					0.8027	0.8103	0.8139
160						0.8073	0.8167
170						0.8040	0.8076
180						0.8010	0.8048
190							0.8020
200							0.7993

Combustion Properties

UL-94 flammability standard

The UL-94 flammability standard established by Underwriters Laboratories is a system by which plastic materials can be classified with respect to their ability to withstand combustion. The flammability rating given to a plastic material is dependent upon the response of the material to heat and flame under controlled laboratory conditions and serves as a preliminary indicator of its acceptability with respect to flammability for a particular application. The actual response to heat and flame of a thermoplastic depends on other factors such as the size, form, and end-use of the product. Additionally, characteristics in end-use application such as ease of ignition, burning rate, flame spread, fuel contribution, intensity of burning, and products of combustion will affect the combustion response of the material.

Three primary test methods comprise the UL-94 standard. They are the horizontal burning test, the 20 mm vertical burning test, and the 500 MW vertical burning test. Udel® PSU grades are available that meet the requirements of the first two tests.

Horizontal burning test

For a 94HB classification rating, injection molded test specimens are limited to a 125 mm (5.0 inch) length, 13 mm (0.5 inch) width and the minimum thickness for which the rating is desired. The samples are clamped in a horizontal position with a 20 mm blue flame applied to the unclamped edge of the specimen at a 45° angle for 30 seconds or so as soon as the combustion front reaches a pre-marked line 25 mm from the edge of the bar. After the flame is removed, the rate of burn for the combustion front to travel from the 25 mm line to a pre-marked 100 mm line is calculated. At least three specimens are tested in this manner. A plastic obtains a 94HB rating by not exceeding a burn rate of 40 mm/min for specimens having a thickness greater than 3 mm or 75 mm/min for bars less than 3 mm thick. The rating is also extended to products that do not support combustion to the 100 mm reference mark.

20 mm vertical burn test

Materials can be classified 94V-0, 94V-1, or 94V-2 based on the results obtained from the combustion of samples clamped in a vertical position.

The 20 mm vertical burn test is more aggressive than the 94HB test and is performed on samples that measure 125 mm (4.9 inch) in length, 13 mm (0.5 inch) in width, and the minimum thickness at which the rating is desired, typically 0.8 mm (0.03 inch) or 1.57 mm (0.06 inch).

The samples are clamped in a vertical position with a 20 mm high blue flame applied to the lower edge of the clamped specimen. The flame is applied for 10 seconds and removed. When the specimen stops burning, the flame is reapplied for an additional 10 seconds and then removed. A total of five bars are tested in this manner. Table 11 lists the criteria by which a material is classified in this test. Table 12 gives the ratings of selected grades of Udel® PSU. The most current ratings of Udel® PSU resins can be found at the Underwriters Laboratories web site.

Table 11: UL criteria for classifying materials V-0, V-1, or V-2

Criteria Conditions	94V-0	94V-1	94V-2
Afterflame time for each individual specimen, (t^1 or t^2)	≤10 s	≤30 s	≤30 s
Total afterflame time for any condition set ($t^1 + t^2$ for the 5 specimens)	≤50 s	≤250 s	≤250 s
Afterflame plus afterglow time for each individual specimen after the second flame application ($t^2 + t^3$)	≤30 s	≤60 s	≤60 s
Afterflame or afterglow of any specimen up to the holding clamp	No	No	No
Cotton indicator ignited by flaming particles or drops	No	No	Yes

Table 12: UL-94 ratings for Udel® PSU

Grade	Thickness [mm (inch)]	Rating
P-1700	1.5 (0.059)	HB
	3.0 (0.118)	HB
	4.5 (0.177)	V-0
P-1720	1.0 (0.039)	V-1
	1.5 (0.059)	V-0
GF-110	1.5 (0.059)	HB
	3.0 (0.118)	HB
	4.4 (0.173)	V-0
GF-120	1.5 (0.059)	HB
	3.0 (0.118)	HB
	4.4 (0.173)	V-0
GF-130	1.5 (0.059)	V-1
	3.0 (0.118)	V-0

Oxygen index

The oxygen index is defined by ASTM test method D2863 as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will support flaming combustion of a material initially at room temperature under the conditions of this method.

Since ordinary air contains roughly 21 % oxygen, a material whose oxygen index is appreciably higher than 21 is considered flame resistant because it will only burn in an oxygen-enriched atmosphere.

Udel® PSU is flame resistant as shown by the oxygen index value in Table 13.

Table 13: Oxygen indices of Udel® PSU resin

Grade	Oxygen Index [%]
P-1700	26
P-1720	32
P-3500 LCD	30
GF-110	31
GF-120	31
GF-130	32

Auto-ignition temperature

The auto-ignition temperature of a material is defined as the lowest ambient air temperature at which, in the absence of an ignition source, the self-heating properties of the specimen lead to ignition or ignition occurs of itself, as indicated by an explosion, flame, or sustained glow. This property was measured using ASTM D1929.

The auto-ignition temperature of Udel® P-1700 is 550 °C (1,022 °F) and P-1720 is 590 °C (1094 °F).

Flash ignition temperature

The flash ignition temperature of a material is defined as the minimum temperature at which, under specified test conditions, sufficient flammable gasses are emitted to ignite momentarily upon application of a small external pilot flame.

The flash ignition temperature of Udel® P-1700 and P-1720 is 490 °C (914 °F).

Smoke density

When a material burns, smoke is generated. The quantity and density of the generated smoke is important in many applications.

ASTM test method E662 provides a standard technique for evaluating relative smoke density. This test was originally developed by the National Bureau of Standards (NBS), and it is often referred to as the NBS Smoke Density test.

The data presented in Table 14 was generated using the flaming condition. A six-tube burner was used to apply a row of flamelets across the lower edge of the specimen. A photometric system aimed vertically is used to measure light transmittance as the smoke accumulates. The specific optical density (D_s) is calculated from the light transmittance. The maximum optical density is called D_m.

Table 14: Smoke density of Udel® PSU

	Grade	
Measurement	**P-1700**	**P-1720**
D^s at 1.5 minutes	1	2
D^m at 4.0 minutes	65	16

Glow wire testing

The ability to support and sustain ignition in plastic materials may be characterized by standardized glow wire test. This test simulates conditions present when an exposed current carrying conductor contacts an insulating material during faulty or overloaded operation. The test method followed is referenced in IEC 695-2-1/VDE 0471 part 2-1 and ASTM D6194.

The glow wire test apparatus consists of a loop of a heavy gauge (10–14 AWG) nickel-chromium resistance wire, a thermocouple, and a sample mounting bracket.

During the test, an electrical current is passed through the nickel-chromium loop in order to obtain a predetermined temperature. The sample is then brought in contact with the wire for 30 seconds. The test is passed if after withdrawal, the sample displays no flame or glowing, or if so, it is self-extinguishing after 30 seconds. Damage must be minimal to surrounding layers of material.

Table 15: Glow wire results for glass-filled Udel® PSU

Grade	Thickness [mm (inch)]	Ignition Temperature [°C (°F)]
GF-120	0.8 (0.031)	875 (1607)
GF-130	0.8 (0.031)	875 (1607)

Thermal Stability

Thermogravimetric analysis

Thermogravimetric analysis (TGA) is one method for evaluating the thermal stability of a material. In this test, a small sample of the test material is heated while its weight is constantly monitored. Two tests are usually run: one with an inert nitrogen atmosphere and the other in air. The difference between the two test results indicates the importance of oxygen in causing degradation.

Figures 35 and 36 illustrate the inherent stability of Udel® PSU. No significant evolution of volatiles from polymer degradation occurs below about 426 °C (800 °F). The TGA plots in air and nitrogen are virtually identical up to that temperature indicating the absence of or limited nature of oxidative pathways to degradation.

Figure 35: Thermogravimetric analysis in nitrogen

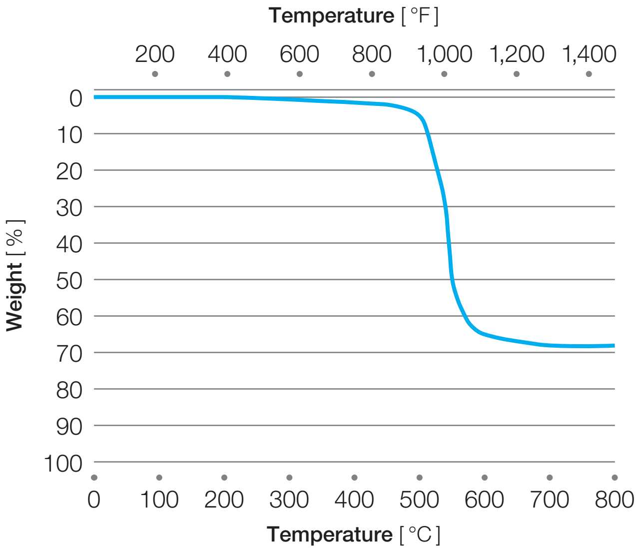
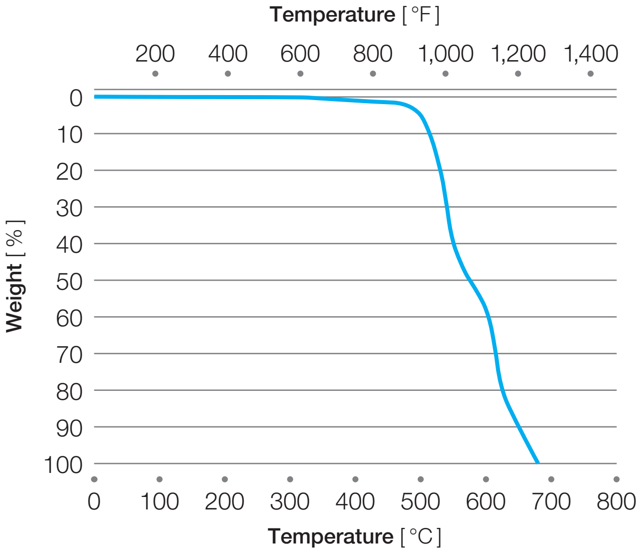
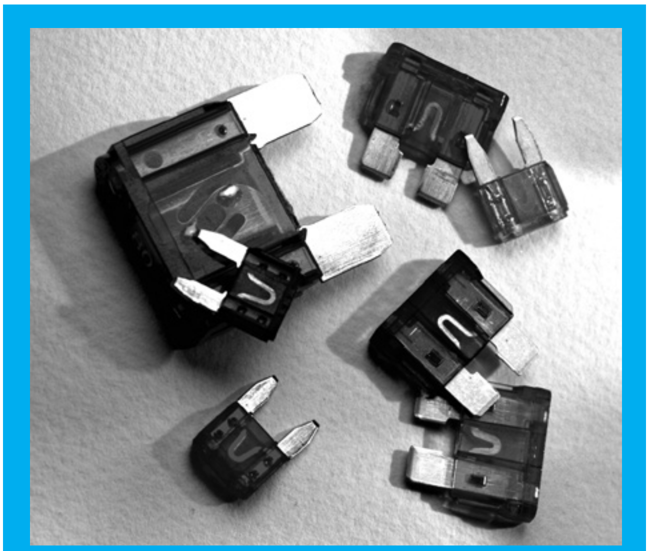


Figure 36: Thermogravimetric analysis in air





Automotive Blade Fuses

Blade fuses are a critical part of an automobile's circuit protection system. Operational reliability is key to ensuring the protection of a car's electronic and electrical devices in the event of abnormal power system surges or short circuit conditions. In addition, the fuse box is often located under hood where it and its contents are subjected to extremes of temperature, and in some cases, direct incidental contact with chemically aggressive fluids. Plastics used to manufacturer blade fuses must be able to withstand these conditions over the life of a vehicle without losing key features such as transparency, electrical insulation properties, and toughness.

Udel® PSU is an excellent blade fuse insulator material, particularly in higher amperage designs where the thermal capabilities of other amorphous materials, such as polycarbonate, are insufficient for the application. In addition, Udel® PSU is a more cost effective alternative to expensive high temperature transparent materials, such as polyetherimide. Because of transparency and high volume resistivity, as well as the ability to retain these properties while resisting embrittlement at continuous use temperatures up to 160 °C (320 °F), Udel® P-1700 is a popular material of choice for manufacturing blade fuses throughout the world.

Thermal aging

Thermo-oxidative stability limits the acceptable long-term use temperature of polymers. To evaluate the long-term effects of elevated ambient temperatures on the properties of Udel® PSU, test specimens were oven aged at several different temperatures. Bars were periodically removed and tested at room temperature for tensile strength.

The heat aging results for Udel® P-1700 resin are shown in Figure 37 and for Udel® GF-130 in Figure 38.

Figure 37: Tensile strength of Udel® P-1700 after heat aging

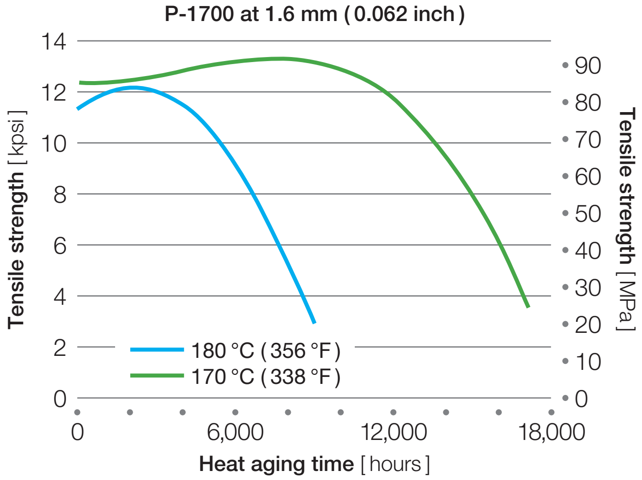
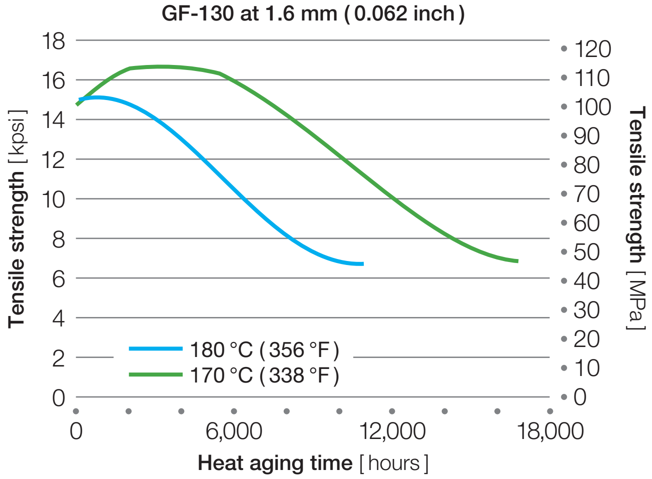


Figure 38: Tensile strength of Udel® GF-130 after heat aging



UL relative thermal index

Thermal aging data similar to those appearing in the previous section are used to establish Relative Thermal Indices per Underwriters Laboratories Standard 746B. This method determines the temperature to which a material can be exposed for 100,000 hours and still retain 50 % of its original properties. The index temperature is frequently considered the maximum continuous use temperature.

The Relative Thermal Indices (RTI) of the major grades of Udel® PSU are shown in Table 16. The most complete and up-to-date ratings are available of Underwriters Laboratories website.

Table 16: Selected UL RTI ratings for Udel® PSU

		Relative Thermal Index [°C (°F)]		
Grade	**Thickness** [mm (inch)]	**Elec-trical**	**Mechanical with Impact**	**Mechanical without Impact**
P-1700[1]	0.51 (0.020)	160 (320)	140 (284)	160 (320)
P-1700[2]	1.5 (0.059)	160 (320)	140 (284)	160 (320)
P-1720[1]	0.51 (0.020)	160 (320)	140 (284)	160 (320)
P-1720[2]	1.9 (0.075)	160 (320)	140 (284)	160 (320)
P-3500 LCD[1]	0.51 (0.020)	160 (320)	140 (284)	160 (320)
GF-110[2]	1.5 (0.059)	160 (320)	140 (284)	160 (320)
GF-120[2]	1.5 (0.059)	160 (320)	140 (284)	160 (320)
GF-130[2]	1.5 (0.059)	160 (320)	140 (284)	160 (320)

(1) *Natural or uncolored*
(2) *All colors*

Electrical Properties

Many applications for thermoplastic resins depend upon their ability to function as electrical insulators. Several tests have been developed to provide the designer with measures of how well a particular resin can perform that function. The electrical properties of the Udel® PSU resins are shown in Tables 2 and 3 on page 12 andpage 13.

Dielectric Strength

Dielectric strength is a measure of a material's ability to resist high voltage without dielectric breakdown. It is measured by placing a specimen between electrodes and increasing the applied voltage through a series of steps until dielectric breakdown occurs. Although the results have units of kV/mm (volts/mil), they are not independent of sample thickness. Therefore, data on different materials are comparable only for equivalent sample thicknesses.

Volume Resistivity

Volume resistivity is defined as the resistance of a unit cube of material. This test is run by subjecting the material to 500 volts for one minute and measuring the current. The higher the volume resistivity, the more effective a material is for electrically isolating components.

Surface Resistivity

The surface resistivity of a material is the electrical resistance between two electrodes on the surface of the specimen. The material is subjected to 500 volts DC for one minute and the current is measured. The surface resistivity is typically expressed in ohms or ohms per square. Although some finite thickness of material is actually carrying the current, this thickness is not measurable, therefore, this property is an approximate measure.

This data is best used to compare materials for use in applications where surface leakage is a concern.

Dielectric Constant

Dielectric constant is defined as the ratio of the capacitance of a condenser using the test material as the dielectric to the capacitance of the same condenser with a vacuum replacing the dielectric. Insulating materials are used in two very distinct ways: (1) to support and insulate components from each other and ground, and (2) to function as a capacitor dielectric. In the first case, it is desirable to have a low dielectric constant. In the second case, a high dielectric constant allows the capacitor to be physically smaller.

Dissipation Factor

Dissipation Factor (also referred to as loss tangent or tan delta) is a measure of the dielectric loss (energy dissipated) of alternating current to heat. In general, low dissipation factors are desirable.

Underwriters Laboratories (UL) Relative Thermal Index

The UL Relative Thermal Index (RTI) is often a consideration for electrical or electronic devices. The index is not an electrical property, rather it relates to the long-term thermal stability of a material. Values for Udel® PSU grades are shown in Table 16.

UL-746A Short-Term Properties

Certain electrical properties are included in the Underwriters Laboratories Standard 746A, entitled Standard for Polymeric Materials Short-Term Property Evaluations and are typically reported by Performance Level Category. For each test, UL has specified test result ranges and the corresponding performance level category. Desired or best performance is assigned to a PLC of 0, therefore the lower the number, the better the material's performance. These properties for Udel® PSU resins are shown in Table 22.

High-voltage, low-current dry arc resistance (D495)

This test measures the time that an insulating material resists the formation of a conductive path due to localized thermal and chemical decomposition and erosion. The test is intended to approximate service conditions in alternating-current circuits operating at high voltage with currents generally limited to less than 0.1 ampere. Table 17 shows the relationship between the arc resistance and the UL assigned performance level categories.

Table 17: High-voltage, low-current, dry arc resistance Performance Level Categories (PLC)

Value Range [sec.]		
≥	<	**Assigned PLC**
420		0
360	420	1
300	360	2
240	300	3
180	240	4
120	180	5
60	120	6
0	60	7

Comparative Tracking Index (CTI)

This test determines the voltage that causes a permanent electrically conductive carbon path when 50 drops of electrolyte are applied to the specimen at the rate of one drop every 30 seconds. This test is used as a measure of the susceptibility of an insulating material to tracking. Table 18 shows the relationship between the Comparative Tracking Index and the UL assigned Performance Level Categories.

Table 18: Comparative tracking index performance level categories

Value Range [volts]		
≥	**<**	**Assigned PLC**
600		0
400	600	1
250	400	2
175	250	3
100	175	4
0	100	5

High-Voltage Arc-Tracking-Rate (HVTR)

This test determines the susceptibility of an insulating material to track or form a visible carbonized conducting path over the surface when subjected to high-voltage, low-current arcing. The high-voltage arc-tracking rate is the rate in millimeters per minute at which a conducting path can be produced on the surface of the material under standardized test conditions. Table 19 shows the relationship between the High-Voltage Arc-Tracking-Rate and the UL assigned Performance Level Categories.

Table 19: High-voltage arc-tracking-rate performance level categories

Value Range [mm/min]		
>	**<**	**Assigned PLC**
0.0	10.0	0
10.0	25.4	1
25.4	80.0	2
80.0	150.0	3
150.0	–	4

Hot Wire Ignition (HWI)

This test determines the resistance of plastic materials to ignition from an electrically heated wire. Under certain operational or malfunctioning conditions, components become abnormally hot. When these overheated parts are in intimate contact with the insulating materials, the insulating materials may ignite. The intention of the test is to determine the relative resistance of insulating materials to ignition under such conditions. Table 20 shows the relationship between the Hot Wire Ignition value and the UL assigned Performance Level Categories.

Table 20: Hot wire ignition performance level categories

Value Range [sec.]		
<	**≥**	**Assigned PLC**
	120	0
120	60	1
60	30	2
30	15	3
15	7	4
7	0	5

High-Current Arc Ignition (HAI)

This test measures the relative resistance of insulating materials to ignition from arcing electrical sources. Under certain conditions, insulating materials may be in proximity to arcing. If the intensity and duration of the arcing are severe, the insulating material can ignite. Table 21 shows the relationship between the High-Current Arc Ignition value and the UL assigned Performance Level Categories.

Table 21: High-current arc ignition performance level categories

Value Range [sec.]		
<	**≥**	**Assigned PLC**
	120	0
120	60	1
60	30	2
30	15	3
15	0	4

Table 22: Short-term electrical properties per UL-746A

		High-Voltage, Low-Current, Dry Arc Resistance ASTM D495	Comparative Tracking Index (CTI)	High-Voltage Arc-Tracking-Rate (HVTR)	Hot Wire Ignition (HWI)	High-Current Arc Ignition (HAI)
Grade	**Thickness** [mm (inch)]	**sec. (PLC)**	**volts (PLC)**	**mm/min (PLC)**	**sec. (PLC)**	**arcs (PLC)**
P-1700	1.5 (0.059)	–	–	152 (4)	21 (3)	6 (4)
	3.0 (0.118)	39 (7)	(4)	–	21 (3)	6 (4)
	4.5 (0.177)	–	–	–	63 (1)	14 (4)
	6.0 (0.236)	–	–	–	91 (1)	16 (3)
P-1720	1.9 (0.075)	–	–	279 (4)	12 (4)	14 (4)
	3.0 (0.118)	61 (6)	135 (4)	135 (3)	27 (3)	19 (3)
	6.0 (0.236)	–	–	173 (4)	109 (1)	20 (3)
GF-110/GF-120	1.5 (0.059)	–	–	–	(3)	6 (4)
	3.0 (0.118)	(7)	165 (4)	–	97 (1)	7 (4)
GF-130	0.8 (0.031)	–	–	–	76 (1)	6 (4)
	1.5 (0.059)	–	–	–	98 (1)	6 (4)
	3.0 (0.118)	124 (5)	165 (4)	203 (4)	97 (1)	7 (4)
P-3500 LCD	0.5 (0.020)	–	–	–	–	–
	3.0 (0.118)	–	(4)	66 (2)	35 (2)	–

PLC = Performance Level Category, (0) is best

Environmental Resistance

Weathering

Because of the aromatic ether backbone, polysulfone is susceptible to chemical degradation upon outdoor exposure. Weather resistance can be improved by the addition of carbon black.

Applications of polysulfone involving outdoor exposure should be evaluated individually, considering the specific exposure conditions and the required material properties. Protective paints or coatings can be used to preserve the properties of polysulfone articles exposed to direct sunlight. Contact our technical personnel for assistance with applications having specific weathering requirements.

Hydrolytic Stability

Hydrolytic stability can be defined as resistance to hydrolysis, or attack by water, especially hot water. Therefore, hydrolytic stability is a specific instance of chemical resistance. Hydrolytic stability has special importance because water is ubiquitous and is very aggressive to many polymers.

Long-term exposure to hot water

To evaluate Udel® PSU for potential use in hot water plumbing systems, the effect of long-term hot water exposure on the physical and mechanical integrity of the polymer was measured. Although, the maximum use temperature of most household hot water systems is 60 °C (140 °F), testing was also performed at 90 °C (194 °F) to accelerate the effects of the hot water. Since the rate of many chemical reactions doubles for each 10 °C (18 °F) of temperature, testing at a temperature 30 °C (54 °F) higher than the expected maximum temperature may provide an acceleration factor of eight.

Test Procedure

Tests were conducted on ASTM D638 (Type I) tensile bars and ASTM D790 flexural bars with a 3.2 mm (0.125 inch) nominal thickness that were injection molded following conventional procedures. Plaques measuring 102 × 102 × 3.2 mm (4 × 4 × 0.125 inch) were molded for instrumented impact testing. Weld line tensile specimens were prepared using a mold for the ASTM D638 Type I tensile specimen with a gate at each end. This mold produces a specimen with a butt weld line in the center of the gauge area.

The samples were laid flat in individual layers on stainless steel wire trays in constant-temperature baths. Water from the municipal water supply of Alpharetta, Georgia, was used. After heating, the water was found to be chlorine free.

Test specimens were periodically removed from the bath and tested without drying. The tests were run at room temperature using the following ASTM test methods.

• Tensile strength, modulus, and elongation	D638
• Flexural strength and modulus	D790
• Weld line tensile strength and elongation	D638
• Notched izod impact	D256
• Tensile impact	D1822
• Instrumented impact energy	D3763

Test Results

The tensile strength retention for Udel® PSU materials is good. Figure 39 shows the tensile strength retention for Udel® P-1700 NT and Udel® GF-120 NT.

As seen in Figure 40, tensile elongation at break for Udel® P-1700 NT shows a large reduction early in the exposure with only a slight change throughout the remaining test time. The large initial drop is typical for ductile amorphous plastics and is attributed to the physical annealing or tempering of the material.

Figure 39: Tensile strength after 90 °C (194 °F) water exposure

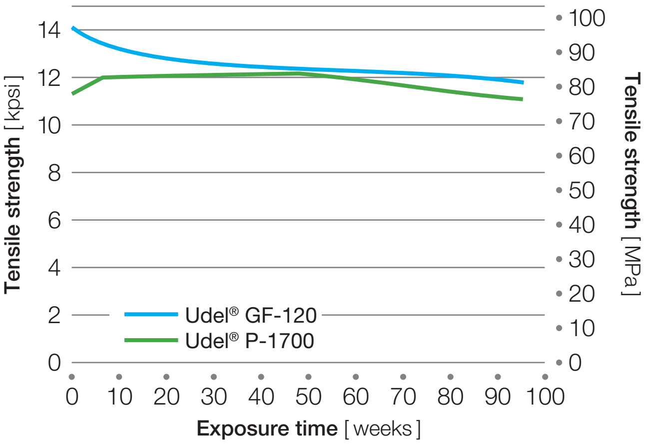
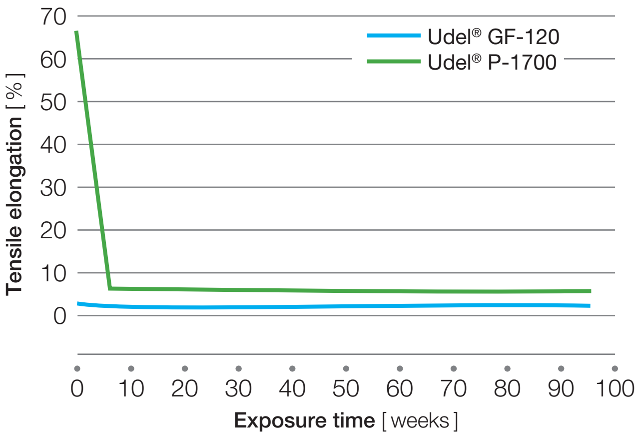
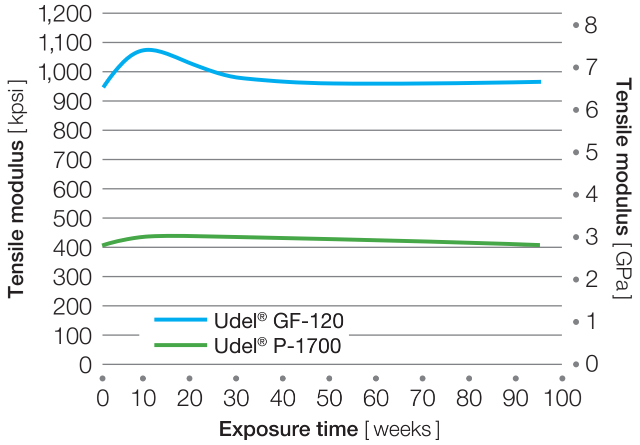


Figure 40: Tensile elongation after 90 °C (194 °F) water exposure



The effect of the hot water exposure on the tensile modulus of these resins is shown in Figure 41. There is very little change in modulus over approximately two years of hot water exposure. The stiffness of the bars after exposure is essentially the same as it was before the exposure.

Figure 41: Tensile modulus after 90 °C (194 °F) water exposure



The effect of the hot water exposure on the impact strength as measured by the Notched Izod method is shown in Figure 42. A minor drop occurs with the initial exposure, then the decline levels out. The impact strength at the nearly two-year exposure is roughly 80 % of the unexposed value.

Weld line strength for the Udel® PSUs, as shown in Figure 43, was very good, indicating that long-term hot water exposure has a minimal effect on the resin.

Figure 42: Notched Izod impact after 90 °C (194 °F) water exposure

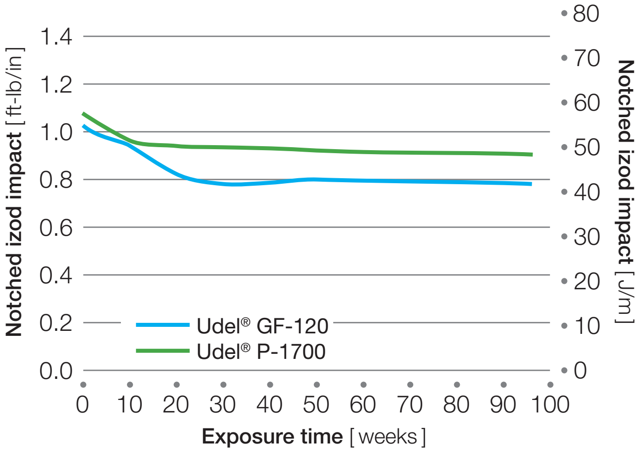
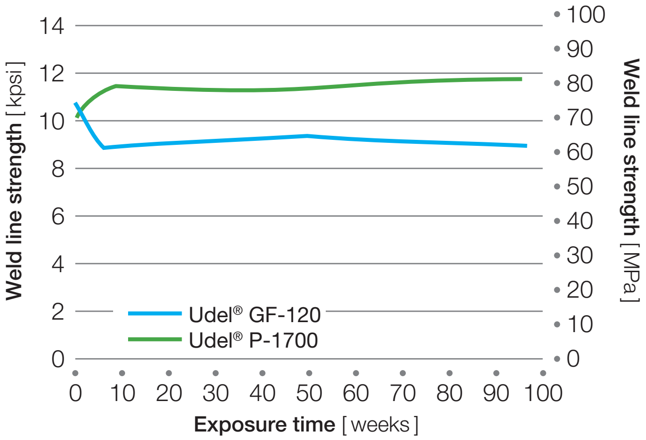


Figure 43: Weld line strength after 90 °C (194 °F) water exposure



Hot chlorinated water

Because residual chlorine in water systems combined with elevated temperatures can produce an oxidizing environment, resistance to hot water is not always enough. Since many plastics are susceptible to oxidation and oxidizing agents, this condition can dramatically shorten the service life of components made from some plastics.

Typical free chlorine levels in most US municipal water supplies at the point of use are in the range of 0.5 ppm to 2 ppm chlorine and are achieved by the addition of hypochlorites or chloramines.

Several studies have demonstrated that Udel® PSU based materials offer very good resistance to hot chlorinated water. Tests were conducted in static water, containing up to 30 ppm chlorine for 6 months at 60 °C (140 °F). As shown in Table 23, Udel® PSU did not exhibit any significant weight loss.

Tests were also conducted using flowing water containing 5 ppm chlorine for 2 months at 90 °C (194 °F). As shown in Table 24, again Udel® PSU did not exhibit any significant weight loss.

Table 23: Weight change in static chlorinated water

	Chlorine Content [ppm]			
Material	**0**	**10**	**20**	**30**
Udel® PSU	−0.02	−0.02	0.09	0.05
Polyacetal	−0.15	−2.96	−4.57	−5.47
CPVC	−0.64	−0.56	−0.04	0.08

Weight change after 6 months in water at 60°C (140°F), %

Table 24: Weight change in flowing chlorinated water

	Chlorine Content [ppm]	
Material	**0**	**5**
Udel® PSU, unfilled	0.0	0.1
Udel® PSU, 20 % glass-filled	0.0	0.0
CPVC	−0.6	1.2

Weight change after 2 months in water at 90°C (194°F), %

Steam sterilization analysis

Steam autoclaves are widely used to sterilize medical devices. If polysulfone resin was used for medical devices, resistance to degradation by steam sterilization would be a requirement.

To evaluate resistance to steam sterilization, molded test specimens with dimensions of 127 × 13 × 3 mm (5 × 0.5 × 0.125 inch) were placed in a steam autoclave. A test cycle consisted of 45 minutes; 30 minutes at a steam pressure of 0.18 MPa (27 psi), which has a temperature of 132 °C (270 °F), followed by 15 minutes at atmospheric pressure. The autoclave is then repressurized to 0.18 MPa (27 psi) for the next cycle. After the desired number of cycles, the test specimens were removed from the autoclave, cooled to room temperature, and after standard conditioning, tested for tensile strength, Izod impact, and tensile impact using the appropriate ASTM methods.

The results are shown in Table 25.

Table 25: Property retention after steam autoclave exposure

		Steam Autoclave Exposure [Cycles]		
Property	**Unit**	**0**	**50**	**100**
Tensile strength	MPa (kpsi)	74 (10.8)	87 (12.6)	88 (12.8)
Notched Izod impact	J/m (ft · lb/inch)	53 (1.0)	48 (0.9)	43 (0.8)
Tensile impact	kJ/m^2 (ft · lb/inch^2)	347 (165)	276 (131)	248 (116)

Radiation Resistance

Test specimens molded from Udel® P-1700 were exposed to gamma radiation at dosages of 50, 75, and 100 kGy (5, 7.5, and 10 megarads). After exposure, the properties were measured and the results compared to the properties of unexposed specimens. The percent retention was calculated by dividing the exposed value by the unexposed value and multiplying by 100.

As shown in Table 26, the mechanical properties were virtually unchanged by exposure to gamma radiation. Some darkening occurs.

Table 26: Gamma radiation resistance of Udel® PSU

	Property Retention [%]		
Gamma Radiation Dosage* [kGy]	**Tensile Strength**	**Tensile Modulus**	**Izod Impact**
50	99	100	96
75	99	94	93
100	98	100	98

**1 megarad = 10 kGy*

Chemical Resistance (Unstressed)

Polysulfone resins have good chemical resistance to most aqueous systems, caustics, and inorganic acids.

Resistance is also good to aliphatic hydrocarbons, detergents, soaps, and certain alcohols. Reagents known to be solvents or to cause stress cracking in polysulfone articles include chlorinated hydrocarbons, aromatics, and oxygenated solvents, such as ketones and ethers. Addition of glass fiber at levels of 10 % to 30 % substantially improves resistance to the more aggressive chemical environments.

A general indication of the chemical resistance of polysulfone is shown in Table 27. Chemical resistance was also evaluated by immersing bars for seven days at room temperature in various media. After seven days, the bars were removed, weighed and inspected. The results are shown in Table 28.

The resistance of polysulfone to aggressive environments depends on: (1) whether the agent is a non-solvent, a poor solvent, or a good solvent for polysulfone; and (2) the total stress present in the part from all sources.

To maximize chemical resistance, the lowest stress must be achieved in the finished part from all operations including molding and post-finishing. In some cases, annealing may be indicated to relieve residual stress. The benefits and disadvantages of annealing are discussed on page 72.

Table 27: General indication of the chemical resistance of unstressed Udel® PSU

		Rating*	
Chemical Family	**Example(s)**	**Unfilled Grades**	**Glass-Filled Grades**
Aliphatic hydrocarbons	n-butane, iso-octane	Excellent	Excellent
Aromatic hydrocarbons	benzene, toluene	Attack	Good
Alcohols	ethanol, isopropanol	Excellent	Excellent
Ketones	acetone, methyl ethyl ketone	Attack	Attack
Esters	ethyl acetate	Attack	Attack
Chlorinated hydrocarbons	1,1,1 trichloroethane, chloroform	Attack	Attack
Non-oxidizing acids	sulfuric acid (20 %), acetic acid (20 %)	Excellent	Excellent
Bases	sodium hydroxide, potassium hydroxide	Excellent	Good

** Rating system*
Excellent = No change
Good = Minor effects, no serious loss of properties
Attack = Rupture or dissolution

Table 28: Chemical resistance of Udel® P-1700 resin by immersion for 7 days at room temperature

Reagent	Concentration [%]	Weight Change [%]	Comments
Organic Chemicals			
Acetone / water	5	0.55	no change
Acetic acid	20	−0.52	no change
Butanol	100	−0.83	no change
Carbon tetrachloride	100	0.24	no change
Citric acid	40	0.41	no change
Cyclohexane	100	0.22	no change
Diethylene glycol monoethyl ether	100	0.13	no change
Ethanol	100	0.08	no change
Ethyl acetate	100	27.44	softened, swollen
Formic acid	10	0.96	no change
Glycerine	100	−0.15	no change
Oleic acid	100	0.07	no change
Oxalic acid	20	0.45	no change
1,1,1-Trichloroethane	100	1.03	no change
Inorganic Chemicals			
Chromic acid	12	0.28	no change
Calcium chloride	saturated	0.01	no change
Hydrochloric acid	20	0.40	no change
Hydrofluoric acid	50	2.02	no change
Hydrogen peroxide	100	0.51	no change
Nitric acid	20	0.43	no change
Nitric acid	40	0.33	no change
Nitric acid	71	3.76	attacked, discolored
Phosphoric acid	100	−0.25	no change
Potassium hydroxide	20	0.29	no change
Potassium hydroxide	35	0.13	no change
Sulfuric acid	40	0.19	slightly darkened
Functional Fluids			
Brake fluid	100	−0.04	no change
Diesel fuel	100	0.00	no change
Gasoline	100	0.05	no change
Hydraulic oil	100	0.35	no change
Jet fuel JP-4	100	0.05	no change
Kerosene	100	0.19	no change
Motor oil	100	0.01	no change
Transmission oil	100	0.01	no change

Stress Cracking Resistance

To evaluate the resistance of Udel® PSU resins to environmental stress cracking, test specimens 127 mm (5 inch) long, 13 mm (0.5 inch) wide, 3.2 mm (0.125 inch) thick were clamped to curved fixtures. The radius of the fixture induces a strain in the specimen. From the tensile modulus of each material, the corresponding stress was calculated as shown in Table 29. The reagents were then applied to the central portion of the fixtured test specimen. After 24 hours of exposure, the specimens were examined for evidence of attack and rated. Table 30 defines the ratings that appear in the subsequent environmental stress cracking resistance tables.

The variables of importance in environmental stress cracking are temperature, stress level, time, and reagent. If a reagent causes stress cracking at a given time, temperature, and stress level, the following generalizations usually apply. At lower stress levels, cracking may not occur. If cracking does occur, longer exposure time will usually be required. Higher temperature generally reduces the exposure time required to cause cracking. Diluting the reagent with liquids to which the polymer is inert will usually reduce or eliminate stress cracking depending upon the reagent and the diluent.

For the purpose of part design, it is important to consider the chemical environment, especially if the part will be stressed.

Table 29: Calculated stresses for strained ESCR test bars

		Stress [MPa (kpsi)]		
Grade	**Modulus** [GPa (kpsi)]	**Strain, 0.28 %**	**Strain, 0.56 %**	**Strain, 1.12 %**
P-1700	2.48 (360)	6.9 (1.0)	13.9 (2.0)	27.5 (4.0)
GF-110	3.65 (530)	10.2 (1.5)	20.7 (3.0)	40.5 (5.9)
GF-120	5.17 (750)	14.5 (2.1)	28.9 (4.2)	57.4 (8.3)
GF-130	7.38 (1,070)	20.7 (3.0)	41.3 (6.0)	81.9 (11.9)

Table 30: Key to environmental stress cracking tables

Symbol	**Definition**
OK	No change in appearance, no softening, no discoloration
D	Dissolved, evidence of solvation, softening, or swelling
C	Crazing
R	Rupture

Coffee Brewer Components

Udel® P-1700 helps Keurig Premium Coffee Systems™ with the manufacture of their patented brewing system. Internal components (heating tank lid, meter cup, mating lid, funnel, and K-Cup holder) made of Udel® PSU resin withstand prolonged exposure to high temperatures and resist residue buildup from mineral acids and alkali and salt solutions – typical contaminants found in water supplies.

Table 31: Environmental stress cracking resistance to organic chemicals after 24-hour exposure

				Strain [%]			
Reagent	**Concentration** [%]	**Temperature** [°C (°F)]	**Grade**	**0**	**0.28**	**0.56**	**1.12**
Acetone	100	23 (73)	P-1700	R	R	R	R
			GF-110	D	D	D	R
			GF-120	D	D	D	R
			GF-130	D	D	D	R
2-Ethoxyethanol	100	23 (73)	P-1700	OK	C	C	C
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	C
			GF-130	OK	OK	OK	OK
Ethyl acetate	100	23 (73)	P-1700	R	R	R	R
			GF-110	D	D	D	R
			GF-120	D	D	D	R
			GF-130	D	D	D	R
Isopropanol	100	23 (73)	P-1700	OK	OK	OK	C
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	C
			GF-130	OK	OK	OK	C
Methanol	100	23 (73)	P-1700	OK	OK	OK	C
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Methylene chloride	100	23 (73)	P-1700	D	D	D	D
			GF-110	D	D	D	D
			GF-120	D	D	D	D
			GF-130	D	D	D	D
Methyl ethyl ketone	100	23 (73)	P-1700	D	D	D	D
			GF-110	D	D	D	D
			GF-120	D	D	D	D
			GF-130	D	D	D	D
1,1,1-Trichloroethane	100	23 (73)	P-1700	OK	R	R	R
			GF-110	OK	C	C	R
			GF-120	OK	OK	R	R
			GF-130	OK	OK	C	R
Toluene	100	23 (73)	P-1700	D	D	D	D
			GF-110	D	D	D	D
			GF-120	D	D	D	D
			GF-130	D	D	D	D

Table 32: Environmental stress cracking resistance to inorganic chemicals after 24-hour exposure

Reagent	Concentration [%]	Temperature [°C (°F)]	Grade	Strain [%] 0	Strain [%] 0.28	Strain [%] 0.56	Strain [%] 1.12
Hydrochloric acid	20	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
	100	100 (212)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Sodium hydroxide	20	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
	100	100 (212)	P-1700	OK	OK	OK	C
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	C	C
			GF-130	OK	OK	C	C
Sodium hypochlorite (household bleach)	5.25	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
	100	100 (212)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Sulfuric acid	50	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
	100	100 (212)	P-1700	OK	OK	OK	C
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R

Table 33: Environmental stress cracking resistance to automotive fluids after 24-hour exposure

				Strain [%]			
Reagent	**Concentration** [%]	**Temperature** [°C (°F)]	**Grade**	**0**	**0.28**	**0.56**	**1.12**
Antifreeze (glycol type)	50	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	OK	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	OK	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Gasoline – unleaded	100	23 (73)	P-1700	OK	R	R	R
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	C
Motor oil 10W40	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	OK	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Power steering fluid	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Transmission fluid (ATF)	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	R	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Windshield washer concentrate	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		100 (212)	P-1700	OK	OK	OK	C
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R

Table 34: Environmental stress cracking resistance to food related products after 24-hour exposure

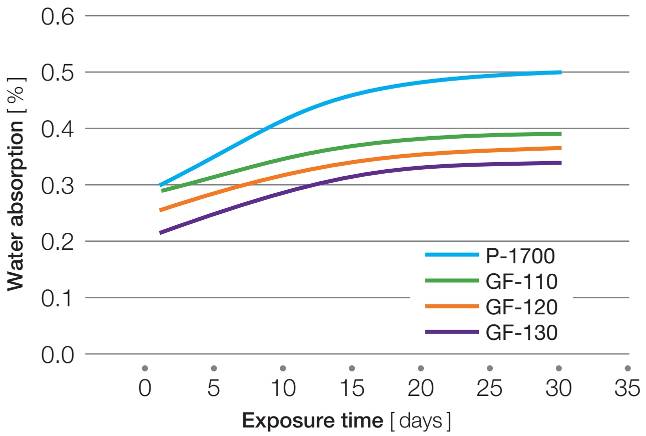
				Strain [%]			
Reagent	**Concentration** [%]	**Temperature** [°C (°F)]	**Grade**	**0**	**0.28**	**0.56**	**1.12**
Butter	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	R	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Corn oil	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	R	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Margarine	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	R	R
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Milk	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
Olive oil	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	OK	R
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Peanut oil	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	OK	OK	R	R
			GF-110	OK	OK	OK	R
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R
Vegetable oil	100	23 (73)	P-1700	OK	OK	OK	OK
			GF-110	OK	OK	OK	OK
			GF-120	OK	OK	OK	OK
			GF-130	OK	OK	OK	OK
		150 (302)	P-1700	R	R	R	R
			GF-110	OK	OK	OK	C
			GF-120	OK	OK	OK	R
			GF-130	OK	OK	OK	R

Physical Properties

Water Absorption

The water absorption of Udel® PSU resins measured by immersion at room temperature following ASTM test method D570 is shown in Figure 44. The graph shows that neat polysulfone absorbs less that 0.6 % weight moisture and the glass-reinforced grades absorb even less. The dimensional change due to moisture absorption is so small that it is negligible for most purposes.

Figure 44: Water absorption of Udel® PSU



Wear Resistance

Udel® PSU offers strength and rigidity at elevated temperatures, long-term heat resistance, dimensional stability, and outstanding resistance to acidic and basic environments. These properties combined with low isotropic mold shrinkage make Udel® PSU an ideal material for precision components.

For applications where sliding speed and load are low, standard Udel® PSU grades (P-1700, GF-120 etc.) may offer sufficiently low wear with a sufficiently low coefficients of friction. However, for applications where higher loads and speeds are required, it may be necessary to modify the material to improve its tribological properties.

Udel® PSU can be modified with additives to significantly improve its tribological properties. Additives found to be effective include reinforcing fibers, certain particulate fillers, fluorocarbon polymers, and silicone oils and resins. Incorporating these additives can significantly reduce the wear factor and coefficients of friction and increase the limiting pressure-velocity values for compounds based on Udel® PSU. Compounds based on Udel® PSU incorporating these additives are available from many independent compounders.

Abrasion resistance

Udel® P-1700 was tested using a Taber abrader with a CS-17 wheel for 1,000 cycles at a 1 kg load. The total weight loss was 20 mg.

Permeability

The permeability of Udel® PSU to various gases was measured in accordance with ASTM test method D1434. The tests were performed at standard conditions of temperature and pressure. The results are shown in Table 35.

Table 35: Permeability of Udel® PSU to various gases

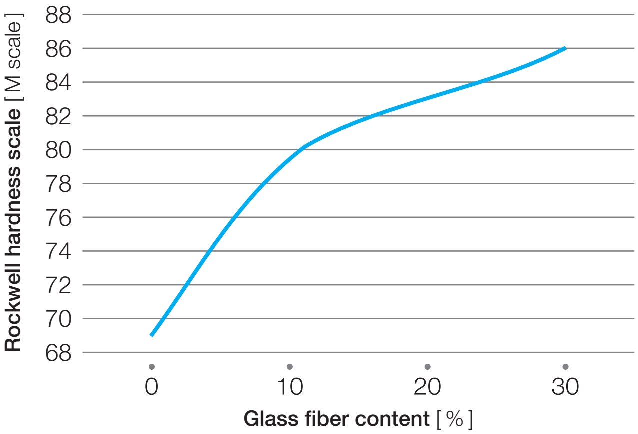
Gas		**Permeability** $\frac{mm^3 \cdot m}{m^2 \cdot MPa \cdot day}$ $\left(\frac{cc \cdot mil}{100\ inch^2 \cdot day \cdot atm}\right)$
Ammonia	NH_3	4,160 (1,070)
Carbon Dioxide	CO_2	3,690 (950)
Helium	He	7,620 (1,960)
Hydrogen	H_2	6,990 (1,800)
Methane	CH_4	146 (38)
Nitrogen	N_2	155 (40)
Oxygen	O_2	894 (230)
Sulfur Hexafluoride	SF_6	7 (2)

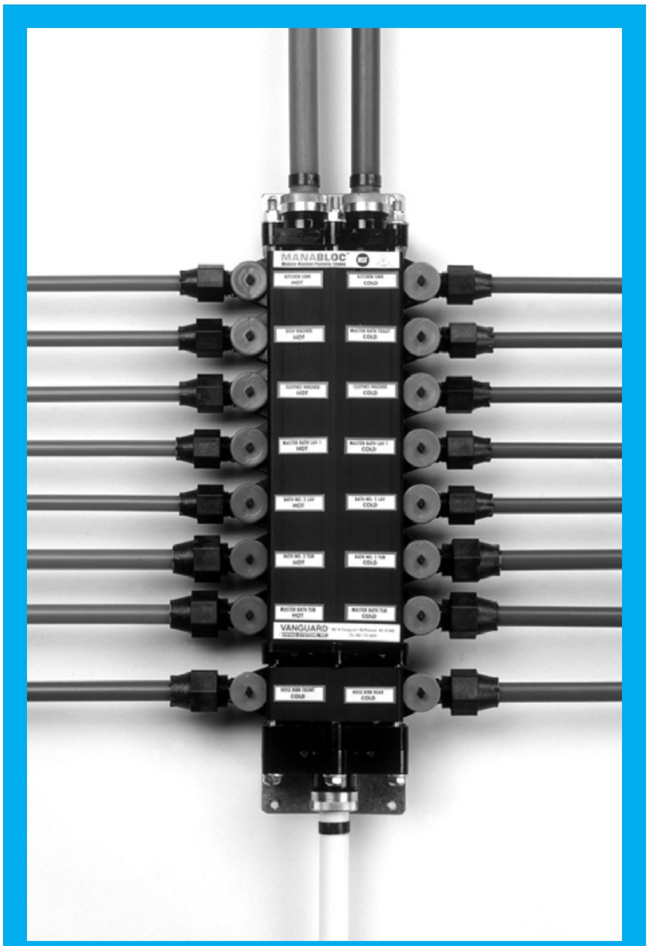
Rockwell Hardness

Rockwell hardness of Udel® PSU was determined according to ASTM test method D785, procedure A using an indenter diameter of 6.35 mm (0.25 inch) and a major load of 100 kg (220 lb) and a minor load of 10 kg (22 lb). This test measures the resistance of a material to indentation by a round steel ball of a specified diameter under specific time and loading conditions. The depth of the indentation is measured after the minor load is applied for 10 seconds, followed by application of the major load for 15 seconds. At the end of the 15 seconds, the major load is removed and the indentation measured. The hardness value is calculated by subtracting the indentation measurement from 150. Therefore, higher values of Rockwell hardness on the same scale indicate more resistance to indentation.

The Rockwell hardness of neat and glass-reinforced polysulfone is shown in Figure 45. As expected, the addition of glass fibers increases the indentation resistance and the Rockwell hardness values are higher.

Figure 45: Rockwell hardness, M scale





Water Distribution Manifold

Vanguard Piping Systems Inc. chose Udel® PSU for use in its unique Manabloc® water distribution system. The low creep of Udel® PSU resin was critical to the design of the manifold. It helped to ensure that sufficient compression would remain on the O-rings to maintain the seal between the modular sections over its expected lifetime.

Other critical design factors included the ability to withstand long-term hydrostatic stress to chlorinated potable water at temperatures typically found in residential plumbing systems and recognition under NSF/ANSI standard 61 for potable water contact.

Optical Properties

In its natural state, Udel® PSU is a transparent material with a slight yellow tinge. It offers relatively high light transmittance and low haze. Typical light transmittance curves for Udel® PSU for three different thicknesses are shown in Figure 46.

The transparency of Udel® PSU coupled with the other high-performance engineering features of the resin are advantageous in many applications. Examples include coffee decanters, sight glasses for process equipment, and the face shield visor for astronaut space suits. Selected optical properties of Udel® PSU are shown in Table 36. In addition to its good transparency attributes, polysulfone offers a high refractive index. A high refractive index is desirable for many lens applications because it allows thinner and/or higher power lenses than are possible with other commercially-available transparent polymers such as polycarbonate and acrylics.

The dispersion and Abbe value of the polymer provides a quantitative measure of the material's refractive index dependence on the wavelength of incident light. This property is usually obtained by measuring the refractive index of the plastic at three characteristic wavelengths of the visible spectrum referred to as the F line, the D line, and the C line. These lines have wavelengths of 486.1, 589.3, and 656.3 nanometers respectively. To generate the data reported in the Table 37, the refractive index, n, was measured at these wavelengths using an Abbe refractometer employing the method of total internal reflection. From these three refractive index values, the dispersion, Abbe value (or Abbe V-number as it is also known), and the slope of the refractive index-wavelength plot were calculated.

Table 36: Optical properties of Udel® P-1700 NT11

	Thickness [mm (inch)]			
Property	**1.78 (0.070)**	**2.62 (0.103)**	**3.33 (0.131)**	**ASTM Method**
Light transmittance	86	85	84	D1003
Haze [%]	1.5	2.0	2.5	D1003
Yellowness index	7.0	10	13	D1925

Figure 46: Light transmittance of Udel® P-1700 NT11 at various wavelengths and thicknesses

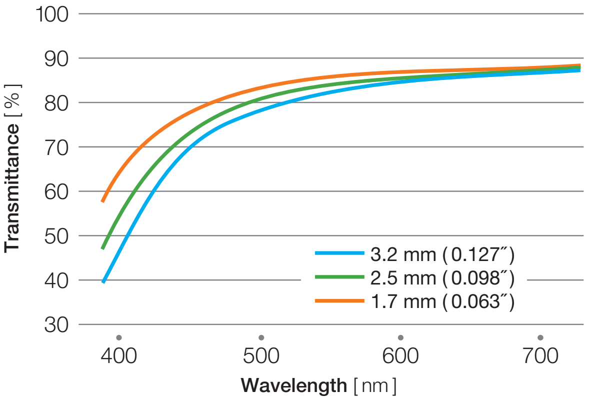
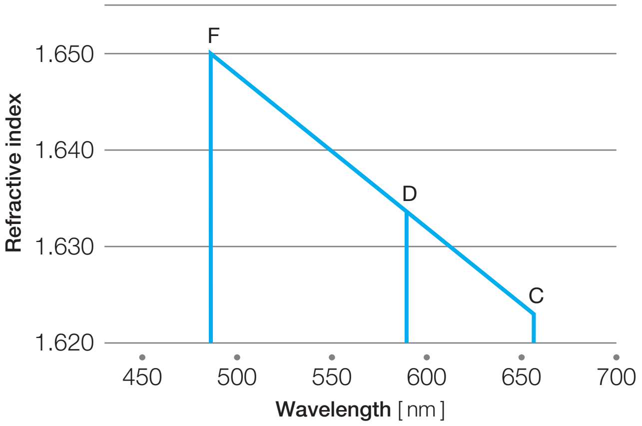


Table 37: Wavelength dependent properties of Udel® P-1700 NT11

Property	Formula	Value
Dispersion	$n_F - n_C$	0.027
Abbe Value	$\frac{n_D - 1}{n_F - n_C}$	23.3
Slope	$\frac{n_F - n_C}{C - F}$	$-1.6 \cdot 10^{-4}$

Figure 47: Refractive index variation with wavelength of Udel® P-1700 NT11



Design Information

The rules for designing articles to be produced using polysulfone are similar to those which apply to other thermoplastics. Good design will not only result in a better product but also a product which is easier to manufacture and will quite often be lower in cost. The goal of a plastic part design is to meet the physical strength and deformation requirements with minimum volume of material, considering the effects of stresses caused by assembly, temperature changes, processing. and environmental factors.

Mechanical Design

The use of classical stress and deflection equations provide starting points for part design. Mechanical design calculations for Udel® PSU resins are similar to those used with any engineering material, except that the physical constants used must reflect the viscoelastic nature of the polymers. The material properties vary with strain rate, temperature, and chemical environment. Therefore the physical constants, like elastic modulus, must be appropriate for the anticipated service conditions.

For example, if the service condition involves enduring load for a long period of time, then the apparent or creep modulus should be used instead of the short-term elastic modulus. When the loading is cyclical and long-term, then the fatigue strength at the design life is the limiting factor.

Stress Levels

The initial steps in the design analysis are to determine the loads that the part will be subjected to and to calculate the resultant stress and deformation or strain. The loads may be externally applied loads or loads that result from the part being subjected to deformation due to temperature changes or assembly.

An example of an externally applied load is the weight of medical instruments on a sterilizer tray. Deformation loads might arise when a switch housing is bolted to a base plate, or when the temperature of the assembly increases and the dimensions of the plastic part change more than the metal part to which it is bolted.

Stress-Strain Calculations

To use the classical equations, the following simplifying assumptions are necessary:

- The part can be analyzed as one or more simple structures.
- The material can be considered linearly elastic and isotropic.
- The load is a single concentrated or distributed static load gradually applied for a short time.
- The part has no residual or molded-in stresses.

Bending stress

A variety of parts can be analyzed using a beam bending model. Figure 48 lists the equations for maximum stress and deflection for some selected beams. The maximum stress occurs at the surface of the beam furthest from the neutral surface, and is given by:

$$\sigma = \frac{Mc}{I} = \frac{M}{Z}$$

Where:

M = Bending moment, inch pounds
c = Distance from neutral axis, inches
I = Moment of inertia, inches^4
$Z = \frac{I}{c}$ = Section modulus, inches^3

Figure 49 lists the cross sectional area (A), the moment of inertia (I), the distance from the neutral axis (c), and the section modulus (Z) for some common cross sections.

Tensile stress

In the elastic region of the stress-strain curve, the strain can be related to the applied stress by Hooke's Law. Hooke's Law can be expressed as

$$\sigma = E\varepsilon$$

where

σ = tensile stress
E = modulus of elasticity
ε = elongation or strain

The tensile stress is defined as:

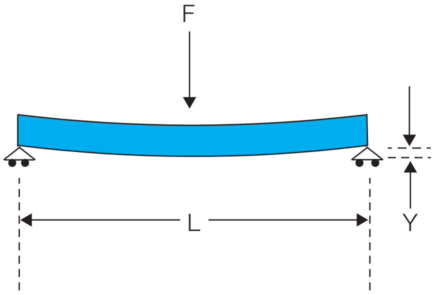
$$\sigma = \frac{F}{A}$$

Where:

F = Total force
A = Cross-sectional area

Figure 48: Maximum stress and deflection equations

Simply supported beam
Concentrated load at center



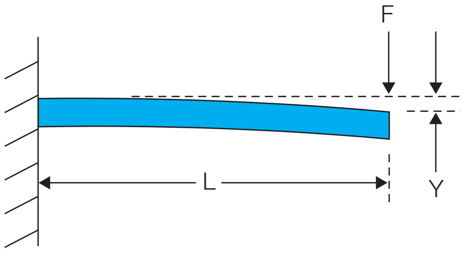
$$\sigma = \frac{FL}{4Z}$$

(at load)

$$Y = \frac{FL^3}{48EI}$$

(at load)

Cantilevered beam (one end fixed)
Concentrated load at free end



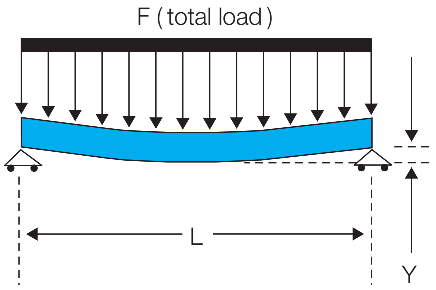
$$\sigma = \frac{FL}{Z}$$

(at support)

$$Y = \frac{FL^3}{8EI}$$

(at load)

Simply supported beam
Uniformly distributed load



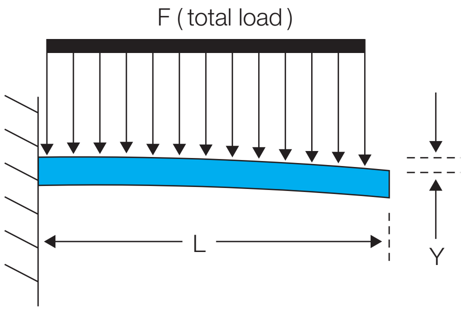
$$\sigma = \frac{FL}{8Z}$$

(at center)

$$Y = \frac{5FL^3}{384EI}$$

(at center)

Cantilevered beam (one end fixed)
Uniformly distributed load



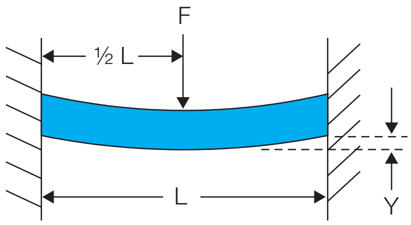
$$\sigma = \frac{FL}{2Z}$$

(at support)

$$Y = \frac{FL^3}{8EI}$$

(at support)

Both ends fixed
Concentrated load at center



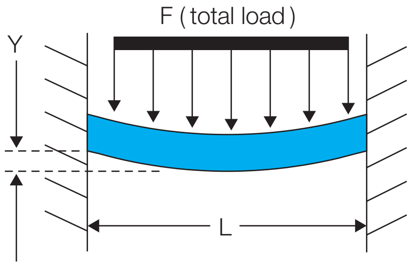
$$\sigma = \frac{FL}{8Z}$$

(at supports)

$$Y = \frac{FL^3}{192EI}$$

(at load)

Both ends fixed
Uniformly distributed load



$$\sigma = \frac{FL}{12Z}$$

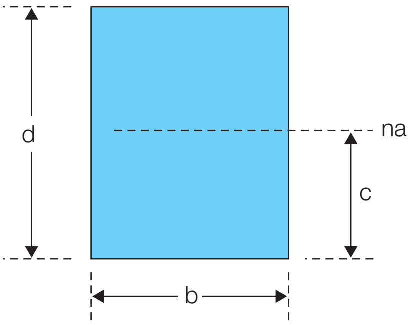
(at supports)

$$Y = \frac{FL^3}{384EI}$$

(at center)

Figure 49: Area and moment equations for selected cross sections

Rectangular



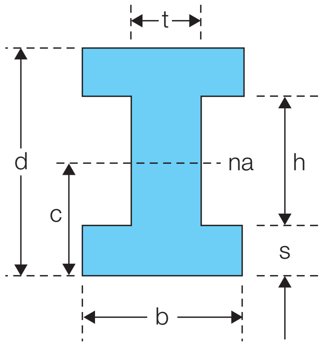
$$A = bd$$

$$c = \frac{d}{2}$$

$$I = \frac{bd^3}{12}$$

$$Z = \frac{bd^2}{6}$$

I-beam



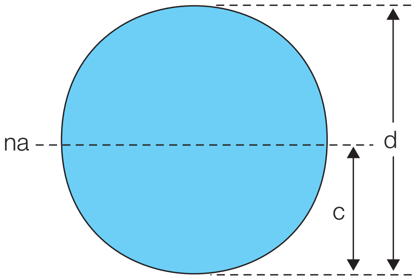
$$A = bd - h(b - t)$$

$$c = \frac{d}{2}$$

$$I = \frac{bd^3 - h^3(b - t)}{12}$$

$$Z = \frac{bd^3 - h^3(b - t)}{6d}$$

Circular



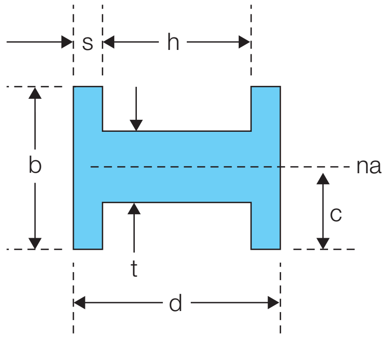
$$A = \frac{\pi d^2}{4}$$

$$c = \frac{d}{2}$$

$$I = \frac{\pi d^4}{64}$$

$$Z = \frac{\pi d^3}{32}$$

H-beam



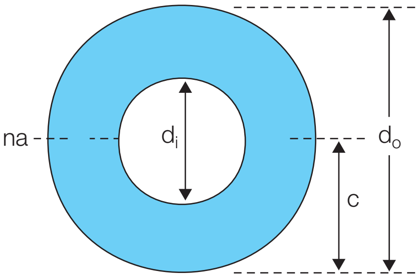
$$A = bd - h(b - t)$$

$$c = \frac{b}{2}$$

$$I = \frac{2sb^3 + ht^3}{12}$$

$$Z = \frac{2sb^3 + ht^3}{6b}$$

Tube



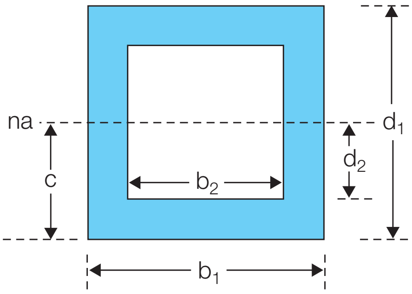
$$A = \frac{\pi(d_o^2 - d_i^2)}{4}$$

$$c = \frac{d_o}{2}$$

$$I = \frac{\pi(d_o^4 - d_i^4)}{64}$$

$$Z = \frac{\pi(d_o^4 - d_i^4)}{32d_o}$$

Hollow rectangular



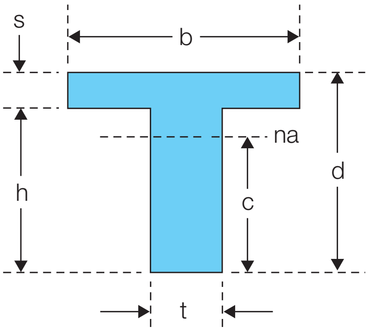
$$A = b_1d_1 - b_2d_2$$

$$c = \frac{d_1}{2}$$

$$I = \frac{b_1d_1^3 - b_2d_2^3}{12}$$

$$Z = \frac{b_1d_1^3 - b_2d_2^3}{6d_1}$$

T-beam or rib



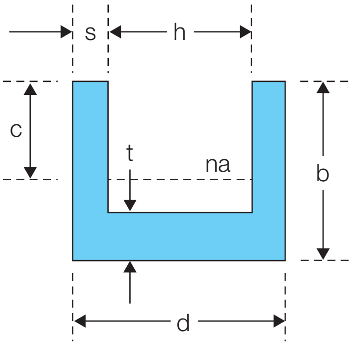
$$A = bs + ht$$

$$c = d - \frac{d^2t + s^2(b - t)}{2(bs + ht)}$$

$$Z = \frac{I}{c}$$

$$I = \frac{tc^3 + b(d - c)^3 - (b - t)(d - c - s)^3}{3}$$

U-beam



$$A = bd - h(b - t)$$

$$c = b - \frac{2b^2s + ht^2}{2A}$$

$$I = \frac{2b^3s + ht^3}{3} - A(b - c)^2$$

$$Z = \frac{I}{c}$$

Designing for Stiffness

When a design engineer considers replacing a metal component with plastic, one consideration is the rigidity or stiffness of the component. If the application requires that the maximum deflection under load remain at the current value, then the plastic component must have stiffness equivalent to the metal component.

Figure 48 provides the deflection equations for a variety of beams. Selecting the beam with both ends fixed and a uniformly distributed load, the deflection (Y) is given by

$$Y = \frac{FL^3}{384EI}$$

To arrive at a part design with equivalent stiffness, start by equating the deflection equations for the plastic and metal parts as follows:

$$\left[\frac{FL^3}{384EI}\right]_{metal} = \left[\frac{FL^3}{384EI}\right]_{plastic}$$

Assuming a constant load and length, and removing the factors common to both sides of the equation, the governing equation becomes:

Equation 1

$$[EI]_{metal} = [EI]_{plastic}$$

Knowing that the modulus of elasticity (E) of these materials are substantially different, it becomes apparent that the dimensions of the parts will need to be changed to adjust the moment of inertia (I).

For example, if the metal part is produced from magnesium with a modulus of 44.9 GPa (6.5 psi · 10^6 psi) and the replacement plastic material is Udel® GF-130 with a modulus of 7.38 GPa (1.07 psi · 10^6 psi), then the required increase in the moment of inertia can be calculated from Equation 2.

Equation 2

$$(44.9\ \text{GPa})(I_{magnesium}) = (7.38\ \text{GPa})(I_{Udel})$$

or $$(6.5\ \text{psi} \cdot 10^6\ \text{psi})(I_{magnesium}) = (1.07\ \text{psi} \cdot 10^6\ \text{psi})(I_{Udel})$$

$$I_{Udel} = 6.07\ I_{magnesium}$$

Increasing section thickness

One way to increase the moment of inertia is to increase the section thickness.

From Figure 49, the formula for the moment of inertia of a rectangular section is:

$$I = \frac{bd^3}{12}$$

where b is the width and d is the thickness of the section.

Substituting into Equation 2 and eliminating common factors:

$$d_{Udel} = \sqrt[3]{6.07d^3_{magnesium}}$$

If the section thickness in magnesium was 0.100 inch (2.54 mm), then

$$d_{Udel} = \sqrt[3]{6.07(.001)}$$

$$d_{Udel} = 0.182\ \text{inch}$$

or

$$d_{Udel} = \sqrt[3]{6.07(16.38)}$$

$$d_{Udel} = 4.63\ \text{mm}$$

To achieve equivalent stiffness by simply increasing section thickness requires an 82 % increase.

Adding ribs to maintain stiffness

Another method of achieving stiffness is to increase the moment of inertia by adding ribs. The use of ribs can reduce wall thickness and weight, and still provide the required stiffness.

Because the material is the same as in the previous example, the moment of inertia of the rib design is equal to the moment of inertia of the 4.63 mm (0.182 inch)-thick plate. The moment of inertia of the plate is given by:

$$I_{plate} = \frac{bd^3}{12}$$

If we assign 25.4 mm (1 inch) to the width, then I = 209 mm^4 (5.02 · 10^{-4} $inch^4$).

Calculating the rib and wall thickness that will give the same moment of inertia is done using the following equations for the distance from the neutral axis to the extreme fiber (c), the moment of inertia (I), and the area (A).

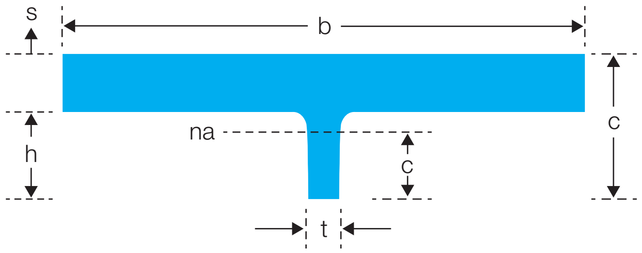
$$c = d - \frac{d^2t + s^2(b - t)}{2(bs + ht)}$$

$$I = \frac{tc^3 + b(d - c)^3 - (b - t)(d - c - s)^3}{3}$$

$$A = bs + ht$$

A typical rib design is shown in Figure 50.

Figure 50: Adding ribs to achieve stiffness



Experience has taught that certain constraints on the rib design are desirable from a processing standpoint. The constraints are:

$t \leq 0.6\ s$
$h = 1.5\ s$

Using an empirical iterative method to solve these equations for the rib geometry that would provide the same moment of inertia as the original metal part or the 4.63 mm (0.182 inch) thick plate with one rib per inch yields these results.

Wall thickness (s) = 3.2 mm (0.125 inch)
Rib width (t) = 1.9 mm (0.075 inch)
Rib height (h) = 4.8 mm (0.1875 inch)

Adding one rib per 25 mm (1 inch) reduces the cross-sectional area required for equivalent stiffness from 117 mm^2 (0.182 $inch^2$) to 90 mm^2 (0.139 $inch^2$).

Designing for Sustained Load

Typical stress strain calculations describe the immediate or short-term response to load. If the load is sustained over a long time interval, the deflection is greater than expected due to the visco-elastic nature of the polymer which leads to the phenomenon known as creep. To more accurately predict deflection under sustained load situations, the apparent or creep modulus can be used in place of the elastic modulus. An example of the calculations for a sustained load is shown below.

Calculating deflection

If the beam shown in Figure 51 is loaded with a uniformly distributed load of 13.8 Pa (2 lbf/in), to calculate the instantaneous deflection in the center and the deflection after 10,000 hours of sustained load, refer to Figure 48. The equation for the deflection of a simply supported beam with a uniformly distributed load is:

$$Y = \frac{5FL^3}{384EI}$$

The moment of inertia for a beam with a rectangular cross section is given in Figure 49 as:

$$I = \frac{bd^3}{12}$$

The width of the beam is 25.4 mm (1 inch). Substituting the beam dimensions in the equation gives:

$$I = \frac{(1)(0.182)^3}{12}$$

$$I = 0.00050238\ \text{inch}^4\ (209\ \text{mm}^4)$$

The short-term deflection for this beam if it were made from Udel® P-1700 is given by:

$$Y = \frac{5FL^3}{384EI}$$

Where:
$F = 10$ pounds (68.9 Pa)
$L = 5$ inch (127 mm)
$E = 360{,}000$ psi (2.48 GPa)
$I = 0.00050238\ \text{inch}^4\ (209\ \text{mm}^4)$

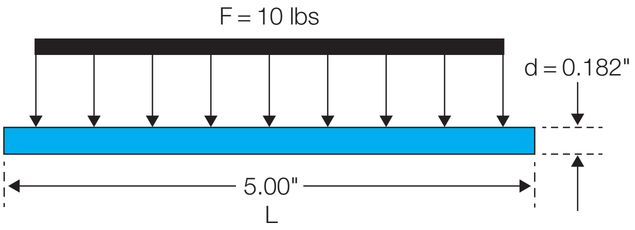
$$Y = \frac{(5)(10)(5)^3}{(384)(360{,}000)(0.00050238)} = 0.09\ \text{inch}\ (2.3\ \text{mm})$$

If the load is sustained for 10,000 hours, then the apparent or creep modulus, which can be found in Figure 22 on page 20, is used instead of the tensile modulus.

$$Y = \frac{(5)(10)(5)^3}{(384)(290{,}000)(0.00050238)} = 0.11\ \text{inch}\ (2.8\ \text{mm})$$

The additional deformation due to creep is 0.5 mm (0.02 inch).

Figure 51: Beam used in sustained load example



Design Limits

After the designer has calculated the maximum stress level and deflection, he then compares that stress value to the appropriate material property, i.e. tensile, compressive, or shear strength. He then decides whether the design incorporates a sufficient safety factor to be viable or whether the design should be modified by changing wall thickness or incorporating ribs or contours to increase the section modulus.

The term "design allowable" has been coined for an estimate of a material's strength that incorporates the appropriate safety factors for the intended loading pattern. Table 38 presents the design allowables for short-term intermittent loading. Table 39 provides the design allowable stresses for constant loading where creep is a major design consideration. These tables do not consider any environmental factors other than temperature. The presence of chemicals may lower the design allowables dramatically.

The design given by the application of the mechanical design equations is useful as a starting point, but some critical factors are not considered by this analysis. For example, the impact resistance of a design is directly related to its ability to absorb impact energy without fracture. Increasing wall thickness generally improves the impact resistance of a molded part. However, increased wall thickness could reduce impact resistance by making the part overly stiff and unable to deflect and distribute the impact energy. Therefore, the ability of the design to withstand impact must be checked by testing the impact resistance of prototype parts.

Industrial Battery Container

Saft chose Udel® PSU for the container or "jar" that holds the battery cell components in their SRM F3 battery cells typically used for electrical system backup in rail transport systems. The cells are filled with potassium hydroxide electrolyte fluid and are expected to function without fluid replenishment for two years. Udel® PSU's resistance to water absorption, shock, and vibration are key to maintaining long-term battery stability. Because the material is transparent, fluid levels can be monitored without opening the vent cap.

Table 38: Allowable design stress for intermittent load, MPa (psi)

	Temperature [°C (°F)]		
Grade	**23 (73)**	**93 (200)**	**149 (300)**
P-1700	36.3 (5,300)	31.2 (4,520)	25.1 (3,640)
GF-110	40.5 (5,880)	33.6 (4,880)	28.3 (4,100)
GF-120	50.2 (7,280)	38.0 (5,510)	33.6 (4,870)
GF-130	55.9 (8,110)	33.6 (4,870)	41.8 (6,060)

Table 39: Allowable design stress for constant load, MPa (psi)

	Temperature [°C (°F)]		
Grade	**23 (73)**	**93 (200)**	**149 (300)**
P-1700	17.6 (2,550)	13.2 (1,910)	8.7 (1,260)
GF-110	19.5 (2,820)	14.8 (2,150)	10.9 (1,580)
GF-120	24.1 (3,500)	17.3 (2,520)	14.1 (2,040)
GF-130	26.9 (3,900)	20.8 (3,020)	18.8 (2,730)

Stress concentrations

Classical mechanical design may result in a component design that fails prematurely or at a much lower stress than predicted due to stress concentration. Stress concentrations occur at sharp corners, around holes, or other part features. Impact and fatigue situations are especially sensitive to stress concentrations.

Minimizing sharp corners reduces stress concentrations and results in parts with greater structural strength. To avoid stress concentration problems, inside corner radii should be equal to at least half of the nominal wall thickness. A fillet radius of 0.4 mm (0.015 inch) should be considered minimum.

Figure 52 shows the effect of inside corner radius on the stress concentration factor. For example, if the nominal wall thickness (t) is 2 mm (0.080 inch) and an inside corner radius (r) is 0.5 mm (0.020 inch), then the radius to thickness ratio (r/t) is 0.25 and the stress concentration factor will be about 2. Effectively a stress of x will act like a stress of 2x at the corner.

Outside corners should have a radius equal to the sum of the radius of the inside corner and the wall thickness to maintain a uniform wall thickness.

Figure 52: Stress concentration factor for inside corners

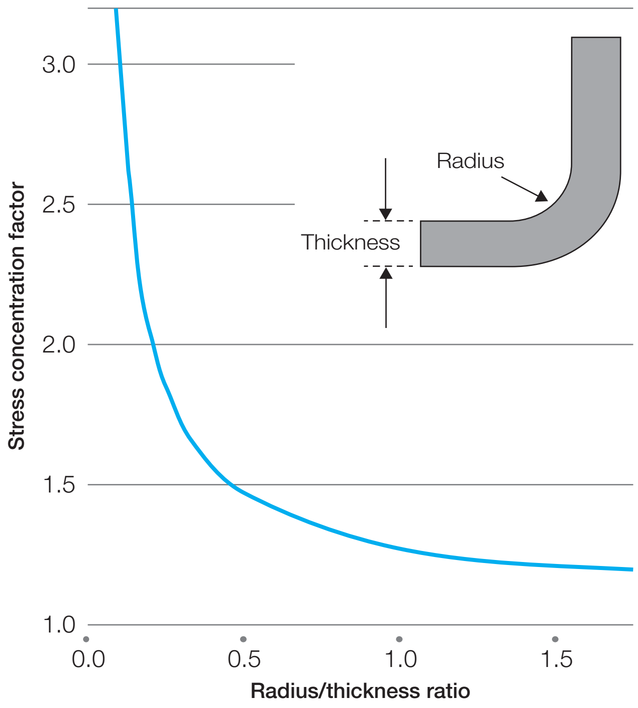
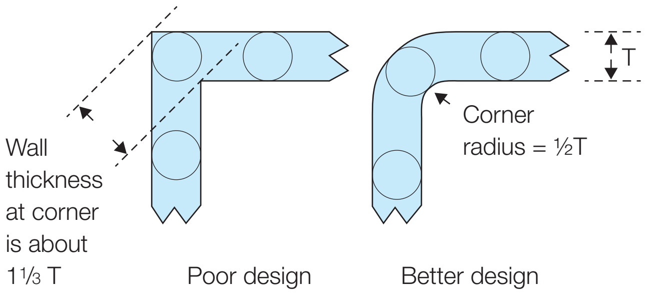


Figure 53 illustrates proper corner design.

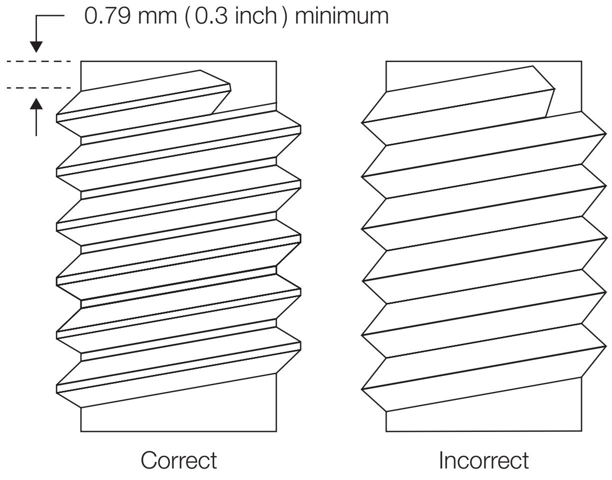
Figure 53: Design corners to minimize stress



Threads

The classes of the Unified Thread Standard with a rounded root should be used. Threads should not run to the very end of a threaded section. A clear area of at least 0.79 mm (0.03 inch) should be provided. Pipe threads are not recommended because they induce a severe wedging action.

Figure 54: Proper thread design



Interference fits

One of the most economical methods that can be used to assemble two parts is a press fit. It joins two parts using a shaft and hub without the use of screws, adhesives, metal inserts, or ultrasonic welding, etc. The joint is achieved by pressing or forcing the shaft into a hole whose diameter is smaller than the diameter of the shaft. The difference in diameter between the hole and shaft is referred to as the diametrical interference. The force maintaining the joint is primarily a compressive stress on the shaft resulting from the hoop stress in the hub created by the insertion of the shaft. Depending upon the relative moduli of the shaft and hub materials, the compressive stress in the shaft can also contribute to maintaining the joint. The stress holding an interference fit will exhibit relaxation over time in a manner that is analogous to creep, because the apparent modulus of the polymeric material decreases over time.

Calculating the allowable interference

The allowable interference between a shaft and a hub can be determined by using the general equation:

$$I = \frac{S_d D_s}{F}\left[\frac{F + \upsilon_h}{E_h} + \frac{1 - \upsilon_s}{E_s}\right]$$

and the geometry factor is given by:

$$F = \frac{1 + \left(\frac{D_s}{D_h}\right)^2}{1 - \left(\frac{D_s}{D_h}\right)^2}$$

Where:
I = Diametrical interference, inch (mm)
S_d = Working stress, psi (MPa)
D_h = Outside diameter of the hub, inch (mm)
D_s = Diameter of the shaft, inch (mm)
E_h = Modulus of elasticity of the hub material, psi (MPa)
E_s = Modulus of elasticity of the shaft material, psi (MPa)
υ_h = Poisson's ratio of the hub material
υ_s = Poisson's ratio of the shaft material
F = Geometry factor

If the shaft and hub are made from the same grade of Udel® PSU resin, then:

$$E_h = E_S = E$$

and the interference is:

$$I = \frac{S_d}{E} D_s \left(\frac{F + 1}{F}\right)$$

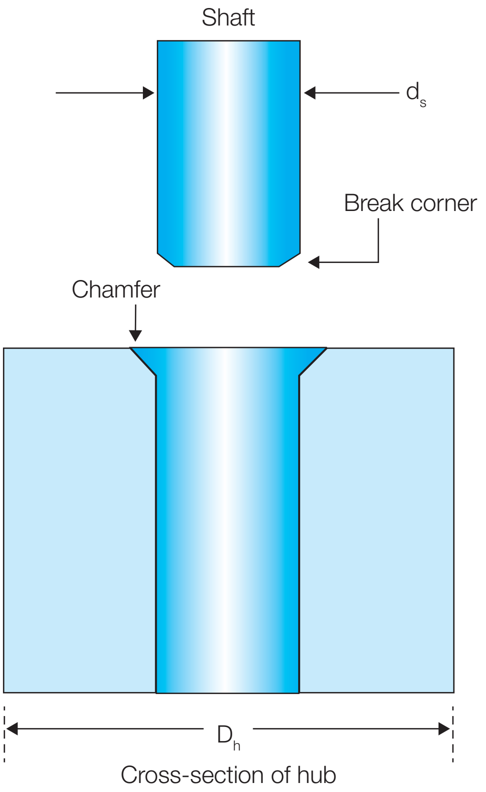
If the hub is made from Udel® PSU resin and the shaft is made from metal, then the interference is:

$$I = \frac{S_d D_s}{E} \frac{F + \upsilon_h}{E_h}$$

When a press fit is used with dissimilar materials, the differences in thermal expansion can increase or decrease the interference between two mating parts. This could increase or reduce the stress affecting joint strength.

A press fit can creep or stress relax over time. This could cause a decrease in the retention force of the assembly. Therefore, testing the assembly under its expected operating conditions is highly recommended.

Figure 55: Press fit example



Designing for Injection Molding

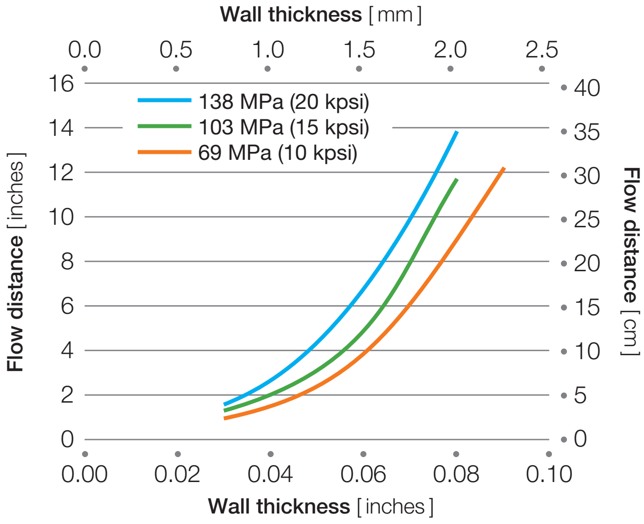
Because many of the applications for Udel® PSU resins will be injection molded components, factors which influence moldability must be considered in the part design. These factors include wall thickness and wall thickness transitions, draft, ribs, bosses, and coring.

Wall Thickness

In general, parts should be designed with the thinnest wall that has sufficient structural strength to support the expected loads, keeps deflection within design criteria limits, has adequate flow, and meets flammability and impact requirements. Parts designed in this manner will have the lowest possible weight, the shortest molding cycle, and therefore the lowest cost.

Occasionally, wall thicknesses greater than those required by the mechanical design analysis are required for molding. The flow of Udel® PSU resins, like other thermoplastics, depends upon the wall thickness as well as the mold design and process variables, such as injection rate, mold temperature, melt temperature, and injection pressure. The practical limits of wall thickness generally lie between 0.8 mm (0.030 inch) and 6.4 mm (0.250 inch). Wall sections of 0.25 mm (0.010 inch) can be molded if flow lengths are short. Figure 56 shows the flow length obtained at different wall thicknesses and injection pressures using a mold temperature of 93 °C (200 °F).

Figure 56: Flow distance versus thickness of Udel® P-1700

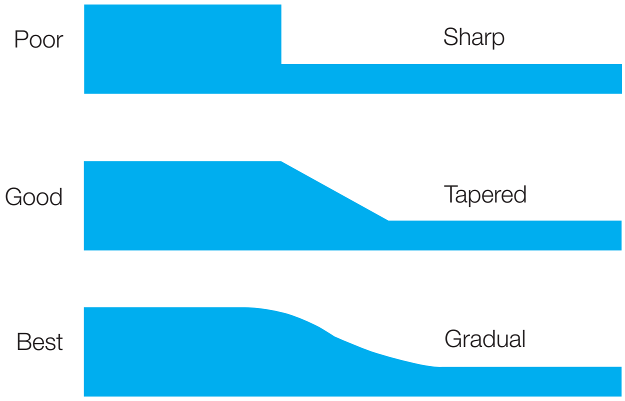


Wall Thickness Variation

While uniform wall thicknesses are ideal, varying wall thickness may be required by structural, appearance, and draft considerations. When changes in wall section thickness are necessary, the designer should consider a gradual transition, such as the 3 to 1 taper ratio shown in Figure 57. Sharp transitions can create problems in appearance and dimensional stability due to cooling rate differentials and turbulent flow.

Also, from a structural standpoint, a sharp transition will result in a stress concentration, which may adversely affect part performance under loading or impact.

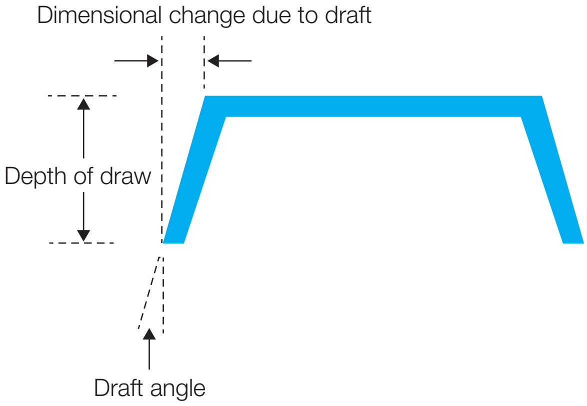
Figure 57: Wall thickness transition



Draft Angle

To aid in the release of the part from the mold, parts are usually designed with a taper in the direction of mold movement. The taper creates a clearance as soon as the mold begins to move, allowing the part to break free. The taper is commonly referred to as “draft”, and the amount of taper referred to as “draft angle.” The use of draft is illustrated in Figure 58.

Figure 58: Using draft to aid mold release



Adequate draft angle should be provided to allow easy part removal from the mold. Generally for Udel® PSU resins, the designer should allow a draft angle of ½° to 1° per side for both inside and outside walls. In some special cases, smaller draft angles, as low as ⅛° to ¼°, have been used with draw polish on the mold surface.

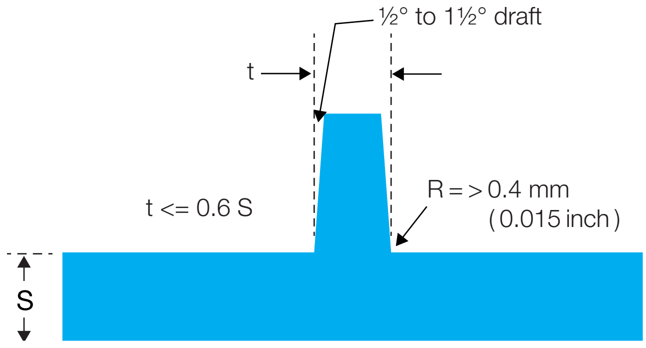
More draft should be used for deep draws or when cores are used. Textured finishes increase draft requirements by a minimum of 1° per side for each 0.025 mm (0.001 inch) of texture depth.

Ribs

The structural stiffness of a part design can be increased with properly designed and located ribs without creating thick walls. Proper rib design allows decreased wall thickness, which in turn saves material and weight, shortens molding cycles and eliminates thick walls, which can cause molding problems like sink marks. Ribs that are correctly positioned may also function as internal runners, assisting material flow during molding.

In general, these guidelines should be followed when designing with ribs. The thickness at the rib base should be equal to one-half the adjacent wall thickness. When ribs are opposite appearance areas, the width should be kept as thin as possible. If there are areas in the molded part where structure is more important than appearance, then ribs are often 75 % or even 100 % of the outside wall thickness. Whenever possible, ribs should be smoothly connected to other structural features such as side walls, bosses, and mounting pads. Ribs need not be constant in height or width, and are often matched to the stress distribution in the part. All ribs should have a minimum of ½° of draft per side and should have a minimum radius of 0.4 mm (0.015 inch) at the base. Figure 59 shows recommended rib size relationships.

Figure 59: Recommended rib design



Coring

Proper design should include uniform wall section thickness throughout a part. Heavy sections in a part can extend cycle time, cause sink marks, and increase molded-in stresses.

Heavy sections should be cored to provide uniform wall thickness. For simplicity and economy in injection molds, cores should be parallel to the line of draw of the mold. Cores placed in any other direction, usually create the need for some type of side action or manually loaded and unloaded loose cores.

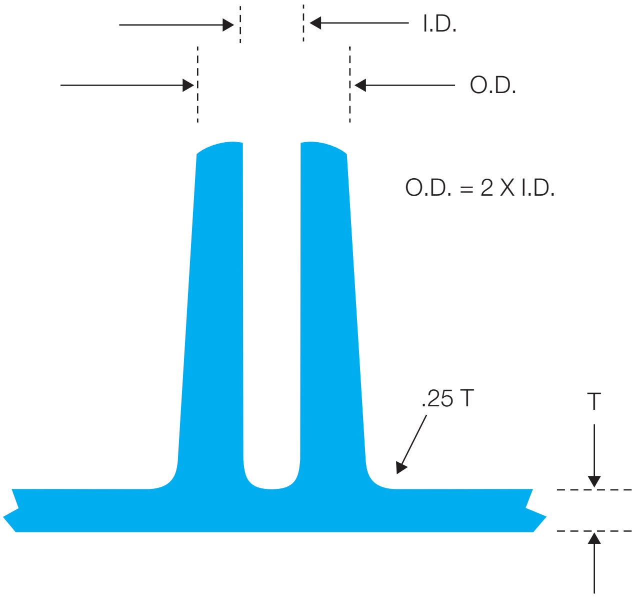
Cores that extend into the cavity are subject to high pressure. For blind cores with diameters greater than 1.5 mm (0.03125 inch), the core lengths should not exceed three times the diameter; blind cores with diameters less than 1.5 mm (0.03125 inch) the core length should not exceed twice the diameter. These recommendations may be doubled for through cores. Draft should be added to all cores and all tooling polished for best ejection.

Bosses

Bosses are protrusions off the nominal wall of a part that are used as mounting or fastening points. The design of bosses is largely dependent upon their role in a given part. Cored bosses can be used with press fits, self-tapping screws, or ultrasonic inserts. These fasteners exert a variable amount of hoop stress on the wall of the boss.

As a general guideline, the outside diameter of a each boss should be twice the inside diameter of the hole, and the wall thickness of each boss should not exceed that of the part. Figure 60 illustrates these guidelines.

Figure 60: Boss design general guidelines



Additional forces imposed on a boss may be transmitted down the boss and into the nominal wall. For this reason, a minimum radius of 25 % of the wall thickness is required at the base of the boss to provide strength and reduce stress concentration. A boss can be further strengthened by using gusset-plate supports around the boss, or attaching it to a nearby wall with a properly designed rib. Heavy sections should be avoided to prevent sink marks on the surface of the part.

Snap-Fits

The ductility of Udel® PSU engineering resins combined with their strength make them well suited for snap-fit assembly. In all snap-fit designs, some portion of the molded part must flex like a spring, usually past a designed interference, and return to its unflexed position to create an assembly between two or more parts. The key to snap-fit design is having sufficient holding power without exceeding the elastic or fatigue limits of the material.

The two most common types of cantilever beam snap-fits are straight beam and tapered beam. Figure 61 and Figure 62 show these typical snap-fit designs and the corresponding equations for calculating the maximum strain during assembly. The proportionality constants for a tapered beam design are shown in Figure 63. The design should not have a maximum strain greater than the permissible strain shown in Table 40.

Table 40: Maximum permissible strains for snap-fit designs

Grade	Maximum Permissible Strain [%]
P-1700	5.5
GF-110	3.0
GF-120	1.5
GF-130	1.0

Figure 61: Snap-fit design using straight beam

Maximum strain $\varepsilon = \frac{3Yh_0}{2L^2}$

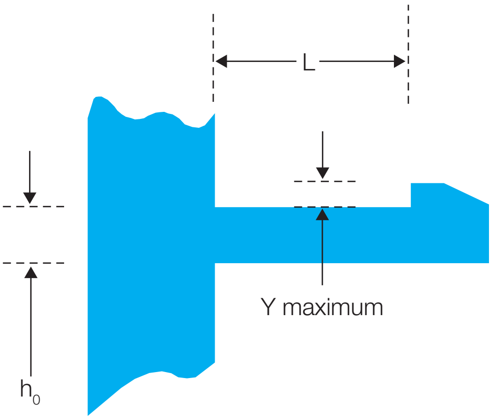


Figure 62: Snap-fit design using tapered beam

$$\text{Maximum strain } \varepsilon = \frac{3Yh_0}{2L^2K}$$

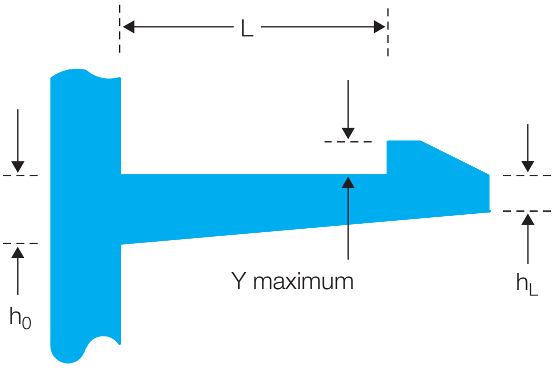
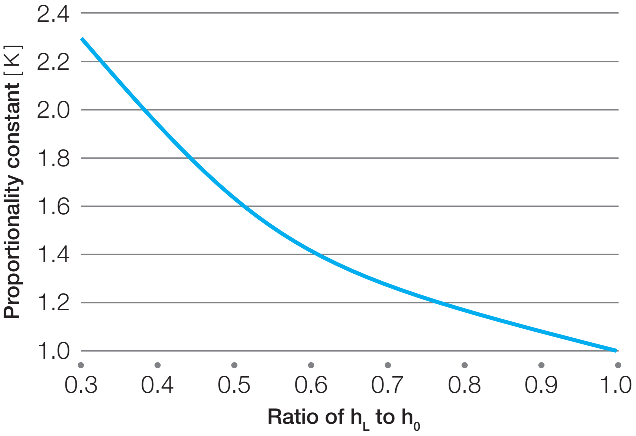


Figure 63: Proportionality constant (K) for tapered beam



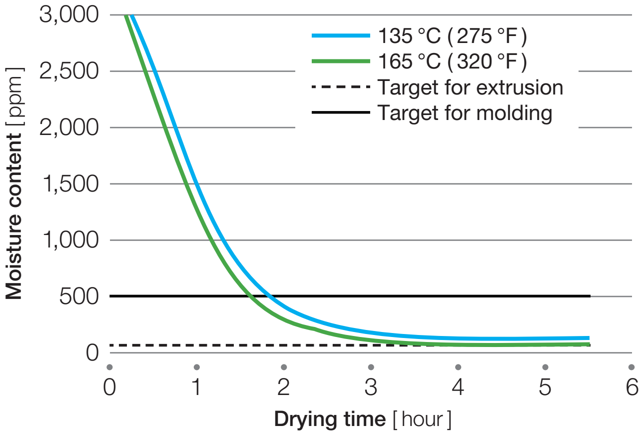
Fabrication

Drying

Polysulfone must be dried before it is molded or extruded. The material absorbs up to about 0.3 % atmospheric moisture in storage. The moisture content must be reduced to about 0.05 % by drying. Otherwise, surface streaks, or splay marks, appear on injection molded parts and extruded forms exhibit severe bubbling. Moisture, however, does not hydrolyze polysulfone or in any way react with it to cause discoloration, chemical degradation or deterioration of its properties. Parts formed from undried resin are only unsatisfactory in appearance, or in some cases weak due to formation of internal bubbles. Any parts unsatisfactory due to moisture can be reground, dried, and then reformed without loss of original properties.

Polysulfone pellets can be dried in a circulating hot air oven or in a dehumidifying hopper dryer. Oven drying can be accomplished by spreading the pellets onto trays to a depth of 25 to 51 mm (1 to 2 inch) and drying for 3½ hours after the pellets have reached 135 °C (275 °F) or 2 hours at 163 °C (325 °F). Drying curves for Udel® PSU are shown in Figure 64.

Figure 64: Drying Udel® PSU



These represent minimum recommendations since polysulfone cannot be “over-dried.” In fact, it can be held at 135 °C (275 °F) for up to a week without harm. If the natural material is dried at temperatures exceeding 166 °C (330 °F), the pellets may sinter after 3 to 4 hours in the oven.

Drying time may have to be increased in highly humid weather. An air-tight oven equipped with a dehumidifying unit in which the air is recirculated over a drying bed is recommended as the most uniform and efficient drying method. The dried resin should be handled to preclude re-absorption of moisture from the atmosphere.

Polysulfone does not require pre-drying if processed in a vented extruder designed for volatile removal. In all other continuous molding and extrusion operations, it is recommended that a dehumidifying hopper dryer be attached directly to the processing equipment. These efficient dryers permit continuous processing operations and the size chosen will depend on the rate of material consumption.

Polysulfone requires a residence time of 3.5 hours through the hopper dryer operating at inlet air temperature of 135 °C (275 °F). The hopper should be insulated so that at equilibrium conditions the temperature drop is no more than 14 to 19 °C (25 to 35 °F). The inlet hot air returning to the hopper dryer after passing over the desiccant bed should be at a maximum dew point of –32 °C (–25 °F).

Rheology

The rheology data for Udel® P-1700 and Udel® P-3500 LCD resins are shown in Figures 65 and 66.

Figure 65: Rheology of Udel® P-1700 resin

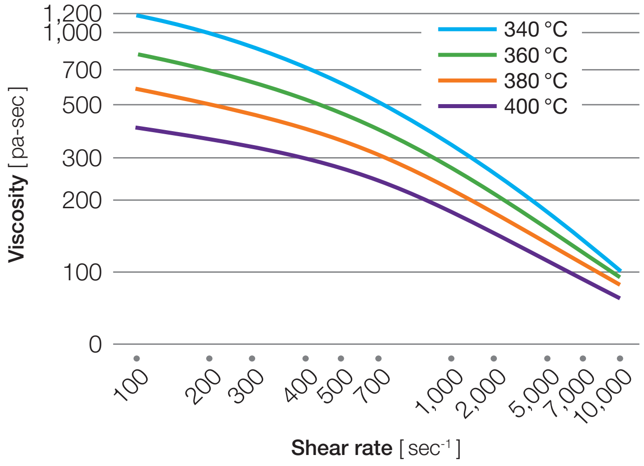
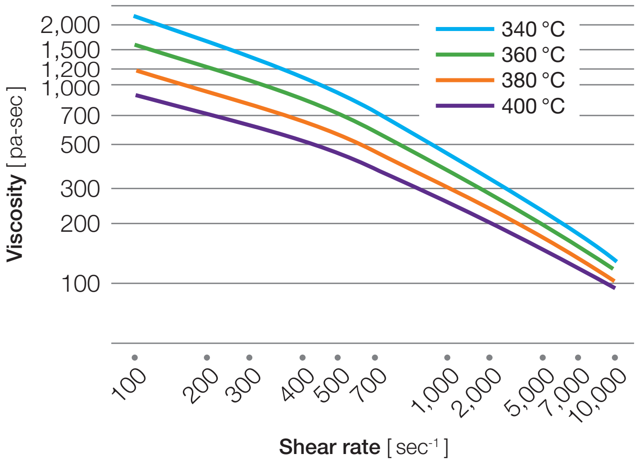


Figure 66: Rheology of Udel® P-3500 LCD resin



Water Heater Dip Tubes

Water heater dip tubes are used to move the incoming cold water in a storage type water heater from inlet at the top of the heater to the bottom to prevent mixing with the hot water. In addition many dip tubes are designed to create movement around the heating elements to prevent collection of scale in the bottom of the tank. Thin wall [0.5 mm (0.020 inch)] tubes of Udel® PSU have been used in this application since the early 1970’s. The material’s long-term hydrolytic stability and resistance to oxidative attack by chlorinated water reduces the threat of product failure, which has been known to happen with lower cost, lower performing materials (PP, PEX).

Injection Molding

Injection Molding Equipment

Udel® PSU can be readily injection molded with most screw injection machines.

Screw Design

The typical general-purpose screw will perform satisfactorily with Udel® PSU resins. A typical screw design for processing these resins is shown in Figure 67.

Screw tips and check valves

The design of the screw tip and the check valve are important for proper processing. The check or non-return valve keeps the melt from flowing backwards over the screw flights during injection and holding. If no check valve is used, it will be difficult or impossible to maintain a consistent cushion.

The check valve or check ring system must be designed for smooth flow, avoiding dead spots or back pressure. Ball check valves are not recommended. The screw tip should also be streamlined to ensure that the quantity of melt stagnant in front of the screw is minimized.

Nozzles

General purpose nozzle tips are recommended. Open nozzles are preferred to nozzles equipped with shut-off devices. The configuration of the bore of the nozzle should closely correspond to the screw tip.

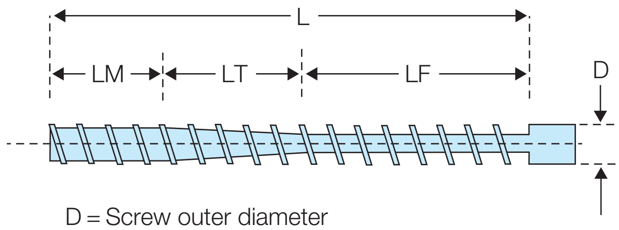
Molds

Standard guidelines for mold design are appropriate for the Udel® PSU resins.

Draft and ejection

In general, the draft in injection molds designed for Udel® PSU resins should be 0.5° to 1°. The contact area of ejector pins or stripper plates should be as large as possible to prevent part deformation or penetration during ejection.

Figure 67: Screw design for injection molding



D = Screw outer diameter	
L = Overall screw length	18 - 22 D
LF = Length of feed section	0.5 L
LT = Length of transition section	0.3 L
LM = Length of metering section	0.2 L
CR = Compression ratio	1.8 - 2.4 : 1

Gates

All conventional gating types, including hot runners, can be used with Udel® PSU resins. Problems may arise with some hot runner designs, which either encourage long residence times or have dead spots where material can accumulate and degrade. Gates must be of adequate size to allow part filling without the use of extremely high injection melt temperatures or pressures. Voids or sink marks may be caused by gates that freeze off before packing is complete.

Venting

Molds for Udel® PSU resins must be vented at the ends of runners and at the position of expected weld lines. The vents should have land lengths of 2 to 3 mm (0.080 to 0.120 inch), with depths up to 0.08 mm (0.003 inch).

Mold temperature control

Controlling the mold temperature is critical to achieving high quality parts. On some especially challenging parts, separate controllers may be required for the mold halves. The temperatures required for molding Udel® PSU resins can be achieved by using a fluid heat transfer system with oil as the fluid, or by using electric heaters.

Table 41: Starting point molding conditions

Grade	Melt Temperature [°C (°F)]	Mold Temperature [°C (°F)]	Shrinkage [%]
P-1700	350–390 (660–730)	138–160 (280–320)	0.6–0.7
P-1720	350–390 (660–730)	138–160 (280–320)	0.6–0.7
GF-110	360–390 (680–730)	138–160 (280–320)	0.5
GF-120	360–390 (680–730)	138–160 (280–320)	0.4
GF-130	360–390 (680–730)	138–160 (280–320)	0.3

Fluid heat transfer systems are always preferable to electric heaters. Although electric heaters can aid in achieving minimum mold temperatures, they don't remove heat from the mold. Mold temperatures may rise above the desired temperature, especially when molding large parts.

Machine Settings

Injection molding temperatures

The injection molding melt temperatures recommended for various Udel® PSU resins are listed in Table 41. In general, higher temperatures should not be used because of the risk of thermal degradation. As a fundamental rule, injection molding melt temperatures higher than 393 °C (740 °F) should be avoided.

Mold temperatures

Mold temperature is an important factor in determining shrinkage, warpage, adherence to tolerances, quality of the molded part finish, and level of molded-in stresses in the part.

The mold temperature for Udel® PSU resin is usually set in the range of 120 to 160 °C (250 to 320 °F). The only products that require higher temperatures to achieve an optimum finish are the glass-reinforced Udel® PSU grades. Table 41 lists the recommended mold temperatures for individual Udel® PSU grades.

Heat losses can be reduced by inserting insulation between the mold and the platen. High-quality molded parts require a well-designed system of cooling channels and correct mold temperature settings.

Barrel temperatures

Udel® PSU pellets can be melted under mild conditions and relatively long residence times in the barrel can be tolerated, if the temperature settings on the band heaters increase in the direction from the hopper to the nozzle. If residence times are short, the same temperature can be set on all the barrel heaters. At least one band heater (rated at 200 to 300 W) is required for the nozzle, where heat losses to the mold may be severe as a result of radiation and conductivity. These heat losses can be reduced by insulating the nozzle.

The band heater control system should be monitored. For instance, a timely alarm may prevent screw breakage if a heater fails in one of the barrel sections.

The pellet feeding can often be improved by maintaining the temperature in the vicinity of the hopper at about 80 °C (175 °F).

Residence time in the barrel

The length of time the plastic remains in the plasticizing cylinder has a significant effect on the quality of the injection molding. If it is too short, the pellets will not be sufficiently melted. If it is too long, thermal degradation is likely and is indicated by discoloration, dark streaks, and even burned particles in the molded parts. Frequently, the residence time can be reduced by fitting a smaller plasticizing unit. Acceptable residence times will be obtained if the shot size is 30 to 70 % of the barrel capacity. At the melt temperatures listed in Table 41, all the Udel® PSU resins can withstand a residence time up to 20 minutes, but 10 minutes or shorter is preferred.

Molding Process

Feed characteristics

Udel® PSU pellets can be conveyed smoothly along the barrel and homogeneously plasticized at the recommended temperatures by screws of the design shown in Figure 67 on page 61.

The temperature in the feed section should not be set too high, because the pellets may melt prematurely resulting in the screw flights becoming choked and bridged over.

Back pressure

Back pressure is usually employed to maintain a constant plasticizing time, to avoid air entrainment, and/or to improve homogenization of the melt. It is not absolutely necessary for Udel® PSU resins. Back pressure that is too high can result in high frictional heating.

Screw speed

Whenever possible, the screw speed should be set so that the time available for plasticizing during the cycle is fully utilized. In other words, the longer the cycle time, the slower the screw speed. For instance, a screw speed of 60 rpm to 100 rpm often suffices for a 50 mm (2 inch) diameter screw. This is particularly important when running high melt temperatures to ensure that the melt does not remain stationary for an undesirably long time in the space in front of the screw tip. Low screw speeds also diminish the temperature increase due to friction.

Injection rate and venting

The injection rate used for filling the mold is another important factor in determining the quality of the molded part. Moderate injection speed should be used. It should be rapid enough to achieve melt homogeneity, but slow enough to avoid shear burning. Rapid injection provides uniform solidification and good surface finish, especially with the glass-reinforced grades.

The mold must be designed to allow air to readily escape cavities during the injection phase. If this is not done, rapid compression of the air in the cavity creates high temperatures causing localized overheating and burn marks. In order to eliminate voids, the screw forward time and the holding pressure must be high enough to compensate for the contraction in volume that occurs during cooling.

Gates must be large enough so the polymer does not solidify in their vicinity before the holding time has elapsed. Any plugs formed in or near the gate prevent packing the interior of the mold.

Demolding

Udel® PSU parts can be readily demolded and do not stick to the walls of the mold, even when they are hot. As a rule, the draft on injection molds for Udel® PSU resins should be 0.5° to 1°. A somewhat larger draft is required for the glass-reinforced products, because of their lower shrinkage. The area of ejectors or stripper plates should be as large as possible. Ejector pins must not be too thin, or they may press into the parts and deform them during rapid cycling or at high mold temperatures.

Mold releases

Some mold release compounds contain carriers that can cause stress cracking of Udel® PSU parts. Mold releases recommended for use with polycarbonate are generally compatible with Udel® PSU resin. However, even these compounds should be tested for compatibility prior to use.

When using mold release compounds for parts that require an Underwriters Laboratory (UL) listing care must be taken to select products that UL has recognized as being compatible with the listings provided for the products being used. Manufacturers should contact Underwriters Laboratories for additional information.

Shrinkage

Shrinkage is defined as the difference between the dimensions of the mold and those of the molded part at room temperature. It is primarily a property of the thermoplastic resin and results from the contraction in volume that occurs when the molding compound cools within the mold. Other factors that effect the magnitude of the shrinkage are the geometry of the part, the wall thickness, the size and location of the gates, and the processing parameters. The interaction of all these factors makes it difficult to predict shrinkage exactly, but close estimates of shrinkage are possible. Typical values appear in Table 41 on page 61.

Troubleshooting guide for Udel® PSU

			Process Parameters												
Problem	**Ensure Resin Dryness**	**Use Mold Release Grade**	**Back Pressure**	**Cooling Time**	**Hold Pressure and Time**	**Injection Speed**	**Injection Time**	**Injection Pressure**	**Melt Decompression**	**Melt Temperature**	**Mold Temperature**	**Nozzle Temperature**	**Screw Speed**	**Shot Size**	**Sprue Break**
Mold flash						3 –		2 –		4 –				5 –	
Slow injection						2 +		1 +		3 +	4 +				
Erratic injection			1 +							2 +					
Nozzle plugs										3 +	4 +	1 +			5
Sprue sticks				6 +	4 –	3 –	7 –	5 –		9 –	8 –	2 +			
Screw squeals			1 –							2 +			3 –		
Slow screw recovery			2 –							3 +			1 +		
Nozzle drool									3 +	2 –		1 –			
Splay	1		3 –			2 –				5 –		4 –			
Short shots			8 +		4 +	2 +	9 +	3 +		6 +	5 +	7 +		1 +	
Jetting						1 –		4 –		2 +	3 +				
Sinks and voids					4 +	7 +	2 +	3 +		5 –	6 ±			1 +	
Parts stick		8		3 +		2 –	4 –	1 –		6 –	5 –				
Rippled surface		9				1 +		4 +		3 +	2 +				
Dark streaks			3 –				4 –			2 –		1 –	5 –		
High shrinkage					3 +			2 +		4 –	5 –			1 +	
Weld lines						4 +		3 +		1 +	2 +				
Warpage				2 +	1 +			5 +		4 –	3 –				
Low gloss						3 +		4 +		2 +	1 +				
High mold stress		7				3 –		5 –		2 +	1 +				
Gate blush						1 –		4 –		3 +	2 +	5 +			

Apply the remedies in numerical order: + Increase, – Decrease, ± Increase or Decrease

Troubleshooting guide for Udel® PSU

			Tooling and Equipment										
Problem	**Ensure Resin Dryness**	**Use Mold Release Grade**	**Increase Cavity Venting**	**Increase Clamp Pressure**	**Increase Draft**	**Increase Gate Size**	**Increase Runner Size**	**Part Wall Thickness**	**Change Gate Location**	**Clean And Polish Mold**	**Insulate Nozzle**	**Nozzle Orifice**	**Polish Sprue Bushing**
Mold flash				1									
Slow injection						6	7					5 +	
Erratic injection													
Nozzle plugs											2	6 +	
Sprue sticks													1
Screw squeals													
Slow screw recovery													
Nozzle drool												4 –	
Splay	1												
Short shots			11			12	13	14 +				10 +	
Jetting						6			5				
Sinks and voids			10			8	9	12 –				11 +	
Parts stick		8			9					7			
Rippled surface		9	7			5		8 +				6 +	
Dark streaks			7			8						6 –	
High shrinkage						6							
Weld lines			5			6							
Warpage						6							
Low gloss			6							5			
High mold stress		7				4						6 +	
Gate blush						6							

Apply the remedies in numerical order: + Increase, – Decrease, ± Increase or Decrease

Regrind

Sprues, runners, and discrepant parts can be reused by grinding them and mixing them with pellets. The ground material, often referred to as regrind, must be dry. It can be dried using the same procedure used for pellets. Polysulfone has excellent thermal stability and regrind can be used multiple times without degradation. A typical regrind utilization scheme is to mix 25 % regrind with 75 % pellets.

To demonstrate the stability of the material, test bars were molded using 100 % regrind. Those bars were then ground and remolded again. This process was repeated until the material had been molded four times. At this point the bars were tested for tensile strength, impact resistance, and deflection temperature. The results, shown in Table 42, indicate that no degradation of properties has occurred.

Table 42: Properties of Udel® P-1700 after 4 moldings

Property	1 Molding	4 Moldings
Tensile Strength [MPa (kpsi)]	68.9 (10.0)	71 (10.3)
Izod Impact [J/m (ft·lb/inch)]	69 (1.3)	69 (1.3)
Deflection Temp [°C (°F)]	175 (347)	173 (343)

Measuring Residual Stress

When working with fabricated polysulfone parts, it is important to minimize residual or molded-in stress. A procedure has been developed for estimating the magnitude of the residual stress. The procedure entails exposing the parts to a series of ethanol/ethyl acetate mixtures. The stress level required for crazing to occur for each mixture was determined using specimens at known stress levels. The mixtures and the stress levels at which they cause crazing are shown in Table 43.

To determine the residual stress, immerse the part for one minute in the first mixture – 75 % by volume ethanol and 25 % by volume ethyl acetate. Then remove the part from the reagent and it allow to dry. Drying can be accelerated by blowing low-pressure compressed air on the surface. Then inspect the part for crazes. If the part is crazed, the residual stress is greater than 19 MPa (2,800 psi). If the part is not crazed, the residual stress is less than 19 MPa (2,800 psi). The test is continued with the next mixture.

Immerse the part in the second mixture, remove after one minute, allow to dry, and inspect for crazing. If crazing occurs, the residual stress is between 15 and 19 MPa (2,200 and 2,800 psi). If crazing does not occur, the residual stress is less than 15 MPa (2,200 psi). The test is continued with the next mixture.

Continue in a like manner until crazing occurs, or the part endures the one-minute immersion in ethyl acetate without crazing.

To maintain accurate stress readings, the reagents must be fresh. Over time, the reagents may absorb water, evaporate, or become contaminated, which can lead to erroneous stress indications. Although reagents can be calibrated by using samples with known stress levels, It may be more practical to replace your reagents with fresh solvent from the sealed container periodically. If you want to calibrate your reagents, contact your Solvay representative for assistance.

Table 43: Reagents for residual stress test

	Mixture Composition		
Mixture	Ethanol [% by volume]	Ethyl Acetate [% by volume]	Critical Stress [MPa (psi)]
1	75	25	19 (2,800)
2	50	50	15 (2,200)
3	43	57	12 (1,700)
4	37	63	9 (1,300)
5	25	75	6 (800)
6	0	100	3 (400)

Extrusion Blow Molding

The extrusion blow molding process consists of the following steps:

- Extruding a tube called a 'parison'
- Enclosing the molten parison in a mold
- Introducing air pressure to expand the parison to fill the mold
- Cooling and ejecting the part

Both Udel® P-1700 and P-3500 LCD resins are suitable for blow molding. However, P-3500 LCD is often preferred because of its higher melt strength.

Drying

Polysulfone resin must be thoroughly dried before molding. Please refer to page 59 for drying recommendations. Drying is more critical for blow molding than it is for injection molding since hot extruded parisons are at atmospheric pressure which allows any water present to easily come to the surface.

Equipment

Commercial blow-molding equipment, including both constant and intermittent extrusion types, are suitable for polysulfone provided they are capable of the 315 to 343 °C (600 to 650 °F) melt temperatures.

Screw configuration in extrusion blow molding equipment is important in blow molding polysulfone. Optimum balance in melt temperature uniformity, temperature control, and power requirements is achieved with screws having a low (2.0 to 2.5:1) compression ratio. High-compression-ratio screws, such as those normally used with polyolefins, should be avoided. They require high drive torques and generate excessive frictional heat with polysulfone.

The temperature uniformity of polysulfone melt obtained in extrusion is much better than that of the polyolefins. Consequently, screen packs and other pressure restrictions are not normally needed.

As in injection molding, mold temperature should be controlled with oil to achieve low molded in stress. Since most parts will have some relatively thin wall area, mold temperature should be in the range of 120 to 149 °C (250 to 300 °F).

Process Conditions

Resin temperatures for blow molding are much lower than for injection molding: 315 to 329 °C (600 to 625 °F) for Udel® P-1700 and 329 to 343 °C (625 to 650 °F) for P-3500 LCD.

However, other blow molding conditions are similar to those used for other materials. Blow air pressures ranging from 0.28 to 0.48 MPa (40 to 70 psi) have been satisfactory in molding bottles. Molding cycles are comparable to those used for polycarbonate. Because of the amorphous, fast-setting nature of polysulfone, cycles should be shorter than those obtained with polyolefins.

Blow molding of polysulfone is facilitated by giving proper attention to head and die design and temperature control. Streamlined heads and dies minimize hang up and improve the control of melt uniformity. Since the polysulfone melt is extremely temperature sensitive, uniform surface temperatures in the die and head should be carefully maintained. Such precautions produce beneficial results in controlling the parison.

Blow molded articles with a glossy, lustrous surface can be produced from polysulfone. The use of polished flow surfaces in heads, pins, and dies help to achieve in the finished part the high gloss inherent in the material. Polished mold surfaces are also recommended for optimum part surface appearance. Polysulfone is not corrosive and chrome plating of flow surfaces is not essential. However, chrome plating may help in the maintenance of the high polish on pins and dies.

The melt viscosity of polysulfone is not shear sensitive, and this results in less parison swelling on emergence from the die than is obtained with most other blow molding materials. As a consequence, the wall thickness of the parison is normally close to the dimensions of the clearance between the pin and die.

Material temperature and extrusion rate from the die are important in controlling parison drawdown of polysulfone. As is the case with most materials, drawdown can become excessive if the parison extrusion rate is too slow or if material temperature is too high. Generally, the best results are obtained with fast parison extrusion at the minimum temperature which gives a smooth parison surface. Parison programming is recommended for optimum wall uniformity.

Extrusion

Udel® PSU can be readily extruded using conventional extrusion equipment to form a number of products, such as sheet, film, profile, rod, slab, and tubing.

Predrying

Udel® PSU resins must be thoroughly dried prior to extrusion to prevent bubbles in the extrudate. The recommendations for drying material that appear on page 59 apply except that drying should be continued until the moisture content is below 100 ppm. Hopper drying requires sufficient insulation and minimal system leakage. Inlet air temperature must be high enough and inlet air moisture content low enough for polymer pellets to be maintained above 149 °C (300 °F) in air with a –40 °C (–40 °F) dew point. This condition must be sustained long enough for the polymer moisture content to drop to below 100 ppm.

Extrusion Temperatures

Depending on the specific extrusion operation, the melt temperature of the extruded stock should be in the range of 315 to 371 °C (600 to 700 °F). Polysulfone is not shear sensitive, which means that the melt viscosity of the material will vary directly with temperature.

Barrel temperature settings of 302 °C (575 °F) at the feed end of the extruder increasing to 315 to 337 °C (600 to 640 °F) at the head are recommended for most operations. These barrel temperature settings should yield the required extruded stock temperature if maintained uniformly in the range of 315 to 371 °C (600 to 700 °F). If a screw with a relatively shallow metering section is used, higher barrel temperature settings of 315 to 357 °C (600 to 675 °F) may be necessary to better control the operation within the pressure and power limitations of the equipment.

Screw Design Recommendations

In general, screws with length-to-diameter ratios of 20:1 to 24:1 are recommended. Compression ratios from 2:1 to 2.5:1 have been shown to give acceptable results. Screw pitch should equal screw diameter, and the transition from feed to metering should be gradual. The transition and metering sections should be longer than the feed section. The transition section should be the longest to provide sufficient time and heat input to adequately soften the resin before trying to pump it. A starting point configuration is 4 flights feed, 14 flights transition, and 6 flights of metering.

Two-stage screws can also be used to allow vacuum venting where optimal compaction of the melt is desired. A two-stage screw design includes a decompression section to allow vacuum venting after the first metering section. The decompression section is followed by another transition zone and another metering zone, following the design principles described for the single-stage screw.

Die Design

The die heaters must be capable of reaching and maintaining temperatures of 315 to 371 °C (600 to 700 °F). Since the viscosity of polysulfone is temperature sensitive, die temperature must be closely controlled to provide a uniform extrudate.

Dies designed for polycarbonate can be used. Dies should always be streamlined. Streamlining the flow channel and incorporating purge plates (i.e. bleeder plugs) in the ends of sheeting dies eliminate the tendency for material to hang up in the die, leading to stagnation and degradation.

Dies should be capable of operating continuously at pressures up to 21 MPa (3,000 psi).

Flow channels, die lips, and lands should be highly polished and chrome-plated for optimum extrudate appearance.

Little die swelling occurs during polysulfone extrusion because the melt viscosity is largely insensitive to shear rate. Furthermore, the rapid stress relaxation time of the resin results in little orientation in extruded products.

Extruded Product Types

Wire

Udel® PSU can be extruded onto wire using a semi-tubing or tubing crosshead die. For good adhesion, wire inlet temperatures should approximate that of the polymer melt. High drawdown of the polymer melt tube can be achieved with Udel® PSU resin. Vacuum on the crosshead is highly recommended to improve adhesion of the polymer tube to the wire. Coated wire should not be quenched but rather cooled slowly using a mister or water bath.

Film

Udel® PSU has excellent drawdown properties for the production of thin film, because of its high melt strength. Slot-cast film possesses excellent optical properties, high modulus, good impact strength, and good electrical properties over a wide temperature range. The film is heat sealable and can be printed without treatment. Udel® grade P-1700 is recommended for general film extrusion.

Typical film extrusion equipment configuration and conditions for a 63 mm (2.5 inch) extruder are:

Die

Standard film dies of coat hanger design and straight manifold-choker bar design are satisfactory. Die lip openings of 1 to 1.5 mm (25 to 40 mils) should be used for 0.025 to 0.25 mm (1 to 10 mil) film. Dies must be capable of continuous operation at 24.1 MPa (3,500 psi).

Breaker plates

Breaker plates are responsible for so-called "die lines", and they should be replaced with a sleeve, that allows the die adapter to seal against the extruder.

Casting roll

An 21.6 cm (8.5 inch) diameter roll at 168 °C (335 °F) is required to prevent wrinkling of the film.

Extruder temperatures

Barrel temperatures from rear to front should be 302 to 329 °C (575 to 625 °F). The die temperature should be 329 to 343 °C (625 to 650 °F).

Output rate

These conditions should give an output rate of 1.36 kg/hr/rpm (3 lb/hr/rpm).

Sheet

Standard round and teardrop manifold sheet dies with choker bars are satisfactory. Sheet thicknesses of 0.5 to 3.2 mm (0.020 to 0.125 inch) can be produced using a die lip opening of 3.2 mm (0.125 inch).

In sheet extrusion, the take-off roll temperature must be maintained high enough to prevent curl and to minimize strains in the sheet. For thicknesses up to 0.8 mm (0.030 inch), an 'S' wrap technique is satisfactory, providing that roll temperatures of 166 to 193 °C (330 to 380 °F) can be obtained. For thicknesses greater than 0.8 mm (0.030 inch), a straight through calendering technique is recommended. This requires maintaining a small bank in the nip of the two rolls across the width of the sheet and a roll temperature of 166 to 177 °C (330 to 350 °F).

A power shear can be used for cutting the sheet to length for sheet thicknesses up to 3.2 mm (0.125 inch). For thicker sheet, sawing is recommended.

Pipe and tubing

Polysulfone pipe and tubing can be extruded using standard pin and spider assemblies. Control of stock temperature is critical in achieving desired melt elasticity. For Udel® P-1700, a stock temperature of 304 to 321 °C (580 to 610 °F) is suggested. For Udel® P-3500 LCD, the melt temperature should be 17 °C (30 °F) higher.

Sizing plate and vacuum tank methods of dimensional control are satisfactory. An extended internal mandrel is not recommended. For best melt control, the extrusion die should be 70 to 100 % larger than the sizing die.

For high-quality extrusion, stress due to processing must be minimized. This is accomplished by minimizing the level of cooling in the vacuum-sizing bath while maintaining dimensional requirements. A water bath only ¼th to ⅕th as long as the water bath needed for polyethylene is usually sufficient.

Start-Up, Shut-Down, and Purging

Start-up procedure

With a non-vented extruder, warm pre-dried resin is charged into the hopper with water cooling on the throat. The screw speed should be 15 to 20 rpm until the feed section of the screw is filled at which point, the speed is decreased to 5 to 10 rpm. This prevents premature pellet fluxing and fouling of the rear of the screw. After material exits from the die, water cooling of the throat is discontinued and screw speed adjusted to the required rate.

Shut-down procedure

If a shut-down is required during a polysulfone extrusion run, certain precautions should be taken. If the shut-down is of a short duration, a few hours at most, simply letting the extruder run dry and restarting using starve feed will be adequate. For shut-downs longer than a few hours, the extruder should be run dry and the extruder and die cooled as rapidly as possible to room temperature. On start-up, the die heaters should be turned on one or two hours before the extruder heaters. Once the extruder reaches 288 to 349 °C (550 to 660 °F), the screw can be turned over periodically until extrusion temperatures are reached. Start-Up is then accomplished using starve feed at low screw speed until resin emerges from the die.

It is not a good practice to allow thermoplastic resin to sit stagnant in an extruder for prolonged periods of time at extrusion temperatures. Some decomposition is likely to occur and it may prove difficult to again start and properly purge the machine.

Purging

Polysulfone can be easily purged with a low melt index, high-density polyethylene or a low melt index polypropylene. In purging, the die, adapter, and breaker plate should be removed after the machine has been run dry of polysulfone. Cool this equipment to about 288 °C (550 °F) and remove the residual resin by blasting with an air hose.

The temperature of the barrel should be increased to 343 °C (650 °F) and the purge material run through until no more polysulfone is visible in the purge. Then reduce the temperature to 149 °C (300 °F). The screw can then be removed and the barrel and screw brushed clean. If polysulfone resin continues to adhere to any tooling, it can be removed by soaking the tooling overnight in a chlorinated solvent, then brushing clean.

Thermoforming

Udel® PSU sheet must be dry before it can be thermoformed. If it isn't dry, it foams when subjected to the heat of the thermoforming operation. Sheet direct from the extrusion line is dry, and is satisfactory for thermoforming. Therefore, an integrated, in-line extrusion-thermoforming operation is indicated. However, a tightly wound roll of sheet will remain suitable for thermoforming for 8 hours to 16 hours, depending on humidity conditions and on how long the sheet remained hot at the wind-up station. Sheet having a thickness of 0.23 mm (9 mils) or less will not bubble and does not require drying prior to thermoforming.

Rolls of thin Udel® PSU sheet can be dried in roll form. For example, about 20 hours at 135 °C (275 °F) is required to dry 0.5 mm (20 mils) sheet with about a 15.2 cm (6 inch) thickness on a core. The time required for drying any roll will depend on the actual thickness of the winding, as the entire roll of sheet must reach a temperature of at least 121 °C (250 °F).

Drying of individual sheets of Udel® PSU 15 mils (0.4 mm) to 20 mils (0.5 mm) thick can be accomplished by oven drying at 135 °C (275 °F) for 2 hours. For sheet 30 mils (0.75 mm) thick, the time should be extended to 3 hours.

The actual sheet temperature at the surface must be 232 to 260 °C (450 to 500 °F) for thermoforming. Heaters should have a minimum density of 21 kW/m^2 (2 kW/ft^2) of heating surface. A heater density of 43 to 54 kW/m^2 (4 to 5 kW/ft^2) is preferable. Heaters with a density of about 43 kW/m^2 (4 kW/ft^2) and set at 426 °C (800 °F) within about 7.6 cm (3 inch) of both sides of 20 mil Udel® PSU sheet will heat the sheet in about 15 seconds. Single side heating can be used for sheet up to about 2.3 mm (90 mils) thick.

During heating, the sheet will appear to draw tight, and then start to buckle between the clamps as the strains are relieved. The sheet will then draw almost uniformly tight, and then start to sag. At this point, it is ready for molding. Heated Udel® PSU sheet will sag relatively quickly, particularly in the heavier gauges when the weight is higher. It must be indexed rapidly over the mold, and sufficient clearance over the lower heaters must be provided.

Most of the conventional thermoforming methods such as vacuum forming, pressure forming, plug assist, and snap to back have been used successfully with Udel® PSU sheet. Parts with an area ratio as high as 9:1 have been formed commercially.

Thermoformed prototypes can be produced with many types of molds such as wood, metal-filled epoxy, or cast aluminum. Hard wood molds only last for about 10 to 30 parts because of the high temperature conditions. Cast epoxy molds may last for 100 to 300 parts. Cast aluminum molds are capable of producing several thousand parts.

Production molds should be metal, and cored for heating with a fluid transfer medium at 149 °C (300 °F). Aluminum or steel molds are satisfactory, and reproduction of the mold surface is excellent. Mold shrinkage of Udel® PSU is a uniform 0.7 %. Ideally, the mold should operate at 149 to 166 °C (300 to 330 °F) to obtain minimum residual stress, and thus, maximum environmental stress cracking resistance in the part. Udel® PSU sets rapidly. Parts can be demolded at 149 to 177 °C (300 to 350 °F).

The design of thermoforming molds for Udel® PSU should follow these conventional standards for rigid, amorphous materials:

- Round all corners as generously as part design permits
- Allow at least 3° draft on shallow parts, and at least 6° draft on deeply drawn parts
- Avoid undercuts
- Drill vacuum holes with a maximum diameter of 0.397 mm ($^1/_{64}$ inch)

Compression Molding

To compress mold a 25 mm (1 inch) thick slab of polysulfone 216 mm (8.5 inch) long and 216 mm (8.5 inch) wide for machining into prototype parts or shapes, the following procedure is suggested.

1. Load the mold cavity with 1,520 grams of Udel® P-1700 pellets.
2. Heat both press platens to 293 °C (560 °F).
3. Place a 13 mm (0.5 inch) thick insulating board on top of the mold. Place the mold in the press and close the press.(1)
4. Apply 18,144 kg (20 tons) pressure and hold for 1 hour.
5. Open press and remove the insulating board and reapply pressure for another 10 minutes.(2)
6. Cool the platens to 121 °C (250 °F), then release the pressure and remove the mold from the press and separate.

To make a slab the same size except 13 mm (0.5 inch) thick, use the above procedure with these modifications. In step 1, use 760 grams of Udel® P-1700 resin In step 4, reduce the time to 30 minutes.

Secondary Operations

Cleaning and Degreasing

Vertrol® XF from E.I. DuPont is recommended for vapor degreasing and cleaning polysulfone parts.

Annealing

Like other high performance amorphous thermoplastics, polysulfone crazes or cracks when exposed to certain aggressive environments while under stress. For example, solvents such as acetone and toluene will cause crazing or cracking in polysulfone containing high residual stresses. Laboratory tests and field experience show that such solvents can be tolerated in cleaning operations if the polysulfone parts are stress relieved prior to exposure by annealing. However, annealing is an added expense and will result in a loss of tensile elongation and impact properties.

Processing for Low Residual Stress

Before considering annealing, make every effort to mold or extrude at conditions to produce lowest stress. Parts should be taken from the processing operation at the highest possible temperature consistent with good final part formation, because cooling slowly results in lower residual stress.

To achieve low stress in injection molding, follow the recommended molding conditions and use a mold temperature of 138 to 149 °C (280 to 300 °F). Similarly, for pipe, tube, and profile extrusion, minimum downstream cooling should be used.

Annealing in Air

Where annealing must be used, treating the parts in a circulating air oven at 166 °C (330 °F) for 30 minutes is recommended. This annealing treatment removes most of the residual fabrication stresses without significantly affecting resin toughness performance attributes such as tensile elongation. More vigorous annealing at a temperature of 170 °C (338 °F) for one hour can be used in special circumstances or if complete residual stress removal is an absolute necessity. The more aggressive set of annealing conditions is less desirable as it can reduce resin toughness attributes.

To evaluate the stress level in a part following annealing, a one minute dip of the part in ethyl acetate can be performed. If the part shows no cracking, it can be considered essentially stress-free. If cracking does occur in ethyl acetate, a similar test can be performed in a 75/25 (by volume) ethyl acetate/ethanol mixture. Absence of cracking in this mixture indicates a stress level of less than 6 MPa (800 psi).

Since annealing is a complex subject and it can produce unintended consequences, it is advisable to contact your Solvay technical service representative for additional guidance suited to your specific situation.

Rapid Annealing

Annealing can also be accomplished by immersing the parts in a liquid, such as glycerine, at 166 °C (330 °F) for a few minutes. It is recommended that the parts be immersed in boiling water for 5 minutes prior to placing them in the glycerine. When the annealing is finished, the parts should again be immersed in boiling water for 5 minutes. This procedure has a time advantage in that annealing in completed in a few minutes as opposed to a few hours in air. The recommended annealing times for various thicknesses is shown in Table 44.

The disadvantages of liquid annealing include the obvious problems of handling hot parts and hot liquids. Liquid annealing is a surface phenomenon and aggressive media, under some conditions, may still attack the material.

Applications requiring chemical or solvent resistance may be better suited for the grades containing glass fiber reinforcement. These materials usually have sufficient stress cracking resistance without annealing.

Table 44: Annealing time in glycerine at 166 °C (330 °F)

Part Thickness [mm (inch)]	**Annealing Time** [min]
1.5 (0.060)	0.75
2.5 (0.100)	1.50
3.2 (0.125)	2.00
6.3 (0.250)	4.00
9.5 (0.375)	5.00

Machining

Udel® PSU resins may be machined with normal metal working tools. Because of their high softening temperatures, relatively high cutting speeds can be used without gumming.

However, where low stress in finished parts is desired for hydrolytic stability or chemical resistance, slower speeds and very sharp tooling are suggested. The slow speed, sharp tool approach develops less heat in the machined surface resulting in lower stress.

All machining operations cause some increase in stress and, depending on the environment to be encountered in end use, annealing of the finished part may be necessary.

Coolants

If coolants are needed, plain water can be used. Most machining coolants for metal should not be used because they are incompatible with Udel® PSU.

One commercial coolant that is, when used at recommended concentrations, compatible with Udel® PSU is Cimcool® Cimtech® 95 from Milacron Marketing.

Drilling

Normal steel-working tools work well with polysulfone. A configuration of 12° to 15° clearance angle, 118° point angle, and 5° rake angle may be used for any drilling operation.

Small holes can be enlarged readily without chipping. When drilling completely through a piece of polysulfone, there is a tendency for the drill to break out of the bottom of the piece or chip the edge of the hole. This can be eliminated by backing up the piece and reducing the rate of feed.

Standard high-speed twist drills are recommended. Cutting speeds of 90 m/min (300 ft/min) at feed rates of 0.15 to 0.40 mm/rev (0.005 to 0.015 inch/rev) are recommended.

Tapping

Standard steel working taps work well with polysulfone. Lubricants or cutting oils are not required, although a light lubricating oil may be used to reduce tap wear.

A two or three flute tap may be used at speeds of 11 to 23 m/min (35 to 75 ft/min) with good results.

Sawing

Polysulfone can be sawed with any type of saw. Wood-cutting blades work somewhat better than metal-cutting blades. Regular pitch, 0.7 teeth/mm (18 teeth/inch) band saw blades cut well. A ten-pitch blade also gives good results. Sawing conditions are generally not critical.

Turning

Conventional variable-speed, metal-turning lathes with either a round-nose or a pointed tool can be used. The recommended configuration for sharp tools is a 3° rake angle, a 10° clearance angle, and a 5° side angle. A round-nose tool typically gives a smoother finish.

Polysulfone can be turned at high speed, up to 4.6 to 5.1 m/sec (900 to 1,000 ft/min), but best results are obtained at approximately 1.5 m/sec (300 ft/min). No coolant or lubricant is required for threading or turning.

A feed rate of 0.051 to 0.102 mm/rev (0.002 to 0.004 inch/rev) and a cut depth of 0.51 mm (0.020 inch) will provide a good cut with a good finish.

Milling and Routing

Milling and routing are readily accomplished at high speeds without coolants or lubricants. Tools for aluminum work well. For example, a groove 13 mm (0.5 inch) wide and 2.5 mm (0.100 inch) deep can be end milled at 1,750 rpm with a feed rate of 114 mm/min (4.5 inch/min).

Finishing and Decorating

Udel® PSU resins are an excellent substrate for finishes and virtually any decorative or functional finishing requirement can be met.

Painting

Various colors can be applied to Udel® PSU resin using organic paints and conventional application techniques. Painting may be an economical means of achieving a desired appearance.

Good adhesion with no embrittlement is a critical paint requirement. For proper paint adhesion, removal of foreign matter, such as dirt, oil, grease, and mold release, from the part surface is critical. When contaminants are present, parts should be cleaned first. Properly handled parts may not need any cleaning and can be painted without such treatment.

Although rolling and dipping are sometimes used, spray painting is the usual method of paint application.

The selection of paint is dependent upon the desired decorative finish or functional requirement, and the application technique. Among the coatings used are polyurethane, polyester, epoxy, acrylic, and alkyd.

Depending upon the paint, the cure may be air drying or oven baking. If baking is required, the high thermal resistance of Udel® PSU resins allows the use of relatively high oven temperatures.

Electroplating

Electroplated plastic parts are very durable and provide lightweight replacement for die castings and sheet metal. After a special pretreatment to form a conductive surface on the plastic part, it can be put through electroplating processes similar to those used in plating metals.

Hot Stamping

Hot stamping is a one-step, economical process for transferring a high-quality image to a plastic part. A heated die transfers the pattern from the transfer tape to a flat plastic surface. Patterns can vary from lettering to decorative designs in pigmented, wood grain, or metallic finishes.

Udel® PSU resin can be successfully hot stamped using either roll-on or vertical action application equipment. The application conditions require no special procedures, and the die temperature, pressure, and dwell time are within conventional ranges.

Printing

Udel® PSU resin can be successfully printed by silk-screen and pad-transfer printing techniques. Pad transfer printing offers economies resulting from high speed reproduction. It also allows the reproduction of images in one or more colors, using simultaneous multi-color printing equipment. The silk-screening process is primarily used for limited volumes. Although slower than the pad transfer process, silk-screening permits the decoration of contoured surfaces, making this method ideal for many molded parts.

Many inks show good adhesion to Udel® PSU resin. Surface pretreatments, such as those commonly used to promote adhesion on polyolefins, are not required.

Because polysulfone has excellent resistance to hydrolysis, it is often used in applications that involve exposure to steam, hot water, and chemicals. Printing inks used on parts for these applications must also be hydrolytically stable if the appearance and adhesion is to be maintained. Inks based on two-part epoxy resin systems are being successfully used in these applications. The maximum resistance to external environments is achieved with formulations that are heat cured to maximize cross-linking in the epoxy. Such inks are available for silk-screen and pad printing from many vendors.

Other suitable decorating methods include hot stamping, flexographic film printing, and laser etching.

Vacuum Metallizing

Udel® PSU resins have been successfully vacuum metallized to accept a decorative or functional metallic coating. Although aluminum is the most frequently used coating, other metals such as gold, silver, brass, and copper may also be used.

For most thermoplastics, the first step of the vacuum metallizing process is the application of a base coat of enamel or lacquer to provide leveling of the part surface and improve the surface brilliance. The base coat also functions as an adhesive, linking the molded part and the metallic coating.

The part is then placed in a vacuum chamber in which a metallic vapor is created and deposited on the part. A protective, clear top coat is then applied over the thin metal layer for abrasion and environmental resistance. The high thermal resistance of Udel® PSU resins allow the use of durable, abrasion resistant coatings that require high-temperature bake conditions.

The application of metallic surfaces to molded parts tends to emphasize mold defects; therefore mold surfaces should be highly polished.

Assembly and Joining

Ultrasonic Bonding

Ultrasonic bonding is an assembly technique that is used to bond plastic parts together. This technique is very rapid and can be fully automated for high-speed and high-volume production. Ultrasonic bonding requires attention to details like joint design, welding variables, fixturing, and moisture content.

The principle involved in ultrasonic joint design is to initially concentrate the energy in a small contact area. The high frequency vibration melts the material, pressure is maintained while the vibrations stop and the melt solidifies. The bond that is formed may be as strong as the original material.

Weldability is dependent upon the concentration of the vibratory energy per unit area. Compared to polycarbonate, Udel® PSU resins have higher melting temperatures and require more energy to melt the material and achieve flow at the joint.

The basic butt joint with energy director is shown in Figure 68. The V-shaped energy director concentrates the ultrasonic energy to this area, which quickly melts and creates a melt pool as the parts are pressed together. A mating flow channel is preferred in cases where an hermetic seal is desired.

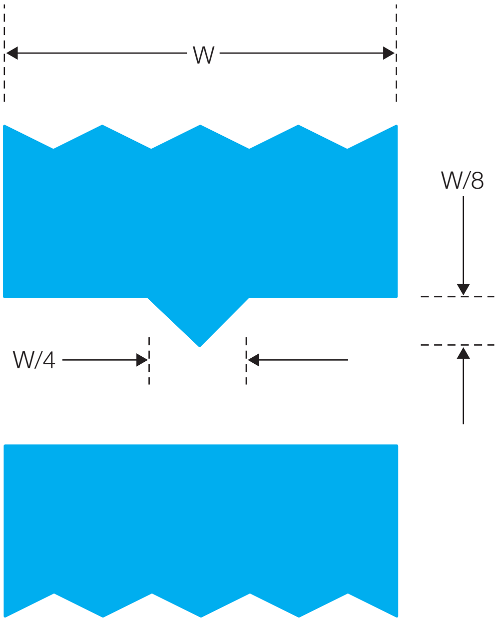
Some additional suggestions to ensure the best results are as follows:

- The welding horn should have a suitable contact area
- The joint/weld area should be located as close as possible to the point where the welding horn contacts the plastic part
- Mating surfaces should be small
- Joint design should allow for adequate flow of molten material

Hot Plate Welding

This method requires a hot plate or other suitable heat source capable of attaining 371 °C (700 °F), coated with a non-stick surface such as polytetrafluoroethylene. The surfaces to be welded are pressed against the hot plate set at 371 °C (700 °F) for about ten seconds and then joined immediately. Because polysulfone contains a small amount of moisture, it is desirable to dry it for 3 hours to 6 hours at 121 °C (250 °F) before attempting to heat weld. A suitable fixture is necessary for fast, proper alignment of the pieces. Metal fixtures heated to about 177 °C (350 °F) have been used successfully.

Figure 68: Energy director design



Polysulfone can also be joined to metal using the direct heat weld method. To join polysulfone to aluminum, the metal should be heated to 371 °C (700 °F) and placed directly against the dried polysulfone part. When a typical lap shear sample was made in this manner and tested for tensile shear strength, the polysulfone bar failed rather than the joint.

With cold-rolled steel, it is necessary to first prime the metal surface with a 5 to 10 % solution of polysulfone. The primer should be dried for 10 minutes at 260 °C (500 °F). The primed piece should then be heated to 260 to 315 °C (500 to 600 °F) before adhering it to the polysulfone.

Solvent Bonding

Solvent bonding is a fast and economical method for joining some plastics. The process involves the application of a liquid solvent to the surfaces to be joined. The solvent softens and/or dissolves the polymer on the surfaces, The softened surfaces are pressed together and held until the solvent evaporates. Under ideal circumstances a true weld is formed.

Solvent bonding of components molded from Udel® PSU resins is not generally recommended because the solvents known to be effective, such as methylene chloride, may present health hazards.

Spin Welding

Spin welding is a rapid technique for joining parts with circular joint interfaces. While one part is held fixed, the rotating part contacts it with a specified pressure. Frictional heat is generated at the joint between the surfaces. After the melting occurs, relative motion is halted and the weld is allowed to solidify under pressure.

Adhesive Bonding

Parts molded from Udel® PSU resin can be bonded to other parts molded from Udel® PSU resin or bonded to other materials using commercially available adhesives. The success of adhesive bonding is very dependent on the joint design and applied stresses, as well as end use environmental factors such as operating temperature and chemical exposure.

Adhesives frequently recommended for thermoplastics are epoxies, acrylics, phenolics, polyurethanes, polyesters, and vinyls. Specific adhesive recommendations can be obtained from the adhesive suppliers. However, the designer should test the performance of the joint in the actual end-use environment.

It is also critical that the bond surface is free of any contaminants, such as grease, oil, fingerprints, or mold release, which can weaken the bond. In some cases, the surfaces to be bonded must be chemically etched or mechanically roughened to allow the adhesive to gain a firm grip. Clamping pressure should be sufficient to insure adequate interface contact, but not so high that the parts are deformed or that solvent is forced from the joint.

The joint area should be designed so that the two parts fit precisely together. Figure 69 shows recommended joint designs for adhesive bonding. Parts should be molded with low residual stresses and to accurate dimensions.

Figure 69: Joint designs for adhesive bonding

Simple lap joint

Offset lap joint

Double scarf lap joint

Tongue and groove joint

Scarf tongue and groove joint

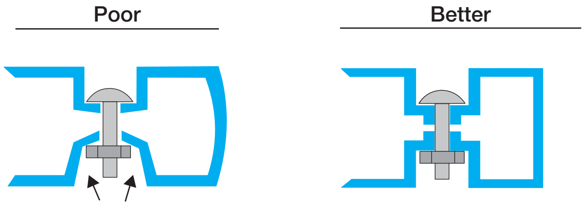
Butt scarf lap joint

Mechanical Fasteners

Fasteners frequently used with injection molded plastic parts include screws, bolts, nuts, lock washers, and lock nuts. When using metal mechanical fasteners, good design practice should be used to avoid overstressing the plastic parts in the assembly.

The most obvious procedure for preventing a high-stress assembly is to control the tightening of the mechanical fasteners with adjusted torque-limiting drivers. When torque cannot be controlled, as might be the case with field assembly, shoulder screws can limit compression on the plastic part. Other alternatives are the use of flange-head screws, large washers, or shoulder washers. Figure 70 presents some preferred designs when using mechanical fasteners.

Figure 70: Designing for mechanical fasteners



High bending stress as bolt is tightened

Added bosses with small gap, when bosses touch, stress becomes compressive

Flathead screw

Truss or round head screw

High stress from wedging action of screw head

Recessed design avoids wedging stresses

Standard screw can allow high stress on tightening

Shoulder screw limits stress when tightened

Molded-In Threads

With molded-in threads mating male and female threads are molded into the parts to be assembled. Molded internal threads usually require some type of unscrewing or collapsing mechanism in the tool.

In some cases, external threads can be molded by splitting them across the parting line. Molding very fine threads which exceed 28 pitch is usually not practical.

Threaded Inserts

Threaded metal inserts provide permanent metallic machine threads in the plastic part. The inserts come in a wide variety of sizes and types. Inserts are usually installed in molded bosses that have an internal diameter designed for the insert. Some inserts are forced into the boss while others are installed by methods that create lower stress and stronger attachments.

Ultrasonic inserts are very popular. They are installed with the same equipment used for ultrasonic welding. Because ultrasonic welding melts material around the metal insert, the installation is usually strong and relatively free of stress.

Besides female threads, inserts can be threaded male styles, locating pins and bushings. Recommendations for installation procedures and boss dimensions can be obtained from the insert supplier.

Self-Tapping Screws

Self-tapping screws are suitable for use with Udel® PSU resins. Self-tapping screws provide an economical method for joining plastics because they eliminate the need for molding an internal thread or a separate tapping operation.

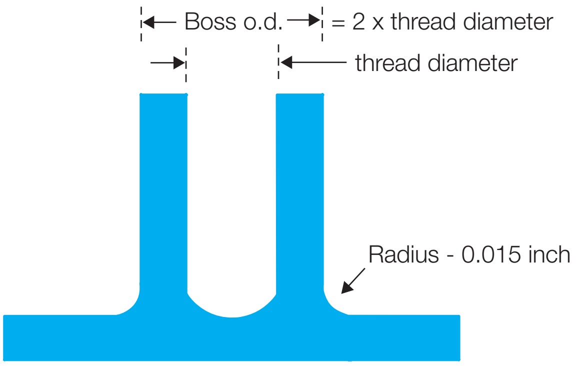
The major types of self-tapping screws are thread-forming and thread-cutting. Each type has advantages and disadvantages. Thread-cutting screws physically remove material, like a machine tap, to form the thread. The thread-cutting screws provide lower boss stresses that require lower driving torque and result in lower stripping torque and pullout strength. Thread-forming screws deform the material into which they are driven, forming threads in the plastic part. Thread-forming screws produce higher boss stress, and require higher driving torque, but provide higher stripping torque and pullout strength. The choice of screw type is best determined by prototype testing.

Figure 71 illustrates the basic guidelines for designing with self-tapping screws. These include:

- Use a hole diameter equal to the pitch diameter of the screw for the highest ratio of stripping to driving torque.
- Use a boss diameter equal to 2 times the screw diameter. Too thin a boss may crack and no increase in stripping torque is achieved with thicker bosses.
- Use a thread engagement of 2.5 times the pitch diameter of the screw. Stripping torque increase rapidly with increasing length of engagement until the engaged length is about 2.5 times the pitch diameter of the screw.
- Use torque controlled drivers on assembly lines to avoid stripping or high stress assemblies.

Avoid repeated assembly and disassembly when using self-tapping screws. If repeated assembly is required, thread forming screws are recommended.

Figure 71: Boss design for self-tapping screws



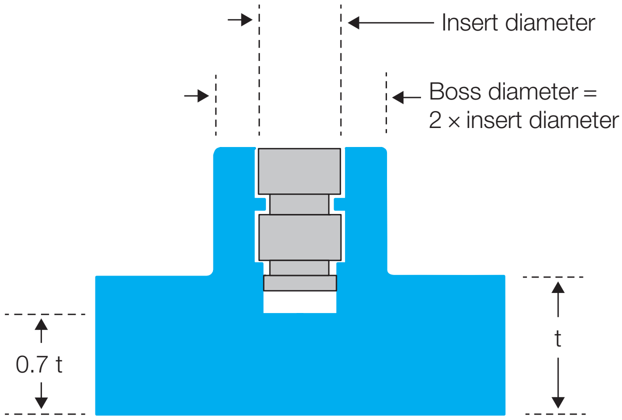
Ultrasonic Inserts

Metal parts can be ultrasonically inserted into plastic parts as an alternative to molded-in or pressed-in inserts. With proper design, ultrasonic insertion results in lower residual stresses compared to other methods of insertion.

There are several varieties of ultrasonic inserts available and all are very similar in design principle. Pressure and ultrasonic vibration of the inserts melt the material at the metal-plastic interface and drive the insert into a molded or drilled hole. The plastic, melted and displaced by the large diameter of the insert, flows into one or more recesses, solidifies and locks the insert in place.

Figure 72 depicts the recommended insert and boss designs for use with Udel® PSU resin.

Figure 72: Boss design for ultrasonic inserts



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