



TORLON[®] polyamide-imide
design guide

version 2.1

SOLVAY
Advanced Polymers



MORE PLASTICS WITH MORE PERFORMANCE

Solvay Gives You More Plastics with More Performance than Any Other Company in the World

With over a dozen distinct families of high-performance and ultra-performance plastics, Solvay Advanced Polymers gives you more material choices to more perfectly match your application needs. Plus, we give you more global support for developing smart new designs.

We offer hundreds of product formulations – including modified and reinforced resins – to help you tailor a solution to meet your precise requirements. From physical properties and processability, to appearance and agency approvals – our plastics deliver more solutions.

Our family of amorphous sulfone polymers:

- **Udel**[®] polysulfone (PSU)
- **Mindel**[®] modified polysulfone
- **Radel**[®] R polyphenylsulfone (PPSU)
- **Radel**[®] A polyethersulfone (PESU)
- **Acudel**[®] modified polyphenylsulfone

Our semi-crystalline aromatic polyamides:

- **Amodel**[®] polyphthalamide (PPA)
- **Ixef**[®] polyarylamide (PA MXD6)

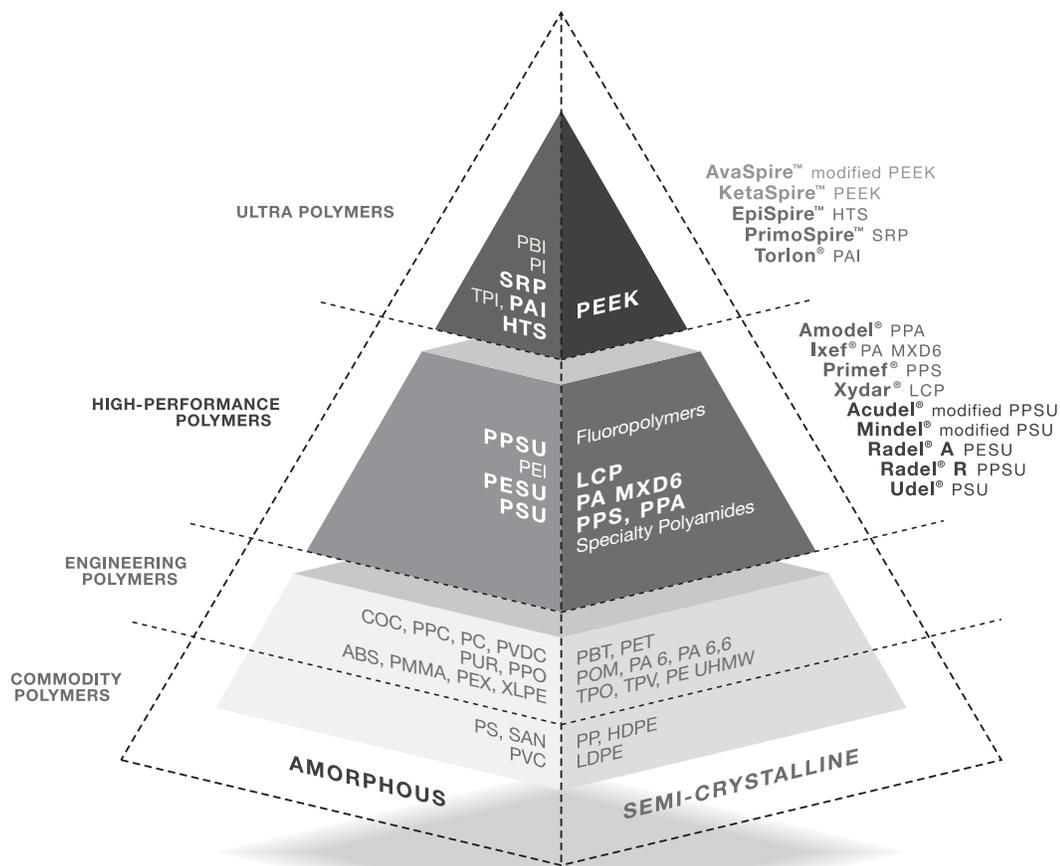
Additional semi-crystalline polymers:

- **Primef**[®] polyphenylene sulfide (PPS)
- **Xydar**[®] liquid crystal polymer (LCP)

Our SolvaSpire™ family of ultra polymers:

- **KetaSpire**[™] polyetheretherketone (PEEK)
- **AvaSpire**[™] modified PEEK
- **PrimoSpire**[™] self-reinforced polyphenylene (SRP)⁽¹⁾
- **EpiSpire**[™] high-temperature sulfone (HTS)
- **Torlon**[®] polyamide-imide (PAI)

⁽¹⁾ Formerly Parmax SRP by Mississippi Polymer Technologies, Inc., a company acquired by Solvay Advanced Polymers.



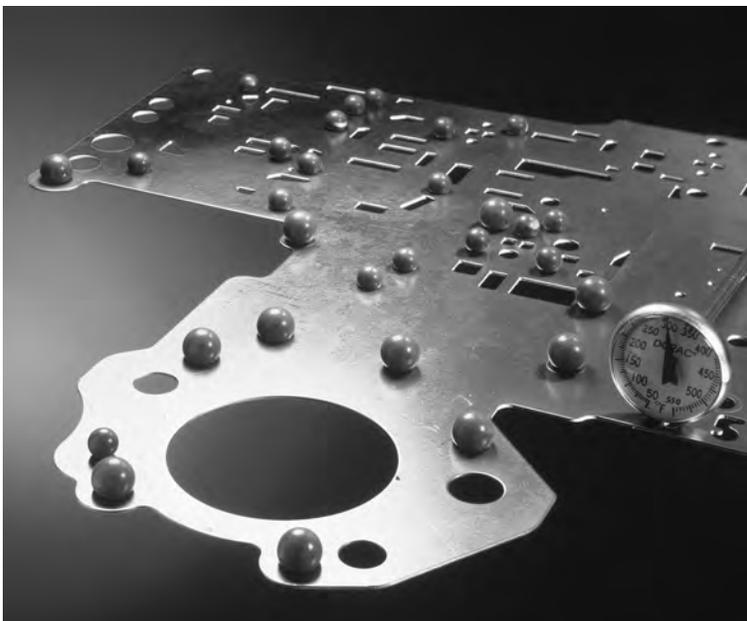
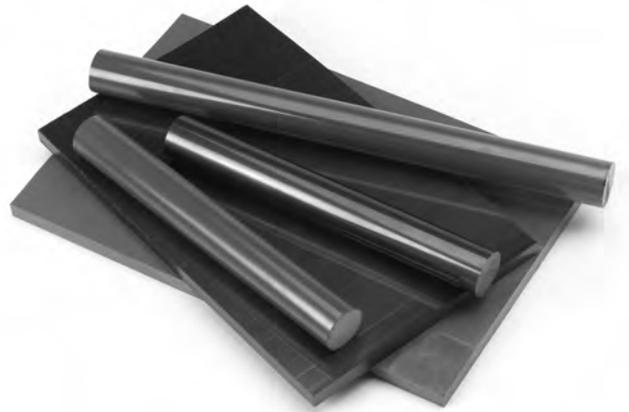


Aircraft Clip Nuts

Clip nuts made of TORLON resin won't scratch through the protective covering to bare metal during installation or corrode during use. This can significantly reduce the hours of labor and costly procedures associated with replacing corroded metal parts. They can withstand torque loads in excess of 100 inch-pounds, yet have enough elongation to clip easily into place.

Stock Shapes of TORLON Resin

TORLON® resins can be formed into stock shapes useful for machining prototypes by injection molding, compression molding, or extrusion. Shapes as large as 36 inches (900 mm) in outside diameter by 6 inches (150 mm) long weighing 120 pounds (54 kg) have been made.



Check Balls for 4-Wheel-Drive Vehicle Transmissions

The durability of high-torque automatic transmissions was improved when Chrysler product development engineers specified Torlon® polyamide-imide resin for the check balls. The resin was selected for multiple variations of three- and four-speed transmissions coupled to the Magnum Engine product line. The check balls withstand system pressures, and provide excellent sealing surfaces without causing metal damage, and without adverse reaction to transmission oil at temperatures approaching 300°F.

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Introduction

TORLON® High Performance Molding Polymers

For reliable performance at extremely high temperature and stress, use TORLON polymers. Parts made of TORLON engineering polymers perform under conditions generally considered too severe for thermoplastics. That's why parts for the space shuttle, automotive transmissions, and many other critical components have been molded from TORLON polymers. Across a wide range of industries — electrical and electronics; business equipment; aerospace; transportation; process; and heavy equipment — TORLON parts meet design challenges.

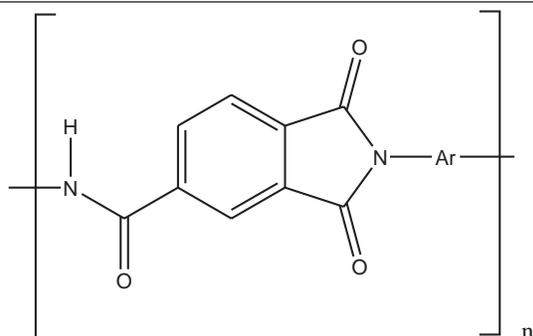
Some other engineering resins may perform at 500°F (260°C), but TORLON polymers maintain superior strength at this extreme temperature. Of the high-temperature plastics, TORLON polymers have the advantage of being injection-moldable. That means exact replication and low unit cost, making TORLON polymers the cost-effective solution to difficult design problems.

This manual introduces the reader to the TORLON polymer family. Numerous graphs and tables present the physical properties and load-bearing capabilities of TORLON polymers. A discussion of design guidelines and secondary operations focuses on the practical aspects of fabricating high-performance TORLON parts. Using this manual, the designer can relate the characteristics of these exceptional resins to his own specific needs.

Solvay Advanced Polymers' TORLON high performance polymer is a polyamide-imide, with the general structure:

Figure 1

Structure of Polyamide-imide



The variety of applications requiring high temperature resistance, high strength, and the economies of injection-molding has led to the commercialization of several TORLON grades, which can be divided into two categories; the high-strength grades and the wear-resistant grades.

The high-strength grades perform more like metals at elevated temperature, even under considerable stress.

These grades are ideally suited for repetitively-used precision mechanical and load-bearing parts.

The inherent lubricity of TORLON polyamide-imide is enhanced with additives in the wear-resistant grades. Moving parts made of TORLON polymers provide dependable service in lubricated and non-lubricated environments.

Table 1

TORLON Engineering Polymers

High Strength	Wear Resistant
4203L	4275
5030	4301
7130	4435

Only TORLON engineering polymers offer a combination of:

- performance from cryogenic to 500°F (260°C)
- outstanding mechanical strength
- easy fabrication
- low flammability and smoke generation
- fatigue strength
- impact strength
- creep resistance
- wear resistance
- low expansion coefficients
- excellent thermal stability
- resistance to aviation and automotive fluids.

The High Performance TORLON Polymers

TORLON polyamide-imide resins are injection-moldable thermoplastics that offer truly outstanding performance. The diversity of end-use applications has led to development of several grades, each designed to maximize specific properties.

If your application requires a special modified grade, we can compound TORLON polymers to your specifications.

This page describes the TORLON family and suggests general application areas. For specific advice concerning a particular application, please contact your Solvay Advanced Polymers representative.

Table 2

Grades and Applications

TORLON Grade	Nominal Composition	Description of Properties	Applications
High strength			
4203L	TiO ₂	Best impact resistance, most elongation, and good mold release and electrical properties.	Connectors, switches, relays, thrust washers, spline liners, valve seats, check balls, poppets, mechanical linkages, bushings, wear rings, Insulators, cams, picker fingers, ball bearings, rollers, and thermal insulators.
5030	30% glass fiber	High stiffness, good retention of stiffness at elevated temperature, very low creep, and high strength.	Burn-in sockets, gears, valve plates, fairings, tube clamps, impellers, rotors, housings, back-up rings, terminal strips, insulators, and brackets.
7130	30% carbon fiber	Similar to 5030 but higher stiffness. Best retention of stiffness at high temperature, best fatigue resistance. Electrically conductive.	Metal replacement, housings, mechanical linkages, gears, fasteners, spline liners, cargo rollers, brackets, valves, labyrinth seals, fairings, tube clamps, standoffs, impellers, shrouds, potential use for EMI shielding.
Wear Resistant			
4301	graphite powder fluoropolymer	General purpose, high-performance, low-friction, wear-resistant compound exhibiting high compressive strength.	Bearings, thrust washers, wear pads, strips, piston rings, seals, vanes, and valve seats.
4275	graphite powder fluoropolymer	Similar to 4301 with better wear resistance at high speeds.	Bearings, thrust washers, wear pads, strips, piston rings, seals, vanes, and valve seats.
4435	graphite powder fluoropolymer other additives	Excellent wear resistance and low friction at higher pressures and velocities (>50,000 ft-lb/in ² -min)	Bobbins, vanes, thrust washers, seal rings, and pistons

Physical Properties

High impact strength, exceptional mechanical strength, and excellent retention of these properties in high temperature environments characterize all TORLON resins.

At room temperature, the tensile and flexural strengths of TORLON 4203L are about twice that of polycarbonate and nylon. At 500°F (260°C), the tensile and flexural strengths of TORLON 4203L are almost equal to that of these engineering resins at room temperature. Superior physical properties are retained after long-term exposure to elevated temperature.

These physical properties are typical of injection-molded, post-cured test specimens.



Footnotes for Typical Property Tables on Pages 4 and 5.

- (1) Tensile properties per ASTM D638 appear on Page 7.
- (2) Note: The test methods used to obtain these data measure response to heat and flame under controlled laboratory conditions and may not provide an accurate measure of the hazard under actual fire conditions.

Table 3

Typical Properties* – US Units

Properties	ASTM Test Method	Units	4203L	4301	4275	4435	5030	7130
Mechanical								
Tensile Strength ⁽¹⁾	D1708	kpsi						
-321°F			31.5		18.8		29.5	22.8
73°F			27.8	23.7	19.0	16.0	29.7	29.4
275°F			16.9	16.3	16.9	13.0	23.1	22.8
450°F			9.5	10.6	8.1	7.5	16.3	15.7
Tensile Elongation	D1708	%						
-321°F			6		3		4	3
73°F			15	7	7	6	7	6
275°F			21	20	15	4	15	14
450°F			22	17	17	3	12	11
Tensile Modulus	D1708	kpsi						
73°F			700	950	1,130	1,410	1,560	3,220
Flexural Strength	D790	kpsi						
-321°F			41.0		29.0		54.4	45.0
73°F			34.9	31.2	30.2	22.0	48.3	50.7
275°F			24.8	23.5	22.4	18.7	35.9	37.6
450°F			17.1	16.2	15.8	13.2	26.2	25.2
Flexural Modulus	D790	kpsi						
-321°F			1,140		1,390		20.4	3,570
73°F			730	1,000	1,060	2,150	1,700	2,880
275°F			560	790	810	1,630	1,550	2,270
450°F			520	720	740	1,500	1,430	1,900
Compressive Strength	D695	kpsi	32.1	24.1	17.8	20.0	38.3	36.9
Compressive Modulus	D695	kpsi	580	770	580	1,240	1,150	1,430
Shear Strength	D732	kpsi						
73°F			18.5	16.1	11.1	8.7	20.1	17.3
Izod Impact Strength (½ in)	D256	ft•lbs/in						
notched			2.7	1.2	1.6	0.8	1.5	0.9
unnotched			20.0	7.6	4.7	4.1	9.5	6.4
Poisson's Ratio			0.45	0.39	0.39	0.42	0.43	0.39
Thermal								
Deflection Temperature	D648	°F						
264 psi			532	534	536	532	539	540
Coefficient of Linear Thermal Expansion	D696	ppm/°F	17	14	14	8	9	5
Thermal Conductivity	C177	Btu in/hr ft ² °F	1.8	3.7	4.5	5.6	2.5	3.6
Flammability ⁽²⁾ , Underwriters' Laboratories			94 V-0	94 V-0	94 V-0	94 V-0	94 V-0	94 V-0
Limiting oxygen index ⁽²⁾	D2863	%	45	44	45		51	52
Electrical								
Dielectric constant	D150							
10 ³ Hz			4.2	6.0	7.3		4.4	
10 ⁶ Hz			3.9	5.4	6.6		4.2	
Dissipation factor	D150							
10 ³ Hz			0.026	0.037	0.059		0.022	
10 ⁶ Hz			0.031	0.042	0.063		0.050	
Volume resistivity	D257	ohm-cm	2 x 10 ¹⁷	8 x 10 ¹⁵	8 x 10 ¹⁵	2 x 10 ⁷	2 x 10 ¹⁷	
Surface resistivity	D257	ohm	5 x 10 ¹⁸	8 x 10 ¹⁷	4 x 10 ¹⁷	6 x 10 ⁶	1 x 10 ¹⁸	
Dielectric strength (0.040 in)	D149	V/mil	580				840	
General								
Density	D792	lb/in ³	0.051	0.053	0.054	0.057	0.058	0.054
Hardness, Rockwell E	D785		86	72	70	62	94	94
Water absorption, 24 hour	D570	%	0.33	0.28	0.33	0.12	0.24	0.26

*Typical properties – Actual properties of individual batches will vary within specification limits.

Table 4

Typical Properties* – SI Units

Properties	ASTM Test Method	Units	4203L	4301	4275	4435	5030	7130
Mechanical								
Tensile Strength ⁽¹⁾	D1708	MPa						
-196°C			218		130		204	158
23°C			192	164	131	110	205	203
135°C			117	113	116	90	160	158
232°C			66	73	56	52	113	108
Tensile Elongation	D1708	%						
-196°C			6		3		4	3
23°C			15	7	7	6	7	6
135°C			21	20	15	4	15	14
232°C			22	17	17	3	12	11
Tensile Modulus	D1708	GPa						
23°C			4.9	6.6	7.8	9.7	10.8	22.3
Flexural Strength	D790	MPa						
-196°C			287		203		381	315
23°C			244	219	212	152	338	355
135°C			174	165	157	129	251	263
232°C			120	113	111	91	184	177
Flexural Modulus	D790	GPa						
-196°C			7.9		9.6		14.1	24.6
23°C			5.0	6.9	7.3	14.8	11.7	19.9
135°C			3.9	5.5	5.6	11.2	10.7	15.6
232°C			3.6	4.5	5.1	10.3	9.9	13.1
Compressive Strength	D695	MPa	220	170	120	138	260	250
Compressive Modulus	D695	GPa	4.0	5.3	4.0	8.5	7.9	9.9
Shear Strength	D732	MPa						
23°C			128	112	77	60	140	120
Izod Impact Strength (3.2 mm)	D256	J/m						
notched			142	63	84	43	79	47
unnotched			1062	404	250	219	504	340
Poisson's Ratio			0.45	0.39	0.39	0.42	0.43	0.39
Thermal								
Deflection Temperature	D648	°C						
1.82 MPa			278	279	280	278	282	282
Coefficient of Linear Thermal Expansion	D696	ppm/°C	30.6	25.2	25.2	14.4	16.2	9.0
Thermal Conductivity	C177	W/mK	0.26	0.54	0.65	0.80	0.37	0.53
Flammability ⁽²⁾ , Underwriters' Laboratories	UL94		94 V-0	94 V-0	94 V-0	94 V-0	94 V-0	94 V-0
Limiting Oxygen Index ⁽²⁾	D2863	%	45	44	45		51	52
Electrical								
Dielectric Constant	D150							
10 ³ Hz			4.2	6.0	7.3		4.4	
10 ⁶ Hz			3.9	5.4	6.6		4.2	
Dissipation Factor	D150							
10 ³ Hz			0.026	0.037	0.059		0.022	
10 ⁶ Hz			0.031	0.042	0.063		0.050	
Volume Resistivity	D257	ohm-cm	2 x 10 ¹⁷	8 x 10 ¹⁵	8 x 10 ¹⁵	2 x 10 ⁷	2 x 10 ¹⁷	
Surface Resistivity	D257	ohm	5 x 10 ¹⁸	8 x 10 ¹⁷	4 x 10 ¹⁷	6 x 10 ⁶	1 x 10 ¹⁸	
Dielectric Strength (1 mm)	D149	kV/mm	23.6				32.6	
General								
Density	D792	g/cm ³	1.42	1.46	1.51	1.59	1.61	1.48
Hardness, Rockwell E	D785		86	72	70	62	94	94
Water Absorption, 24 hour	D570	%	0.33	0.28	0.33	0.12	0.24	0.26

*Typical properties – Actual properties of individual batches will vary within specification limits.

Performance Properties

The unrivaled properties of TORLON engineering polymers meet the requirements of the most demanding applications. Strength retention over a wide range of temperatures and sustained stress, low creep, flame resistance, outstanding electrical properties, and exceptional integrity in severe environments place TORLON polyamide-imide in a class by itself among engineering resins.

Mechanical Properties

Tensile and Flexural Strength at Temperature Extremes

Ultra High Temperature

TORLON polyamide-imide can be used in applications previously considered too demanding for many other engineering plastics because of its outstanding tensile and flexural strength combined with retention of these properties in continuous service at temperatures in excess of 450°F (232°C).

While many competitive resins can claim “excursions” up to 500°F (260°C), TORLON polymers function with integrity at extremely high temperatures, as shown by Figures 2 and 3, which demonstrate the exceptional retention of tensile and flexural strength of TORLON resins at elevated temperatures.

Even at 400°F (204°C), the strengths in both tensile and flexural modes of TORLON engineering polymers are better than other high performance engineering resins. Figures 4 and 5 compare reinforced TORLON polymers to other high performance reinforced resins.

Figure 2
TORLON Resins Have Outstanding Tensile Strengths

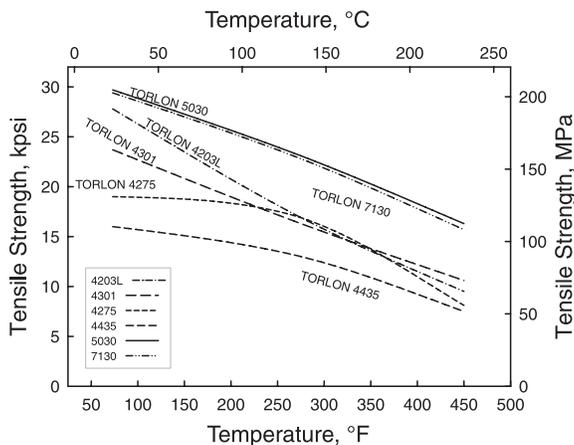


Figure 3
Flexural Strengths of TORLON Resins Are High Across a Broad Temperature Range

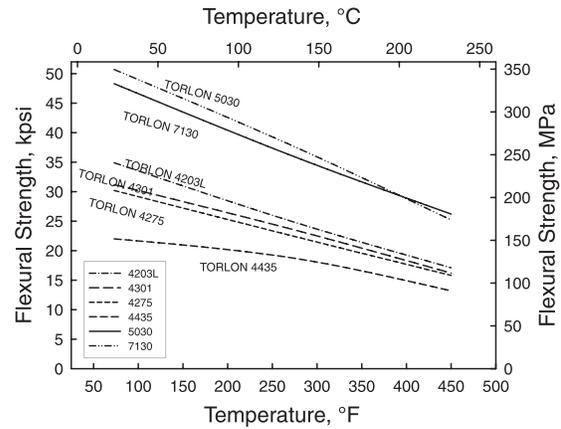


Figure 4
Tensile Strengths of Reinforced TORLON Resins Surpass Competitive Reinforced Resins at 400°F (204°C).

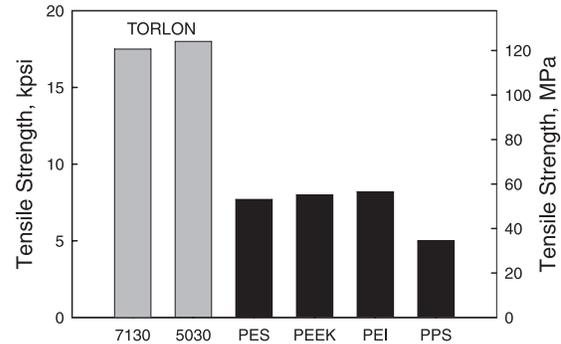
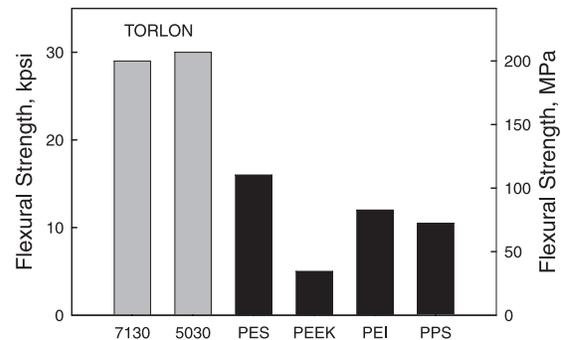


Figure 5
Flexural Strengths of Reinforced TORLON Resins Surpass Competitive Reinforced Resins at 400°F (204°C)



Tensile Properties Per ASTM Test Method D 638

Tensile properties reported in the preceding section were obtained in accordance with ASTM Test Method D 1708. Since tensile properties are frequently measured using ASTM test method D 638, TORLON polymers were also tested in accordance with this method. The data appear in Table 6.

Table 6

Room Temperature Tensile Properties per ASTM D638

Property	Units	TORLON grade					
		4203L	4301	4275	4435	5030	7130
Tensile Strength,	kpsi	22.0	16.4	16.9	13.6	32.1	32.0
	(MPa)	(152)	(113)	(117)	(94)	(221)	(221)
Elongation,	%	7.6	3.3	2.6	1.0	2.3	1.5
Tensile modulus,	kpsi	650	990	1,280	2,100	2,110	2,400
	(GPa)	(4.5)	(6.8)	(8.8)	(14.5)	(14.6)	(16.5)



Ultra Low Temperature

At the other end of the temperature spectrum, TORLON polymers do not become brittle as do other resins. Table 5 shows TORLON resins have excellent properties under cryogenic conditions.

Table 5

Properties of TORLON Molding Resins at -321°F (-196°C)

Property	Units	TORLON grade			
		4203L	4275	7130	5030
Tensile strength ⁽¹⁾	kpsi (MPa)	31.5 (216)	18.8 (129)	22.8 (157)	29.5 (203)
Elongation at break ⁽¹⁾	%	6	3	3	4
Flexural strength ⁽²⁾	kpsi (MPa)	41.0 (282)	29.0 (200)	45.0 (310)	54.4 (374)
Flexural modulus ⁽²⁾	kpsi (GPa)	1,140 (7.8)	1,390 (9.6)	3,570 (24.6)	2,040 (14.0)

⁽¹⁾ ASTM D 1708

⁽²⁾ ASTM D 790

Flexural Modulus – Stiffness at High Temperature

TORLON polyamide-imide has high modulus, making it a good replacement for metal where stiffness is crucial to performance. TORLON parts can provide equivalent stiffness at significantly lower weight. Excellent retention of part stiffness and resistance to creep or cold flow is predicted from the high and essentially constant modulus of TORLON resins, even at 450°F (232°C), as shown in Figure 6. Unlike competitive materials, which lose stiffness at higher temperatures, TORLON polymers have high moduli at elevated temperatures, as Figure 7 demonstrates.

Figure 6

Flexural Moduli of TORLON Polymers

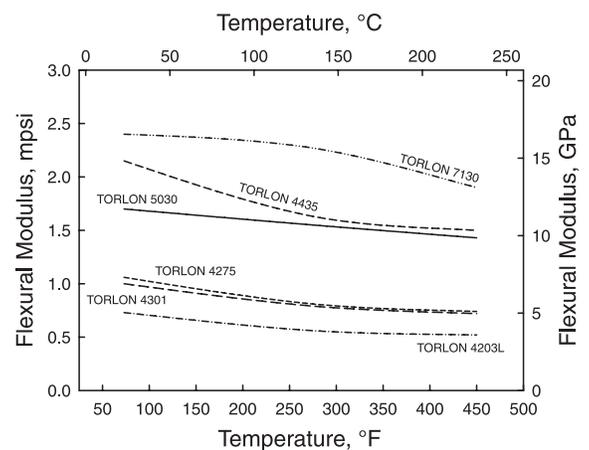
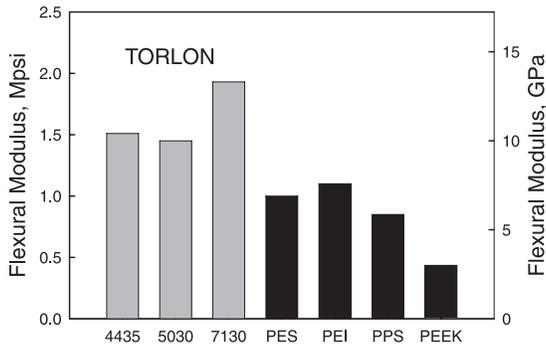


Figure 7

Flexural Moduli of Reinforced TORLON Grades are Superior to Competitive Reinforced Resins at 400°F (204°C)



Stress-Strain Relationship

TORLON polyamide-imide does not yield at room temperature, therefore, strain at failure or rupture is recorded as the elongation. Figure 8 show the stress-strain relationship for TORLON grades at room temperature. Figure 9 shows just the first 1% strain – the nearly linear (“Hookean”) portion of the room temperature curve. Figure 10 shows the initial portion of stress-strain curve measured at 275°F (135°C).

Figure 9

Stress-Strain Detail at 73°F (23°C)

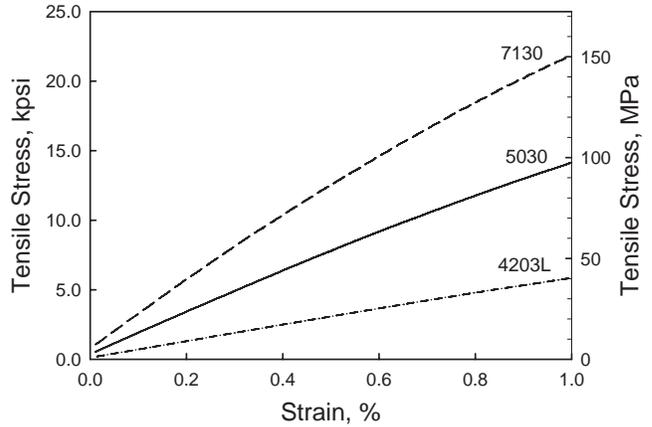


Figure 10

Stress-Strain in Tension for TORLON Resins at 275°F (135°C)

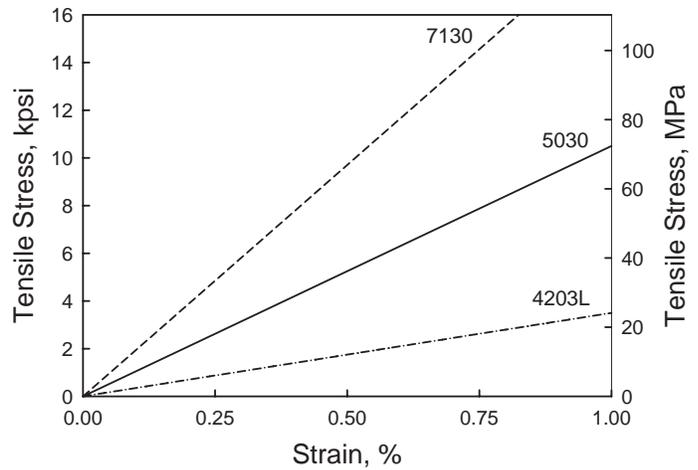
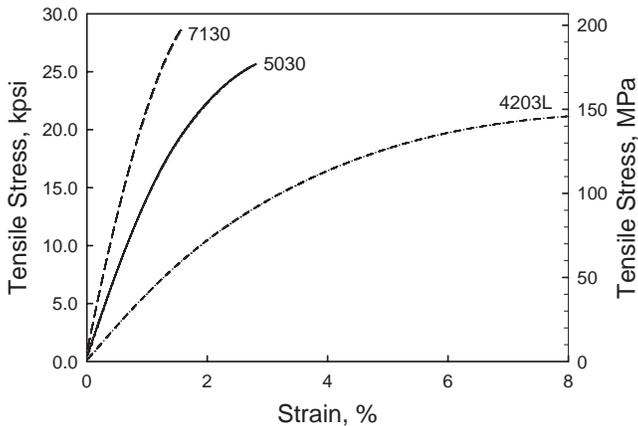


Figure 8

Stress-Strain in Tension at 73°F (23°C)



ASTM D 638 Type 1 specimen

Resistance To Cyclic Stress

Fatigue Strength

When a material is stressed cyclically, failure will occur at stress levels lower than the material's ultimate strength. Resistance to failure under cyclical loading or vibration, called fatigue strength, is an important design consideration. TORLON engineering polymers offer excellent fatigue strength in both the tensile mode and the very severe flexural mode, a form of reverse bending.

S-N diagrams, showing maximum stress versus cycles to failure, are useful in predicting product life. The maximum stress using the anticipated force, appropriate stress concentration factors, and section modulus is determined. The maximum stress is then compared to the fatigue strength S-N curve for the applicable environment to determine the maximum cyclic stress the material can be expected to withstand.

The values obtained in fatigue testing are influenced by the specimen and test method; therefore, the values should serve as guidelines, not absolute values. TORLON parts resist cyclic stress. TORLON 7130, a graphite-fiber-reinforced grade, has exceptional fatigue strength, and is superior to competitive engineering resins. Figure 11, the S-N curves for selected TORLON grades, shows that even after 10,000,000 cycles, TORLON polyamide-imide has excellent resistance to cyclical stress in the flexural mode, and Figure 12 demonstrates the integrity of TORLON 7130 under tension/tension cyclical stress. At lower frequencies, the fatigue strength of TORLON 7130 is even higher, as shown in Figure 13.

Figure 11

Flexural Fatigue Strength of TORLON resins at 30Hz

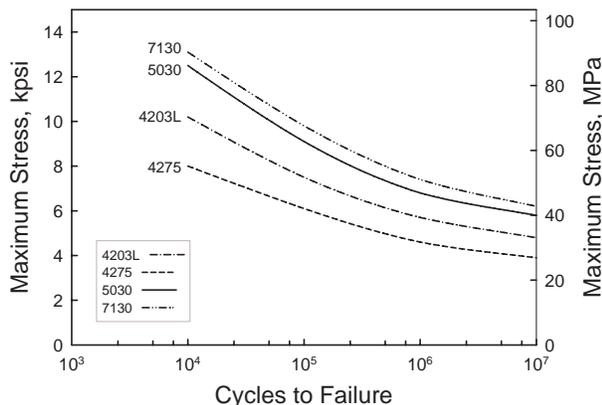


Figure 12

Tension/Tension Fatigue Strength of TORLON 7130 and 4203L, at 30Hz, A ratio: 0.90

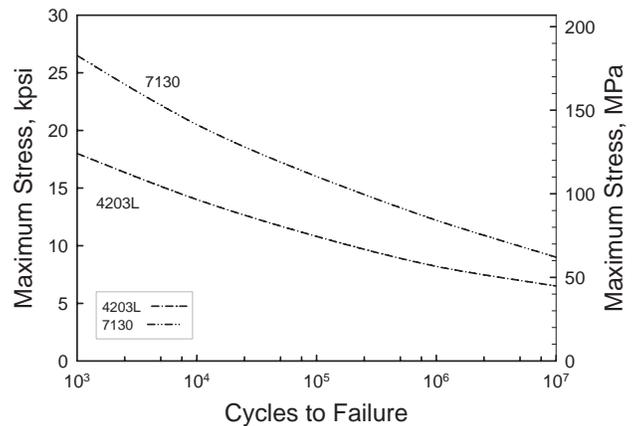
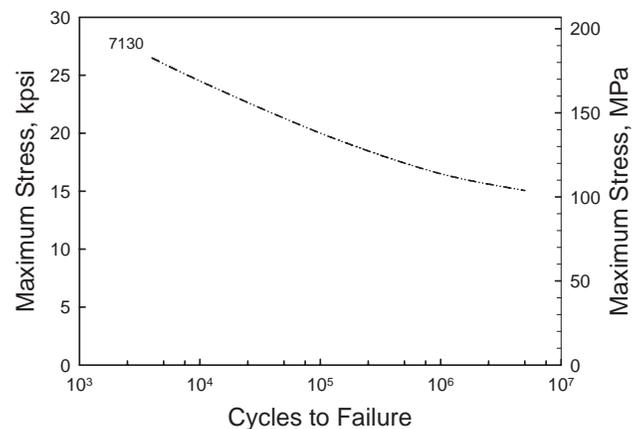


Figure 13

Tension/Tension Low Cycle Fatigue Strength of TORLON 7130, at 2Hz, A ratio: 0.90



Even at high temperature, TORLON polymers maintain strength under cyclic stress. Flexural fatigue tests were run at 350°F (177°C) on specimens preconditioned at that temperature. The results, shown in Figure 14, suggest TORLON polymers are suitable for applications requiring fatigue resistance at high temperature.

Figure 14

High Temperature Flexural Fatigue Strength of TORLON Resins at 350°F (177°C), 30Hz

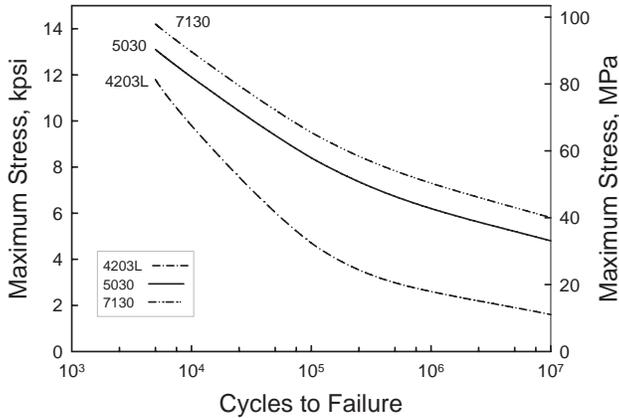
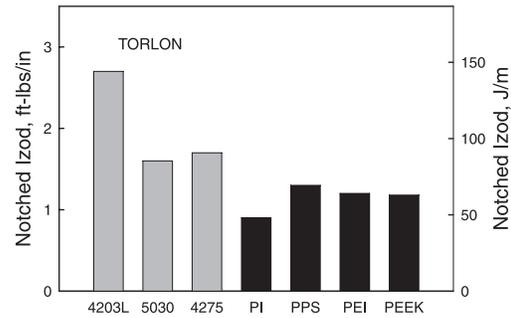


Figure 15

Izod Impact Resistance of TORLON Resins vs. Competitive Materials



Impact Resistance

TORLON resins absorb impact energy better than most high-modulus plastics. In tests using the notched Izod method (ASTM D256), TORLON resins give results superior to those of other high-temperature resins (Figure 15). Table 7 summarizes both notched and unnotched impact data for TORLON resins.

Table 7

Izod impact resistance of 1/8" (3.2 mm) bars

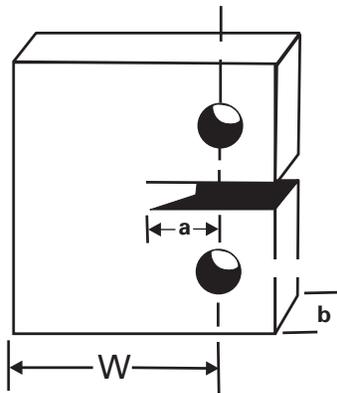
TORLON grade	Notched		Unnotched	
	ft•lb/in	J/m	ft•lb/in	J/m
4203L	2.7	142	20.0	1062
4301	1.2	63	7.6	404
4275	1.6	84	4.7	250
4435	0.8	42	4.1	220
5030	1.5	79	9.5	504
7130	0.9	47	6.4	340

Fracture Toughness

Fracture toughness can be assessed by measuring the fracture energy (G_{IC}) of a polymer. The Naval Research Laboratory (NRL) uses a compact tension specimen (Figure 16) to determine G_{IC} a measure of a polymer's ability to absorb and dissipate impact energy without fracturing — larger values correspond to higher fracture toughness. Table 8 shows selected data from NRL Memorandum Report 5231 (February 22, 1984). As expected, thermosetting polymers cannot absorb and dissipate impact energy as well as thermoplastics and consequently have lower fracture energies. TORLON polyamide-imide exhibits outstanding fracture toughness, with a G_{IC} of 1.6 ft-lb/in² (3.4 kJ/m²). Glass transition temperatures (T_g) are included in the table to indicate the tradeoff between fracture toughness and useful temperature range. polyamide-imide is characterized by a balance of toughness and high T_g .

Figure 16

Compact Tension Specimen



$$G_{IC} = \frac{Y^2 P_c^2 a}{EW^2 b^2}$$

Where:

$$Y = 29.6 - 186 (a/w) + 656 (a/w)^2 - 1017 (a/w)^3 + 639 (a/w)^4$$

P = critical fracture load

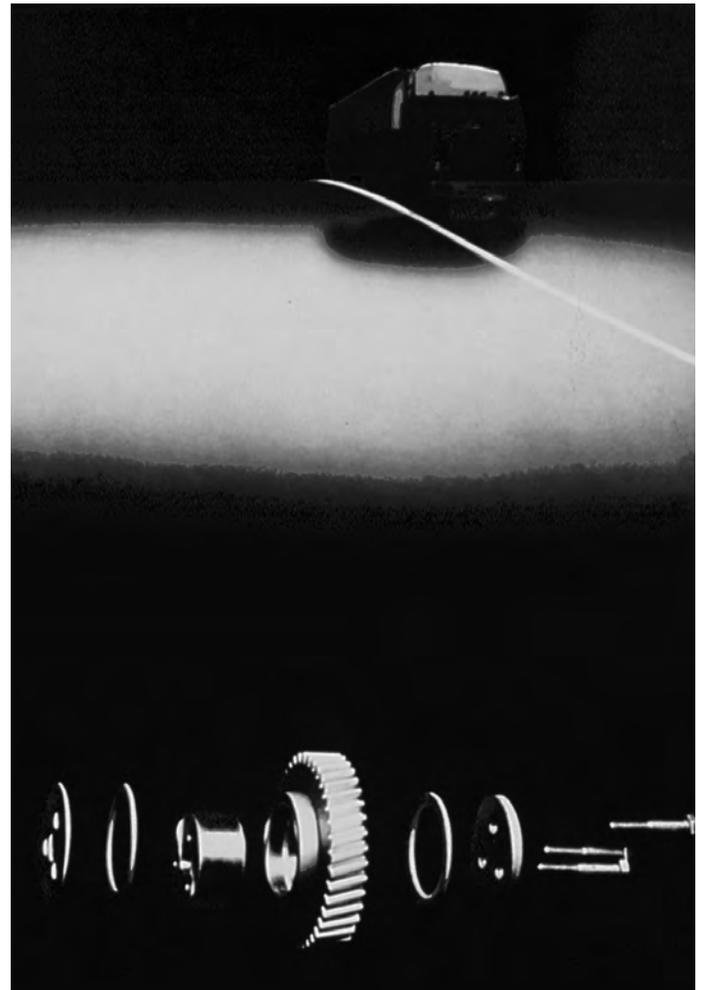
a = crack length

E = sample modulus

Table 8

Polyamide-Imide Balances Fracture Toughness and High Glass Transition Temperature

	Fracture energy		Tg	
	ft•lb/in ²	kJ/m ²	°F	°C
Thermosets				
Polyimide-1	0.095	0.20	662	350
Polyimide-2	0.057	0.12	680	360
Tetrafunctional epoxy	0.036	0.076	500	260
Thermoplastics				
polyamide-imide	1.6	3.4	527	275
Polysulfone	1.5	3.1	345	174
Polyethersulfone	1.2	2.6	446	230
Polyimide-4	1.0	2.1	689	365
Polyimide-3	0.38	0.81	619	326
Polyphenylene sulfide	0.10	0.21	—	—



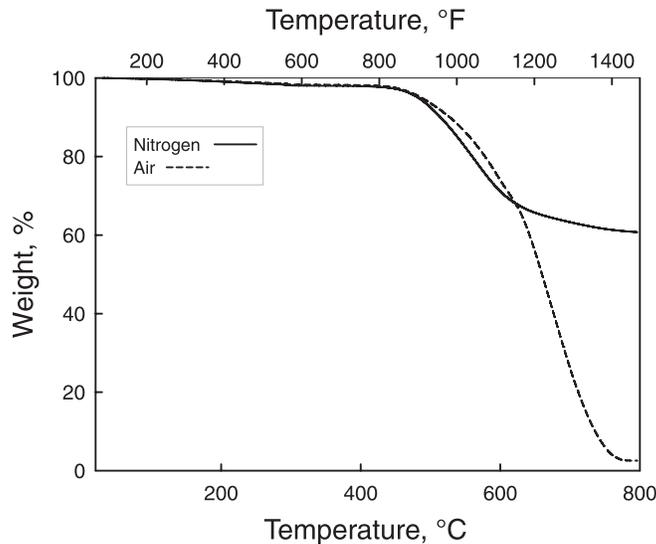
Thermal Stability

Thermogravimetric Analysis

TORLON resins are exceptionally stable over a wide range of temperatures. When heated at a rate of 18°F (10°C) per minute in air or nitrogen atmospheres, TORLON 4203L shows virtually no weight loss over its normal service temperatures and well beyond, as shown in Figure 17.

Figure 17

Thermogravimetric Analysis of TORLON 4203L



Effects of Prolonged Thermal Exposure

UL Relative Thermal Index

The UL Relative Thermal Index provides an estimate of the maximum continuous use temperature and is defined by the method prescribed by Underwriters' Laboratories.

Initial properties, including tensile strength, impact strength, dielectric strength, arc resistance, dimensional stability, and flammability, are determined for the test material. For each property and each aging temperature, a record is kept of elapsed time and the change in that property as a percent of initial. The "end-of-life" for a property is the time required at the aging temperature to reach 50 percent of initial. End-of-life points are plotted and regression applied to predict "life expectancy" at any operating temperature. The Relative Thermal Index is that temperature at which life expectancy is 100,000 hours. TORLON polymers were tested in accordance with the above procedure for 50 percent degradation of dielectric strength (Electrical), Izod impact (Mechanical-with impact), and tensile strength (Mechanical-without impact). The other properties did not change significantly.

Table 9

Relative Thermal Indices of TORLON Resins

	Minimum thickness		Mechanical					
			Electrical		With impact		Without impact	
					°F	°C	°F	°C
TORLON 4203L	0.031	0.81	428	220	*	*	410	210
	0.047	1.2	428	220	*	*	410	210
	0.096	2.4	428	220	*	*	410	210
	0.118	3.0	428	220	392	200	428	220
TORLON 4301	0.118	3.0	*	*	392	200	392	200
TORLON 5030	0.062	1.5	428	220	*	*	*	*
	0.096	2.4	428	220	*	*	*	*
	0.118	3.0	428	220	392	200	428	220

*not tested

The UL Relative Thermal Index predicts at least 100,000 hours of useful life at the index temperature. TORLON polymers have UL relative thermal indices as high as 220°C, which is equivalent to more than eleven years of continuous use at 428°F, and is significantly higher than most high-temperature engineering resins. Table 9 summarizes the relative thermal indices of TORLON PAI grades 4203L, 4301, and 5030. Refer to Underwriters' Laboratories website for the latest information, www.ul.com.

Retention of Properties After Thermal Aging

TORLON polyamide-imide resists chemical breakdown and retains high strength after prolonged thermal exposure. One method for determining the thermal stability of polymers is to measure mechanical properties of samples after aging at elevated temperatures.

Injection molded and post-cured tensile bars (ASTM D1708 configuration, 1/8 inch thick) were aged in forced air ovens at 482°F (250°C). Specimens were periodically removed from the ovens, conditioned at 73°F (23°C) and 50 percent relative humidity then tested for tensile strength.

TORLON resins retain strength after long-term aging at high temperature, as shown in Figure 18. After 10,000 hours, tensile strengths of TORLON polymers exceed the ultimate strength of many competitive resins. TORLON 4203L, for example, still has tensile strength of over 25,000 psi. It is interesting to note that the specimens actually increase in tensile strength initially, because even greater strength is attained beyond the standard post cure.

TORLON polymers maintain exceptional electrical and mechanical properties and UL flammability ratings after long-term heat aging. Table 10 demonstrates that TORLON 4203L is still suitable for demanding applications even after extended exposure to 482°F (250°C).

Figure 18

TORLON Resins Retain Strength After Thermal Aging at 482°F (250°C)

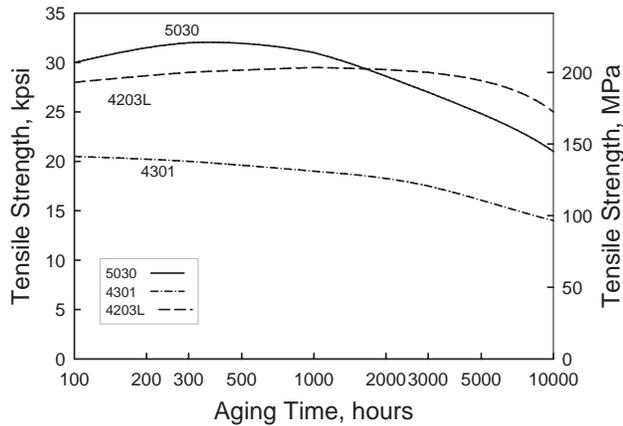


Table 10

TORLON 4203L Retention of Properties After Thermal Aging

Property	Hours at 480°F (250°C)		
	2,000	12,000	17,000
Dielectric strength*, V/mil (kV/mm)			654
Flammability**, UL 94	94 V-0	94 V-0	94 V-0
Dimensional change**, %	0.0	0.5	0.9
Tensile strength retained**, %	110	86	67
Izod impact strength retained**, %	101	67	38

*specimen thickness 0.035" (0.9 mm)
 **specimen thickness 0.125" (3.2 mm)

Specific Heat

Specific heat as a function of temperature was determined using a differential scanning calorimeter

The data for four TORLON grades at four temperatures are presented in Table 11.

Table 11

Specific Heat of TORLON Polymers

TORLON grade	Specific Heat, cal/gm°C			
	4203L	4301	5030	7130
Temperature, °F (°C)				
77 (25)	0.242	0.240	0.229	0.230
212 (100)	0.298	0.298	0.276	0.285
392 (200)	0.362	0.359	0.327	0.346
482 (250)	0.394	0.385	0.353	0.375

Thermal Conductivity

TORLON resins have low thermal conductivity, and are suitable for applications requiring thermal isolation. TORLON heat shields protect critical sealing elements from high temperatures, and protect sensitive instrument elements from heat loss. Table 12 shows the thermal conductivity of TORLON resins measured using ASTM C177 with 0.06 in. (1.6 mm) thick specimens and a cold plate temperature of 122°F (50°C) and a hot plate temperature of 212°F (100°C).

Table 12

Thermal Conductivity of TORLON Resins

TORLON Grade	Thermal conductivity	
	Btu•in/hr•ft ² •°F	W/m•K
4203L	1.8	0.26
4301	3.7	0.54
4275	4.5	0.65
4435	5.6	0.80
5030	2.5	0.37
7130	3.6	0.53

Coefficients of Linear Thermal Expansion (CLTE)

As shown in Table 13, the thermal expansion of filled TORLON polyamide-imide nearly matches that of common metals.

Table 13

CLTE for TORLON Resins and Selected Metals.*

	CLTE	
	ppm/°F	ppm/°C
TORLON 7130	5.0	9.0
Inconel X, annealed	6.7	12.1
Plain carbon steel AISI-SAE 1020	6.7	12.1
Titanium 6-2-4-2	7.0	12.6
TORLON 5030	9.0	16.2
Copper	9.3	16.7
Stainless steel, type 304	9.6	17.3
Commercial bronze, 90%, C2200	10.2	18.4
Aluminum alloy 2017, annealed, ASTM B221	12.7	22.9
TORLON 4275	14.0	25.2
TORLON 4301	14.0	25.2
Aluminum alloy 7075	14.4	26.0
TORLON 4203L	17.0	30.6

*The CLTE data for TORLON resins were determined per ASTM D 696, over a temperature range of 75-300°F (24-149°C). CLTE data for metals are from the CRC Handbook of Chemistry and Physics, 54th ed. and Materials Engineering, 1984 Materials Selector edition, Dec. 1983.

Creep Resistance

A limitation of most plastics is deformation under stress, commonly called creep. TORLON polyamide-imide resists creep, and handles stress more like a metal than a plastic. To get measurable creep, TORLON polymer must be stressed beyond the ultimate strength of most other plastics. The designer must consider the long-term creep behavior of plastics under the expected stress and temperature conditions of the proposed application. Figures 19 through 23 summarize selected data from tensile creep tests (ASTM D2990) at applied stresses of 5,000, 10,000, and 15,000 psi (34.5, 68.9, and 103.4 MPa) at room temperature.

Figure 19

TORLON 4203L Strain vs. Time at 73°F (23°C)

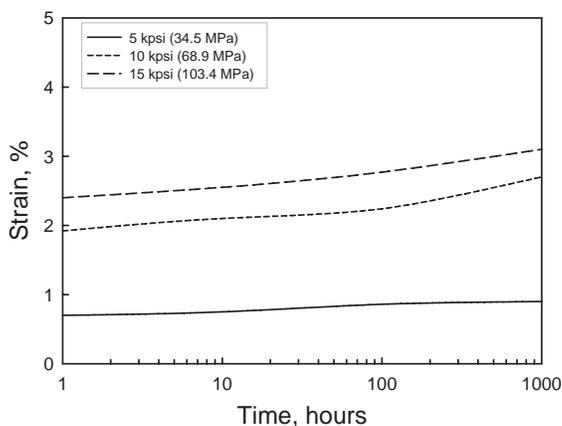


Figure 20

TORLON 4275 Strain vs. Time at 73°F (23°C)

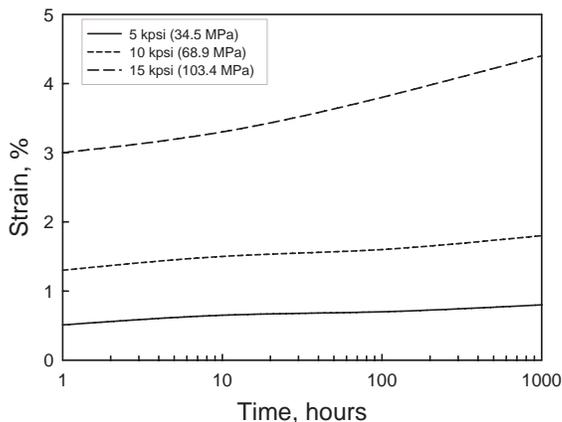


Figure 21

TORLON 4301 Strain vs. Time at 73°F (23°C)

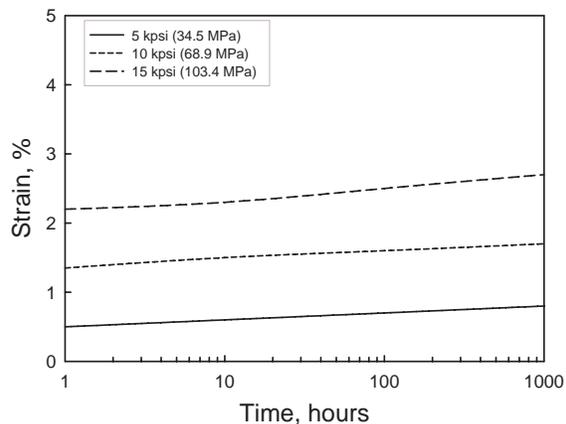


Figure 22

TORLON 5030 Strain vs. Time at 73°F (23°C)

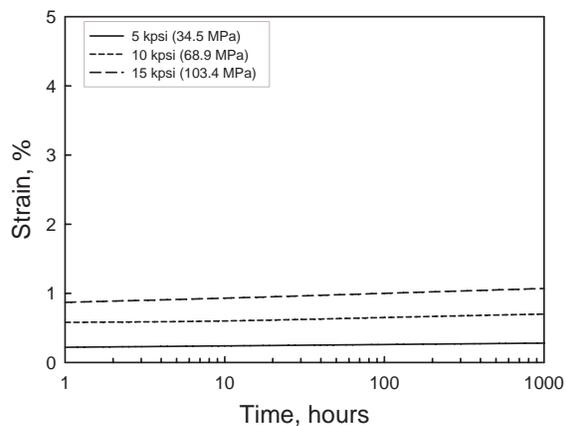
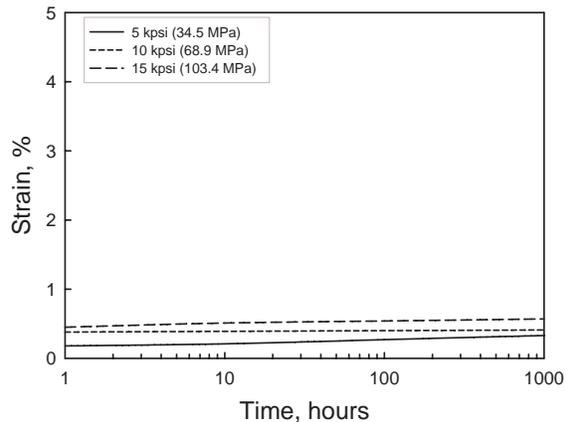


Figure 23

TORLON 7130 Strain vs. Time at 73°F (23°C)



Figures 24 through 28 show this data for tests performed at 400°F (204°C).

Non-reinforced TORLON grades may creep or rupture at extremely high temperatures – over 400°F (204°C) – when stress exceeds 5,000 psi (34.5 MPa). For these applications, a reinforced grade is recommended.

Figure 26

TORLON 4301 Strain vs. Time at 400°F (204°C)

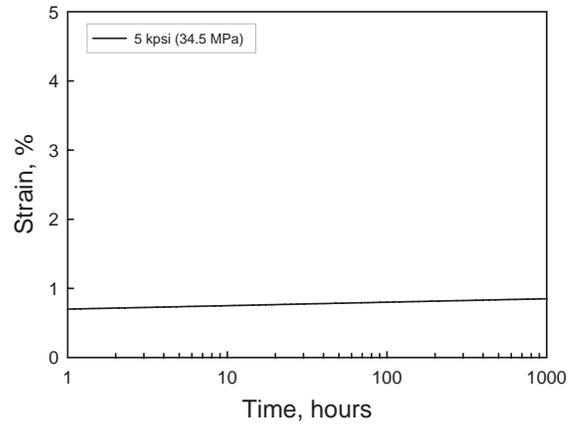


Figure 24

TORLON 4203L Strain vs. Time at 400°F (204°C)

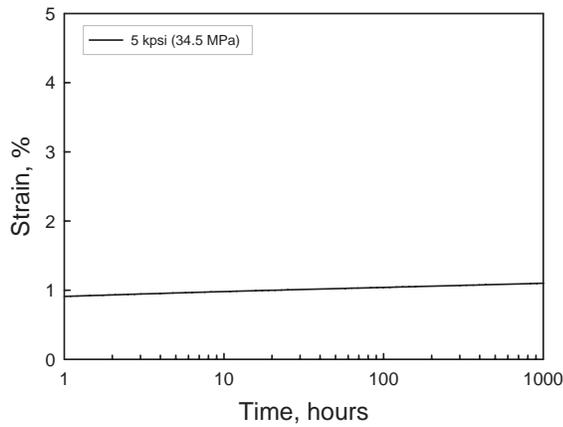


Figure 27

TORLON 5030 Strain vs. Time at 400°F (204°C)

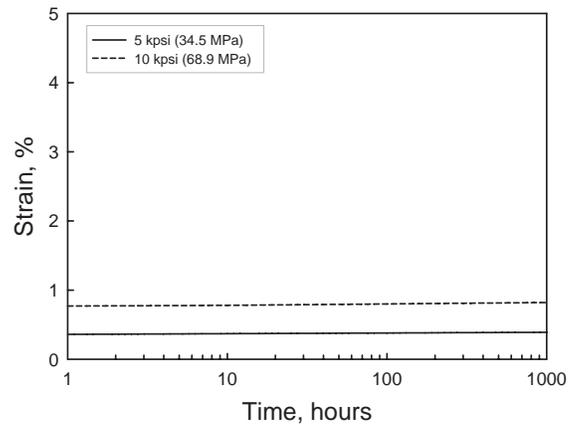


Figure 25

TORLON 4275 Strain vs. Time at 400°F (204°C)

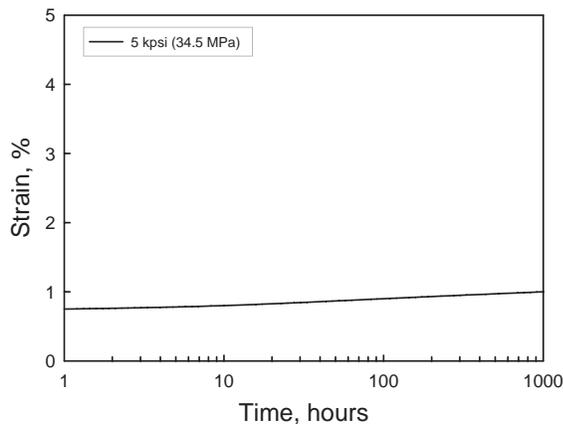
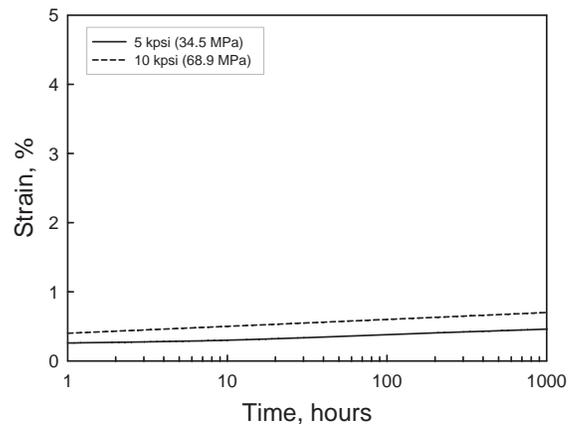


Figure 28

TORLON 7130 Strain vs. Time at 400°F (204°C)



Flammability

Test data indicate the suitability of TORLON parts for electrical, electronic, aerospace, and other applications where flammability is of great concern. TORLON 5030 and 7130 exceed FAA requirements for flammability, smoke density, and toxic gas emission, and surpass, by a large margin, the proposed requirements for aircraft interior use.

Oxygen Index

The oxygen index is defined by ASTM D 2863 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 percent 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. The oxygen indices of several TORLON resins are shown in Table 14. The high values indicate a high degree of combustion resistance.

Table 14

Oxygen Index, ASTM D2863

TORLON Grade	Oxygen Index, %
4203L	45
4301	44
4275	45
5030	51
7130	52

NBS 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 E 662 provides a standard technique for evaluating relative smoke density. This test was originally developed by the National Bureau of Standards (NBS), and is often referred to as the NBS Smoke Density test.

TORLON resins were tested using both the smoldering and flaming modes. The results are shown in Table 15.

Table 15

NBS Smoke Density

NFPA 258. Specimen thickness 0.05-0.06 inch (1.3-1.5 mm)

Sm= Smoldering, Fl = Flaming

	TORLON 4203L		TORLON 5030		TORLON 7130	
	Sm	Fl	Sm	Fl	Sm	Fl
Minimum light transmittance T_M , %	92	6	96	56	95	28
Maximum specific optical density (D_m)	5	170	2	35	3	75
Time to 90% D_m , minutes	18.5	18.6	10.7	15.7	17.0	16.0

Toxic Gas Emission Test

Table 16

FAA Toxic Gas Emission Test

National Bureau of Standards, NFPA 258

Specimen thickness 0.05-0.06 inch (1.3-1.5 mm)

Sm= Smoldering, Fl = Flaming

	TORLON 5030		TORLON 7130	
	Sm ppm	Fl ppm	Sm ppm	Fl ppm
Hydrochloric acid	0	<1	0	<1
Hydrofluoric acid	0	0	0	0
Carbon monoxide	<10	120	<10	100
Nitrogen oxides	<2	19	0	14
Hydrocyanic acid	0	4	0	5
Sulfur dioxide	0	0	0	4

Ignition Properties

The ignition properties of TORLON 4203L resin were measured using ASTM Test Method D 1929 and the results are shown in Table 17.

Flash ignition temperature is defined as the lowest temperature of air passing around the specimen at which a sufficient amount of combustible gas is evolved to be ignited by a small external pilot flame.

Self-ignition temperature is defined as the lowest temperature of air passing around the specimen 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.

These values can be used to rank materials according to their ignition susceptibility.

Table 17

Ignition Properties of TORLON 4203L		
ASTM D1929	°F	°C
Flash ignition temperature	1058°F	570°C
Self ignition temperature	1148°F	620°C

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*.

Horizontal Burning Test

For a 94HB classification rating, injection molded test specimens are limited to a 5.0 in. (125 mm) length, 0.5 in. (13 mm) 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-degree 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 in length, 13 mm in width, and the minimum thickness at which the rating is desired (typically 0.8 mm or 1.57 mm).

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 18 lists the criteria by which a material is classified in this test.

Table 18

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)	≤ 10s	≤ 30s	≤ 30s
Total afterflame time for any condition set ($t_1 + t_2$ for the 5 specimens)	≤ 50s	≤ 250s	≤ 250s
Afterflame plus afterglow time for each individual specimen after the second flame application ($t_2 + t_3$)	≤ 30s	≤ 60s	≤ 60s
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 19 gives the ratings of selected grades of TORLON resins. The most current ratings of TORLON resins can be found at the Underwriters' Laboratories web site at <http://data.ul.com/iqlink/index.asp>.

Table 19

Vertical Flammability by Underwriters' Laboratories (UL 94)

Grade	Thickness		UL 94 Rating
	in.	mm	
4203, 4203L	0.047	1.2	V-0
	0.094	2.4	V-0
	0.118	3.0	V-0
4301	0.047	1.2	V-0
	0.094	2.4	V-0
	0.118	3.0	V-0
5030	0.047	1.2	V-0
	0.059	1.5	V-0
	0.094	2.4	V-0
	0.118	3.0	V-0

FAA Flammability

TORLON 5030 and 7130 were tested by the FAA vertical Flammability test for Transport Category Airplanes as described in 25.853(a) and Appendix F. The results are shown in Table 20.

Samples of TORLON 5030 and 7130 were also tested for horizontal flammability (FAA Transport Category Airplanes, 25.853(b-3) and Appendix F) and 45 flammability (FAA Cargo and Baggage Compartment, 25.855(1-a)). In both cases, the test specimens did not ignite. Based on that result, TORLON 5030 and 7130 meet the requirements of these codes.

Table 20

FAA Vertical Flammability

Grade	Average burn length	
	in.	mm
TORLON 5030	0.6	15.2
TORLON 7130	0.6	15.2

UL 57 Electric Lighting Fixtures

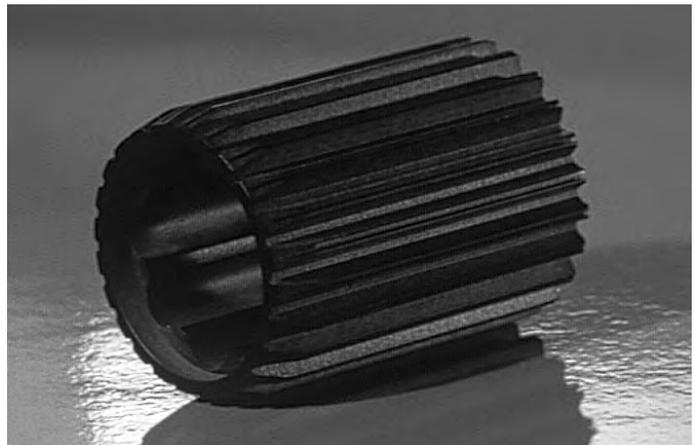
Torlon 4203L resin was tested for conformance to the flammability requirements of this standard. The results shown in Table 21 show that the requirements are met.

Table 21

Electric Lighting Fixtures, Flammability Requirements, UL 57

Grade	Test Results
TORLON 4203L	Noncombustible by Section 81.12. for thickness of 0.040, 0.125 and 0.200 inches (1.02, 3.18, 5.08 mm)

Note: The test methods used to obtain the data in this section measure response to heat and flame under controlled laboratory conditions detailed in the test method specified and may not provide an accurate measure of fire hazard under actual fire conditions. Furthermore, as Solvay Advanced Polymers has no control over final formulation by the user of these resins including components incorporated either internally or externally, nor over processing conditions or final physical form or shape, these results may not be directly applicable to the intended end use.



Performance in Various Environments

Chemical Resistance

TORLON polyamide-imide is virtually unaffected by aliphatic and aromatic hydrocarbons, chlorinated and fluorinated hydrocarbons, and most acids at moderate temperatures. The polymer, however, may be attacked by saturated steam, strong bases, and some high-temperature acid systems. The effects of a number of specific chemicals on the tensile strength of TORLON 4203L are presented in Table 22. Proper post-cure of TORLON parts is necessary to achieve optimal chemical resistance.



Table 22

Chemical Resistance of TORLON 4203L, 24 hr at 200°F (93°C)

(except where noted otherwise)

Chemical	Rating	Chemical	Rating
Acids			
Acetic acid (10%)	A	Ethylene diamine	F
Glacial acetic acid	A	Morpholine	A
Acetic anhydride	A	Pyridine	F
Lactic acid	A	Aldehydes & ketones	
Benzene sulfonic acid	F	Acetophenone	A
Chromic acid (10%)	A	Benzaldehyde	A
Formic acid (88%)	C	Cyclohexanone	A
Hydrochloric acid (10%)	A	Formaldehyde (37%)	A
Hydrochloric acid (37%)	A	Furfural	C
Hydrofluoric acid (40%)	F	Methyl ethyl ketone	A
Phosphoric acid (35%)	A	Chlorinated organics	
Sulfuric acid (30%)	A	Acetyl chloride (120°F)	A
Bases			
Ammonium hydroxide (28%)	C	Benzyl chloride (120°F)	A
Sodium hydroxide (15%)	F	Carbon tetrachloride	A
Sodium hydroxide (30%)	F	Chlorobenzene	A
Aqueous solutions (10%)			
Aluminum sulfate	A	2-Chloroethanol	A
Ammonium chloride	A	Chloroform (120°F)	A
Ammonium nitrate	A	Epichlorohydrin	A
Barium chloride	A	Ethylene chloride	A
Bromine (saturated solution, 120°F)	A	Esters	
Calcium chloride	A	Amyl acetate	A
Calcium nitrate	A	Butyl acetate	A
Ferric chloride	A	Butyl phthalate	A
Magnesium chloride	A	Ethyl acetate	A
Potassium permanganate	A	Ethers	
Sodium bicarbonate	A	Butyl ether	A
Silver chloride	A	Cellosolve	A
Sodium carbonate	A	P-Dioxane (120°F)	A
Sodium chloride	A	Tetrahydrofuran	A
Sodium chromate	A	Hydrocarbons	
Sodium hypochlorite	A	Cyclohexane	A
Sodium sulfate	A	Diesel fuel	A
Sodium sulfide	A	Gasoline (120°F)	A
Sodium Sulfite	A	Heptane	A
Alcohols			
2-Aminoethanol	F	Mineral oil	A
n-amyl alcohol	A	Motor oil	A
n-butyl alcohol	A	Stoddard solvent	A
Cyclohexanol	A	Toluene	A
Ethylene glycol	A	Nitriles	
Amines			
Aniline	A	Acetonitrile	A
n-Butyl amine	A	Benzonitrile	A
Dimethylaniline	A	Nitro compounds	
		Nitrobenzene	A
		Nitromethane	A
		Miscellaneous	
		Cresyldiphenyl phosphate	A
		Sulfolane	A
		Triphenylphosphite	A

Key to Compatibility Ratings

- A - Excellent – no attack, negligible effect on mechanical properties.
- B - Good – slight attack, small reduction in mechanical properties.
- C - Fair – moderate attack, material will have limited life.
- F - Poor – material will fail, decompose, or dissolve in a short time.

Resistance To Automotive and Aviation Fluids

Of particular interest to aerospace and automotive engineers is the ability of a polymer to maintain its properties after exposure to commonly used fluids. Total immersion tests show TORLON polyamide-imide is not affected by common lubricating fluids at 300°F (149°C), aircraft hydraulic fluid at low temperatures, and turbine oil, even under stress at elevated temperatures. At 275°F (135°C), aircraft hydraulic fluid reduces strength slightly. Tables 23 and 25 summarize the methods and results of specific fluid immersion tests.

Automotive Lubricating Fluids

ASTM D790 specimens were tested at room temperature after immersion in 300°F (149°C) lubricating fluids for one month. TORLON 4203L and 4275 have excellent property retention under these conditions (Table 23).

Table 23

Property Retention After Immersion in Automotive Lubricating Fluids at 300°F (149°C)

Tested at room temperature

Lubricant	TORLON 4203L		TORLON 4275	
	Weight change %	Flexural strength retained, %	Weight change %	Flexural strength retained, %
Motor oil ¹	0.0	99.4	0.0	95.5
Transmission fluid ²	0.0	100.3	0.0	94.2
Gear lube ³	+0.2	102.7	+0.2	100.6
¹ Valvoline SAE 20W	² Exxon 11933		³ Penzoil 80W-90	

In a separate experiment, TORLON 4301 and TORLON 4275 were exposed to 3 different versions of FORD automatic transmission fluid for 1,500 hours at 302°F (150°C). After exposure, the tensile strength and flexural modulus was determined and compared to the values obtained before exposure. The results shown in Table 24 indicate excellent resistance to degradation by these fluids.

Table 24

Effect of FORD ATF after 1,500 hours at 302°F (150°C)

Fluid	Tensile Strength Retained, %		Flex Modulus Retained, %	
	TORLON 4301	TORLON 4275	TORLON 4301	TORLON 4275
1	87	95	97	93
2	89	88	93	96
3	85	97	94	92

Aircraft Hydraulic Fluid (SKYDROL 500B)

TORLON bearing grades 4301 and 4275 were immersed in aircraft hydraulic fluid for 41 days at -108°F (-80°C) and 275°F (135°C). The change in tensile properties is shown in Table 25.

Both TORLON grades were mildly affected by the fluid at 275°F (135°C), showing a loss in tensile strength of about 10 percent. It is noteworthy that this loss was not a result of embrittlement as tensile elongation was maintained. Tests show TORLON 4203L bar specimens resist cracking, softening, and breakage under high stress in aircraft hydraulic fluid. Low temperature testing showed no significant effect on either grade.

Aircraft Turbine Oil, With and Without Stress

TORLON parts have exceptional resistance to Aeroshell® 500 turbine oil⁵ under stress at elevated temperatures. Turbine oil affects TORLON 4203L and 7130 only slightly; after 100 hours of exposure under stress, 4203L maintains more than 80 percent of its ultimate tensile strength at temperatures up to 400°F (204°C) without rupturing, and 7130, a graphite-fiber-reinforced grade, is even better, tolerating stress levels of 80 percent of ultimate at temperatures up to 450°F (232°C).

Table 25

Tensile Strength After Immersion in Aircraft Hydraulic Fluid

Skydrol® 500B		
Grade	Tensile strength, % retained	Elongation, % retained
TORLON 4301		
1,000 hours at 275°F (135°C)	89.6	94.1
1,000 hours at -108°F (-80°C)	94.0	95.8
TORLON 4275		
1,000 hours at 275°F (135°C)	92.7	119.3
1,000 hours at -108°F (-80°C)	101.3	129.8

Skydrol is a registered trademark of Monsanto Company
Tested at room temperature

In another test, without stress, essentially no change in the tensile strengths of TORLON 4203L and 4301 was observed after 1000 hours in Aeroshell®* 500 at 302°F (150°C).

*Aeroshell is a registered trademark of Shell Oil Company.

Chemical Resistance Under Stress

TORLON parts which had been thoroughly post-cured were tested for chemical resistance under stress. Test specimens, 5 x 0.5 x 0.125 inch (12.7 x 1.3 x 0.318 cm) were clamped over a fixture with a 5.0 inch (12.7 cm) radius curved surface. The test chemical was applied to the middle of each specimen for one minute. The application was repeated after one and two hours. Specimens were inspected after 24 hours for breakage, cracking, swelling, and softening.

Resistance to the following chemical environments was tested: aviation gasoline, turbine fuel (Jet A/A-1), hydraulic fluid, methyl ethyl ketone, methylene chloride, 1,1,1 trichloroethane, and toluene. None of the TORLON specimens showed any breakage, cracking, swelling, or softening.

Effects of Water

Like other high-temperature engineering resins and composites, TORLON parts absorb water, but the rate is slow and parts can be rapidly restored to original dimensions and properties by drying.

Absorption Rate

TORLON polyamide-imide must be exposed to high humidity for a long time to absorb a significant amount of water. The rate of absorption depends on polymer grade, temperature, humidity, and part geometry.

Figures 29 and 30 report results obtained with uniform bars 5 x 1/2 x 1/8 inch (127 x 13 x 3 mm). Water absorption is dependent on diffusion into the part and is inversely proportional to part thickness.

Equilibrium Absorption at Constant Humidity

At constant humidity, a TORLON part will absorb an equilibrium amount of water. The levels for a range of relative humidity are shown in Figure 31 using uniform panels whose dimensions were 5 x 1/2 x 1/8 inch (127 x 13 x 3 mm).

Figure 29

Water Absorption of TORLON Polymers at 73°F (23°C), 50% RH

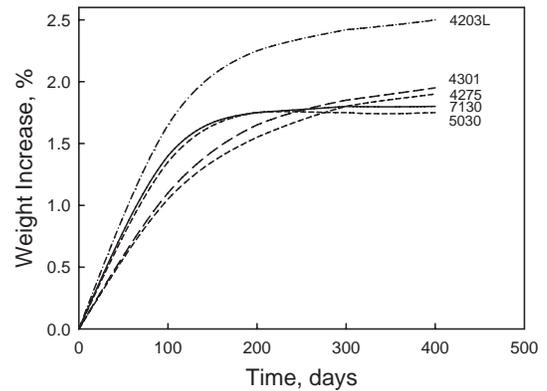


Figure 30

Water Absorption of TORLON Polymers at 110°F (43°C), 90% RH

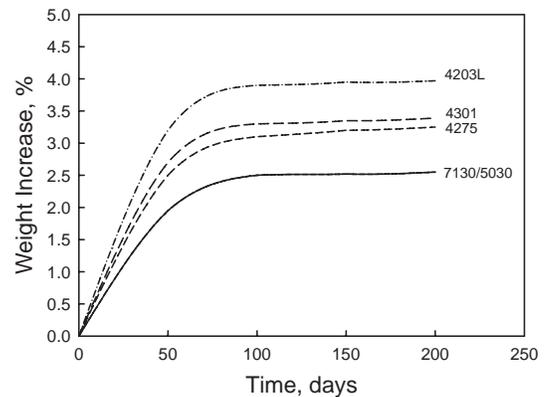
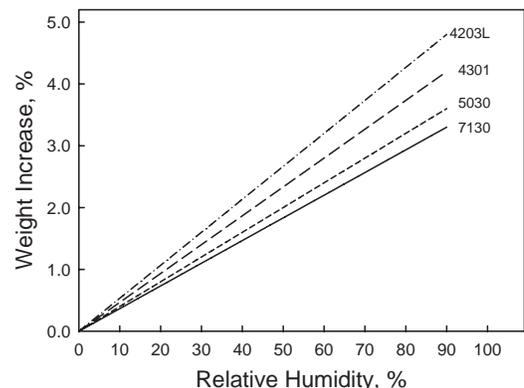


Figure 31

Equilibrium Moisture Absorption vs. Relative Humidity



Dimensional Changes

Small dimensional changes occur as TORLON parts absorb water. Figures 32 and 33 show dimensional changes of the standard test part with exposure to atmospheric moisture at specified temperatures. As with absorption rate, the change is greatest for TORLON 4203L resin, the grade with least filler or reinforcement.

Restoration of Dimensions and Properties

Original dimensions and properties can be restored by drying TORLON parts. The temperature and time required depend on part size and geometry. For the test panels in this study, original dimensions were restored by heating for 16 hours at 300°F (149°C).

Changes in Mechanical and Electrical Properties

To illustrate the change in mechanical properties with water absorption, test specimens were immersed in water until their weight increased by 2 percent. Table 26 compares the properties of these panels with those of panels conditioned for 40 hours at 73°F (23°C) and 50 percent relative humidity. A slight reduction in stiffness is the most noticeable change.

Absorbed water reduces the electrical resistance of TORLON resin and slightly changes dielectric properties. With 2 percent moisture, TORLON specimens had volume and surface resistivities of 1×10^{16} ohm/inch (3×10^{14} ohm/m) and 1×10^{17} ohm respectively, and dielectric strength of 620 V/mil (24 kV/mm).

Figure 32

Dimensional Change of TORLON Polymers at 73°F (23°C), 50% RH

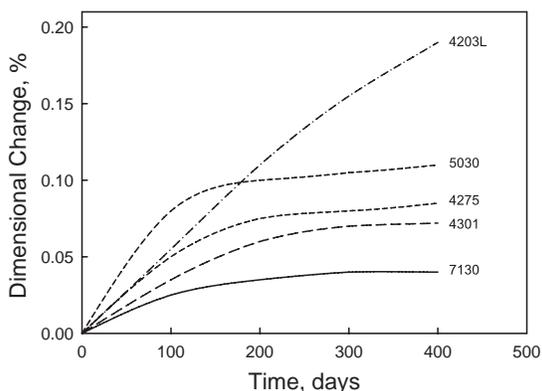


Figure 33

Dimensional Change of TORLON Polymers at 110°F (43°C), 90% RH

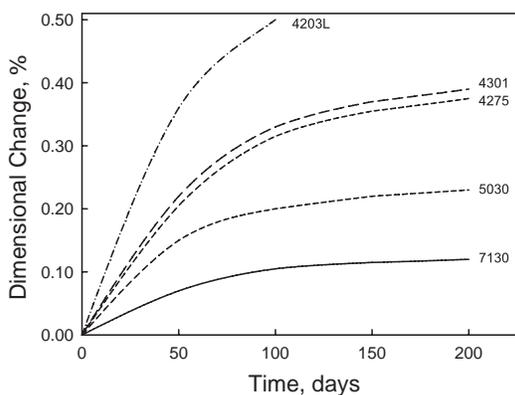


Table 26

Property Change of TORLON 4203L at 2% absorbed water

Property	Change, %
Tensile strength	-7
Tensile modulus	-11
Elongation	13
Shear strength	1
Izod impact strength	20
Dielectric constant	18
Dissipation factor	53

Constraints on Sudden High Temperature Exposure

Absorbed water limits the rate at which TORLON parts can be heated. Sudden exposure to high temperature can distort or blister parts unless absorbed water is allowed to diffuse from the part. Solvay Advanced Polymers uses the term “thermal shock temperature” to designate the temperature at which any distortion occurs upon sudden exposure to heat.

To determine the thermal shock temperature, test specimens 5 x ½ x ⅛ inch (127 x 13 x 3 mm) are exposed to 57.8 percent relative humidity and 73°F (23°C) over a specified period of time. The TORLON resin will absorb water. The amount absorbed will depend upon the exposure time and the grade of TORLON resin. The dimensions of the bars are measured and recorded.

The bars are then placed in a circulating air oven preheated to the test temperature. After one hour, the samples are removed, visually inspected, and measured. Failure occurs if blisters or bubbles appear or if dimensions increase by more than 0.001 inch (0.025 mm). The lowest temperature at which failure is seen is designated the thermal shock temperature.

Figure 34 relates thermal shock temperature to moisture content for TORLON 4203L, the grade most sensitive to water absorption. At 2½ percent absorbed water (which is equilibrium at 50 percent relative humidity and room temperature) the thermal shock temperature is well over 400°F (204°C). Thermal shock is related to exposure time in Figure 35. Even after over 200 hours at 57.8 percent relative humidity and 73°F (23°C), the test part made with TORLON 4203L did not distort until sudden exposure to over 400°F (204°C). Other grades of TORLON resin exhibit lower equilibrium water absorption (refer to Figure 31) and their thermal shock temperatures are therefore higher. Thermal shock temperature can be restored to its highest level by drying at 300°F (149°C) for 24 hours for each ⅛ inch (3 mm) of part thickness.

Figure 34

Thermal Shock Temperature vs. Moisture Content of TORLON 4203L

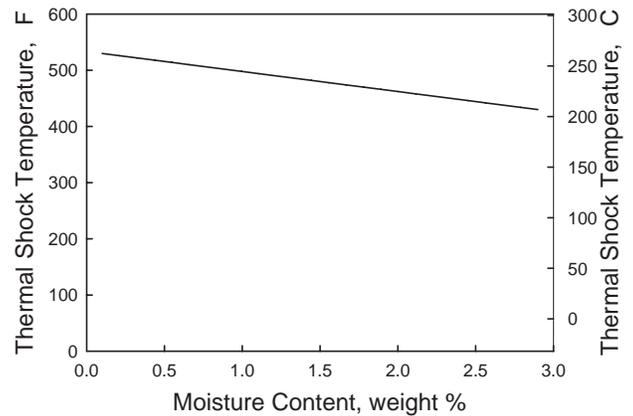
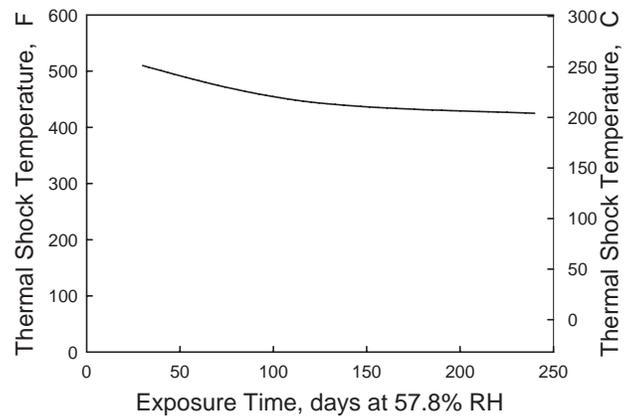


Figure 35

Thermal Shock Temperature vs. Exposure Time for TORLON 4203L



Weather-Ometer® Testing

TORLON molding polymers are exceptionally resistant to degradation by ultraviolet light. TORLON 4203L resin did not degrade after 6,000 hours of Weather-Ometer exposure (Figures 36 and 37) which is roughly equivalent to five years of outdoor exposure. The bearing grades, such as 4301, contain graphite powder which renders the material black and screens UV radiation. These grades are even more resistant to degradation from outdoor exposure.

Tensile bars conforming to ASTM test method D 1708 were exposed in an Atlas Sunshine Carbon Arc Weather-Ometer. Bars were removed after various exposure periods and tensile strength and elongation were determined. The test conditions were a black panel temperature of 145°F (63°C), 50 percent relative humidity and an 18-minute water spray every 102 minutes.

Resistance to Gamma Radiation

Figure 38 shows the negligible effect gamma radiation has on TORLON polyamide-imide — only about 5 percent loss in tensile strength after exposure to 10^9 rads.



Figure 36

The Elongation of TORLON 4203L is Essentially Constant after Exposure to Simulated Weathering

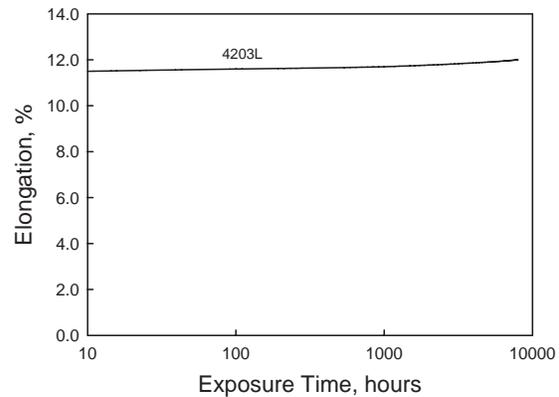


Figure 37

Change in Tensile Strength of TORLON 4203L With Exposure to Simulated Weathering

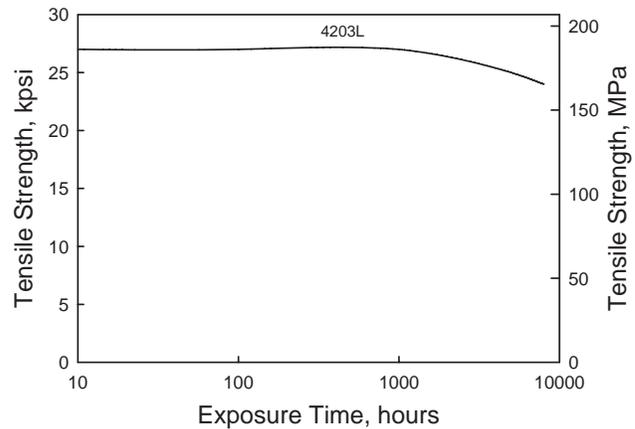
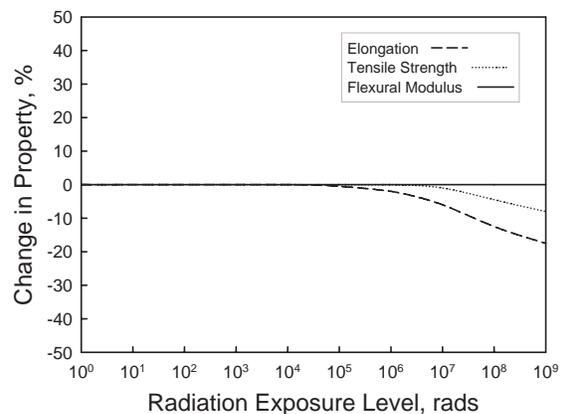


Figure 38

Properties Change of TORLON 4203L Due to Gamma Radiation



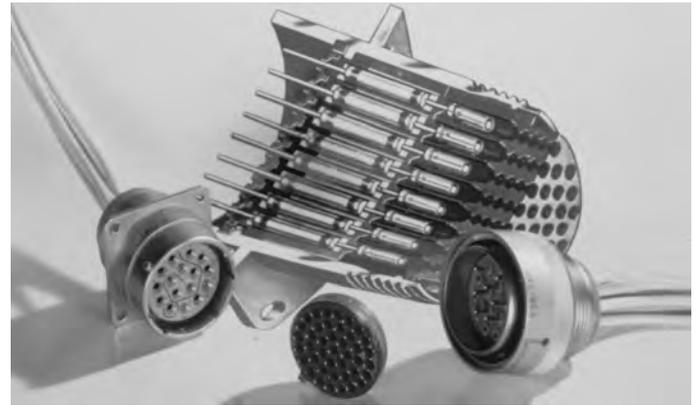
Electrical Properties

Most TORLON grades provide electrical insulation. TORLON polyamide-imide provides a unique combination of high temperature service and ease of moldability into complex electrical and electronic parts. Special grades of TORLON engineering polymer are conductive. TORLON 7130, a conductive grade, effectively shields electromagnetic interference. The design engineer should consider the significant electrical properties of a material, such as those summarized in Table 27.

Table 27

Important Electrical Considerations

Property	ASTM test method	Significance
Dielectric constant	D150	The ratio of the capacity of a condenser filled with the material to the capacity of an evacuated capacitor. It is a measure of the ability of the molecules to become polarized in an electric field. A low dielectric constant indicates low polarizability; thus the material can function as an insulator.
Dissipation factor	DI50	A measure of the dielectric loss (energy dissipated) of alternating current to heat. A low dissipation factor indicates low dielectric loss, while a high dissipation factor indicates high loss of power to the material, which may become hot in use at high frequencies.
Volume resistivity	D257	The electrical resistance of a unit cube calculated by multiplying the resistance in ohms between the faces of the cube by the area of the faces. The higher the volume resistivity, the better the material will function as an insulator.
Surface resistivity	D257	The resistance to electric current along the surface of a one square centimeter sample of material. Higher surface resistivity indicates better insulating properties.
Dielectric strength	D149	A measure of the voltage an insulating material can take before failure (dielectric breakdown). A high dielectric strength indicates the material is a good insulator.



TORLON Polymers for Insulating

TORLON PAI resin has excellent electrical insulating properties and maintains them in a variety of environments. TORLON grades 4203L and 5030 have high dielectric strengths and high volume and surface resistivity as shown in Table 28.

The TORLON polyamide-imide grades intended for wear-resistant applications – 4301, 4275, and 4435 – contain graphite which under some conditions can conduct electricity. Although these materials have high resistivities by the ASTM test method D 257, which uses direct current for its measurements, these materials may demonstrate some conductivity at higher frequencies and voltages.

Table 28

Electrical Properties of TORLON Resins

	TORLON Grade				
	4203L	4301*	4275*	4435*	5030
Volume resistivity (ASTM D257)					
ohm•cm	2 x 10 ¹⁷	8 x 10 ¹⁵	8 x 10 ¹⁵	2 x 10 ⁷	2 x 10 ¹⁷
Surface resistivity (ASTM D257)					
ohm	5 x 10 ¹⁸	8 x 10 ¹⁷	4 x 10 ¹⁷	6 x 10 ¹⁰	1 x 10 ¹⁸
Dielectric strength, 0.040 in (ASTM D 149)					
V/mil	580				840
kV/mm	24				33
Dielectric constant (ASTM D150)					
10 ³ Hz	4.2	6.0	7.3		4.4
10 ⁶ Hz	3.9	5.4	6.6		4.2
Dissipation factor (ASTM D150)					
10 ³ Hz	0.026	0.037	0.059		0.022
10 ⁶ Hz	0.031	0.042	0.063		0.023

*Contains graphite powder. By these tests, they behave as insulators, but they may behave in a more conductive manner at high voltage or high frequency.

Service in Wear-Resistant Applications

An Introduction to TORLON PAI Wear-Resistant Grades

New possibilities in the design of moving parts are made available by TORLON wear-resistant grades: 4301, 4275, and 4435. These materials offer high compressive strength and modulus, excellent creep resistance, and outstanding retention of strength and modulus at elevated temperatures, as well as self-lubricity and low coefficients of thermal expansion, which make them prime candidates for wear surfaces in severe service. TORLON PAI bearings are dependable in lubricated, unlubricated, and marginally lubricated service. Some typical applications which lend themselves to this unique set of properties are plain bearings, thrust washers, seal rings, vanes, valve seats, bushings, and wear pads.

Bearing Design Concepts

Whenever two solids rub against each other, some wear is inevitable. The force pressing the sliding surfaces together (pressure) and the speed at which the sliding occurs (velocity) impact the rate at which wear occurs.

Wear Rate Relationship

The rate at which wear occurs can be related to the pressure and velocity by the following empirical equation:

$$t = KPVT$$

where:

t = wear

K = wear factor determined at a given P and V

P = pressure on bearing surface

V = bearing surface velocity

T = time

This equation seems to suggest that the wear will be directly proportional to the pressure and velocity. That would be true if the wear factor K were constant. For polymeric materials, the wear factor is not constant and varies with the pressure and velocity. The equation is only useful for calculating the wear depth at a particular PV from the wear rate at that PV and the expected service life, corrected for duty factor.

Calculating the Pressure and Velocity

Bearings

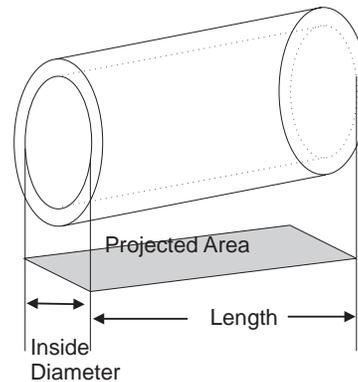
A typical plain bearing application consists of a sleeve bearing around a rotating shaft. To calculate the sliding velocity in feet per minute, multiply the shaft diameter in inches by the revolutions per minute (rpm), and then by 0.262; or to get the velocity in meters per minute, multiply the shaft diameter in millimeters by the rpm, then by 0.003144. For example, a ½-inch shaft rotating at 1200 rpm would have a velocity of 157.2 feet per

minute. Or in the SI system, the 12.7 mm shaft rotating at 1200 rpm, would have a velocity of 47.9 meters per minute or (dividing by 60) 0.8 meters per second.

To calculate the pressure, divide the total load by the area. For sleeve bearings, the projected area is typically used, so the length of the sleeve would be multiplied by the inside diameter of the bearing as shown in Figure 39. In US customary units, the pressure is expressed in pounds per square inch. In the SI system, pressure is usually expressed in Pascals, which is the same as Newtons per square meter.

Figure 39

Calculating Bearing Projected Area

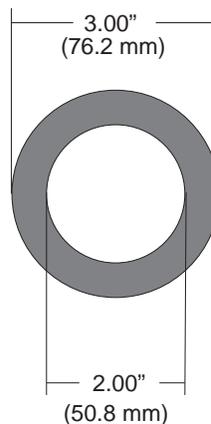


Thrust Washers

To calculate the sliding velocity of a thrust washer application, the mean diameter is typically used to determine the length per revolution. For example, a thrust washer with an outside diameter of 3 inches (76 mm) and an inside diameter of 2 inches (51 mm), would have a mean diameter of 2.5 inches (63.5 mm), and the distance slid per revolution would be obtained by multiplying that diameter by π or 3.14. That value would be multiplied by the rpm and, in the US system, divided by 12 to

Figure 40

Thrust Washer Calculation Example



US Customary Units

$$\begin{aligned} \text{Area} &= \pi \times (3/2)^2 - \pi \times (2/2)^2 \\ \text{Area} &= 3.14 \times (2.25 - 1.0) \\ \text{Area} &= 3.14 \times (1.25) \\ \text{Area} &= 3.925 \text{ in}^2 \end{aligned}$$

SI Units

$$\begin{aligned} \text{Area} &= \pi \times (76.2/2)^2 - \pi \times (50.8/2)^2 \\ \text{Area} &= 3.14 \times (1451 - 645) \\ \text{Area} &= 3.14 \times 806 \\ \text{Area} &= 2531 \text{ mm}^2 \\ \text{Area} &= 0.002531 \text{ m}^2 \end{aligned}$$

get velocity in feet per minute. In the SI system, the mean diameter in millimeters would be multiplied by 3.14 and the rpm, and then divided by 60000 to get velocity in meters per second. To continue the example, assume an rpm of 100, then the velocity in U.S. units is $2.5 \times 3.14 \times 100 \div 12$, or 65.4 feet per minute. In SI units, the velocity would be $63.5 \times 3.14 \times 100 \div 60000$, or 0.33 meters per second.

To calculate the pressure, the total load is divided by the bearing area. Figure 40 depicts the thrust washer used for this example and details the calculation of the bearing area. If the load on the washer is 100 pounds (444.8 Newtons), the pressure would be 100 divided by 3.925 or 25.47 psi. In the SI system, the pressure would be obtained by dividing the 444.8 N by 0.002531 m^2 . The result (175740.8) would have units of N/m^2 , which is defined as the Pascal (Pa). Dividing this value by 10^6 gives a value of 0.1757 MPa.

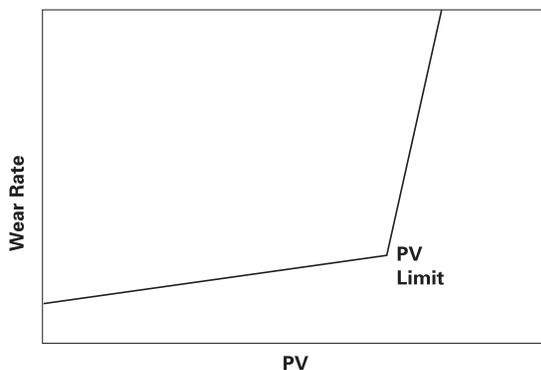
For this example, the PV would be 1666 ft-lb/in²min or 0.058 MPa-m/s.

PV Limit Concept

Either increasing the pressure or the velocity will cause added friction and subsequently additional frictional heat. Because the properties of polymeric materials vary with temperature, the product of the pressure and velocity is useful for predicting the performance of a polymeric bearing material. If a polymeric bearing material is tested at varying pressures and velocities, and the results related to the pressure-velocity product (PV), the behavior shown in Figure 41 is typical. At low to moderate PV's, wear is low. As the PV is increased, at some point the wear becomes rapid. The PV at which this transition occurs is commonly called the PV limit or limiting PV. Due to heat of friction, bearings in service above the PV limit of the material wear very rapidly and may actually melt.

Figure 41

Material wear rate is a function of the Pressure-Velocity (PV) product



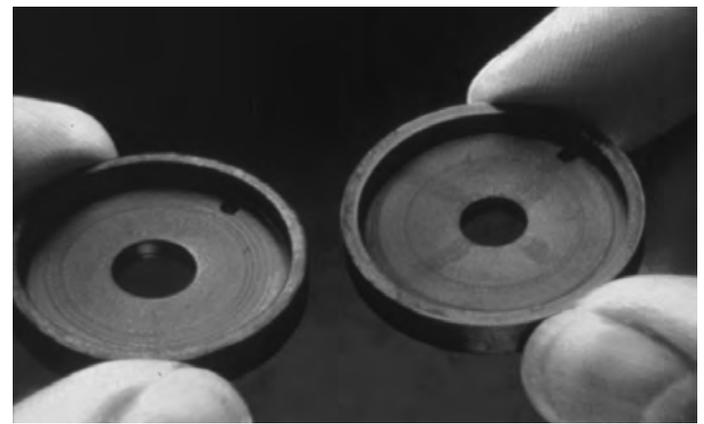
Measuring Wear Resistance

There are a variety of methods for evaluating relative wear resistance. Because of the large number of independent variables, there is little correlation between methods.

The method used for the wear resistance data in this document was ASTM D 3702, using a manual thrust bearing, 3-pin machine. The test specimens were prepared by injection molding a disc and machining it to the final configuration shown in Figure 42.

Figure 42

Thrust Washer Test Specimen



The samples were tested against a stationary washer made of AISI C-1018 steel having a surface finish of 16 μin . Testing was performed at ambient temperature and humidity without any external lubrication. Thrust washer specimens were broken in to remove any surface irregularities at a velocity of 200 ft/min and a pressure of 125 psi for a period of 20 hours. Then each sample was tested at the specified velocity and pressure for 20 hours. Height measurements were taken before and after at 4 equidistant points on the thrust washer disk and the average wear depth in inches was reported and used in the calculation of the wear factor.

TORLON Wear-Resistant Grades

Three grades of TORLON PAI have been compounded with additives to improve their resistance to wear in unlubricated service. These grades are 4301, 4275, and 4435.

Low wear factors (K) are characteristic of wear resistant materials. Fluoropolymers, which have low coefficients of friction, have very low wear factors, but limited mechanical properties and poor creep resistance. At low PV's, TORLON wear resistant grades have wear factors comparable to filled polytetrafluoroethylene (pTFE), a fluoropolymer, but TORLON polymers offer superior creep resistance and strength.

TORLON polymers have wear factors similar to those of more expensive polyimide resins, and there is a distinct cost advantage in choosing TORLON polyamide-imide. In addition, TORLON resins are injection moldable; polyimides are not.

The wear factors obtained when the three wear resistant grades of TORLON PAI were tested at various PV's are shown in Table 31.

Table 31

Wear Factors and Wear Rates

U.S. Units

Velocity - 50 ft/min		Wear Factor, 10 ⁻¹⁰ in ³ -min/ft-lb-hr					Wear Rate, 10 ⁻⁶ in/hr				
		TORLON			Vespel®	PEEK™	TORLON			Vespel®	PEEK™
Pressure, psi	PV	4301	4275	4435	SP-21	X50FC30	4301	4275	4435	SP-21	X50FC30
200	10000	17	8	NT	19	45	17	8	NT	19	45
500	25000	42	49	NT	52	129	105	122.5	NT	130	322
1000	50000	82	55	27	38	249	410	275	135	190	1245
1500	75000	NT	28	20	28	melted	NT	210	150	210	melted
2000	100000	NT	24	20	cracked	NT	NT	240	200	cracked	NT
Velocity - 200 ft/min											
50	10000	17	18	NT	18	74	17	18	NT	18	74
125	25000	83	39	98	104	69	208	98	245	260	172
250	50000	156	74	33	47	168	780	370	165	235	840
375	75000	NT	222	21	36	168	NT	1665	158	270	1260
500	100000	NT	melted	20	28	melted	NT	melted	200	280	melted
Velocity - 800 ft/min											
12.5	10000	95	13	NT	52	21	95	13		52	21
31.25	25000	385	69		69	154	962	172		172	385
62.5	50000	896	118	92	63	1419	4480	590	460	315	7095
93.75	75000	NT	214	77	52	melted	NT	1605	578	390	melted
125	100000	NT	melted	52	40	NT	NT	melted	520	400	NT

SI Units

Velocity - 0.25 m/s		Wear Factor, 10 ⁻¹⁰ mm-s/mPa-hr					Wear Rate, 10 ⁻⁶ m/hr				
		TORLON			Vespel®	PEEK™	TORLON			Vespel®	PEEK™
Pressure, MPa	PV	4301	4275	4435	SP-21	X50FC30	4301	4275	4435	SP-21	X50FC30
1.379	0.350	8	6	NT	14	33	0.3	0.2	NT	0.5	1.1
3.447	0.876	30	36	NT	38	94	2.7	3.1	NT	3.3	8.2
6.895	1.751	59	40	20	28	181	10.4	7.0	3.4	4.8	31.6
10.342	2.627	NT	20	15	20	melted	NT	5.3	3.8	5.3	melted
13.790	3.503	NT	17	15	cracked	NT	NT	6.1	5.1	cracked	NT
Velocity - 1.02 m/s											
0.345	0.350	12	13	NT	13	54	0.4	0.5	NT	0.5	1.9
0.862	0.876	60	28	71	75	50	5.3	2.5	6.2	6.6	4.4
1.724	1.751	113	54	24	34	122	19.8	9.4	4.2	6.0	21.3
2.586	2.627	NT	126	15	26	122	NT	33.1	4.0	6.9	32.0
3.447	3.503	NT	melted	15	20	melted	NT	melted	5.1	7.1	melted
Velocity - 4.06 m/s											
0.086	0.350	69	9	NT	38	15	2.4	0.3	NT	1.3	0.5
0.215	0.876	102	50	NT	50	112	8.9	4.4	NT	4.4	9.8
0.431	1.751	135	86	67	46	1030	23.6	15.0	11.7	8.0	180.2
0.646	2.627	NT	155	56	38	melted	NT	40.8	14.7	9.9	melted
0.862	3.503	NT	melted	38	29	NT	NT	melted	13.2	10.2	NT

These data which are plotted in Figures 43 through 45 clearly show that TORLON 4435 has superior wear resistance over a wide PV range.

Figure 43

Wear Resistance at Low Velocity

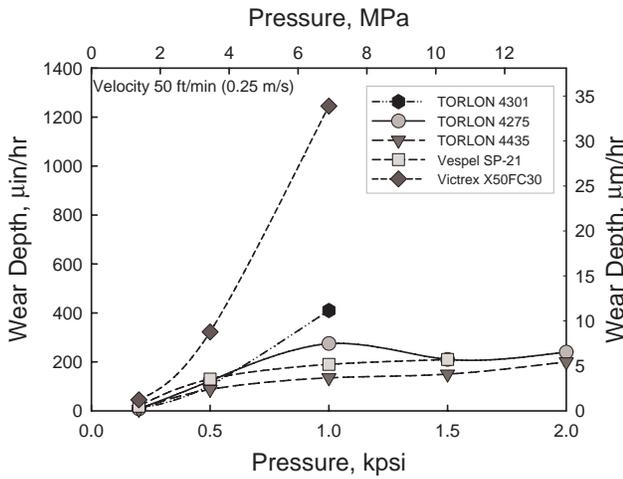


Figure 44

Wear Resistance at Moderate Velocity

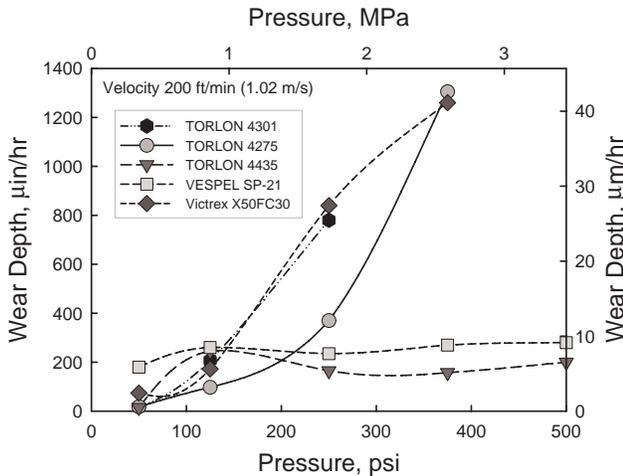
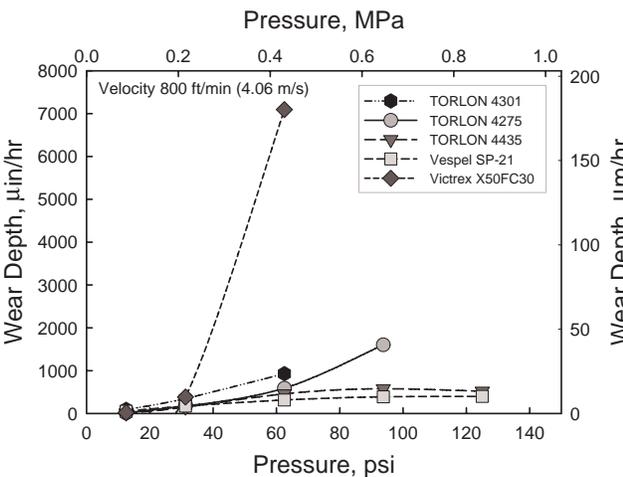


Figure 45

Wear Resistance at High Velocity



Effect of Mating Surface on Wear Rate

The wear data presented in Table 31 and Figures 43 through 45 were determined using C1018 steel hardened to 24 on the Rockwell C scale. Other metals were tested against TORLON 4301 to evaluate the effect of the mating surface on wear resistance. The results are shown in Table 32.

Table 32

Wear Characteristics of TORLON 4301 PAI Against Various Metals

Metal used as mating surface for TORLON 4301					
C1018 (Standard)	C1018 Soft	316 Stainless steel	Brass	Aluminum die casting alloys	
				A360	A380
Rockwell hardness, C scale					
24	6	17	-15	-24	-28
Relative Wear Factor at High Velocity					
1.0	1.4	7.5	2.1	1.3	1.2
Relative Wear Factor at Low Velocity					
1.0	1.2	1.2	1.5	1.5	0.9

Lubricated Wear Resistance

The impressive performance of TORLON bearing grades in nonlubricated environments is insurance against catastrophic part failure or seizure upon lube loss in a normally lubricated environment. In a transmission lubricated with hydrocarbon fluid, TORLON thrust washers are performing well at PVs of 1,300,000 ft-lbs/in²-min. In a water-lubricated hydraulic motor vane, excellent performance has been attained at over 2,000,000 PV. Table 33 summarizes the wear characteristics of TORLON 4301 immersed in hydraulic fluid.

Table 33

Lubricated wear resistance of TORLON 4301

PV (P/V = 50/900)	45,000
Wear factor, K (10 ⁻¹⁰ in ³ •min/ft•lb•hr)	1.0
Coefficient of friction, static	0.08
Coefficient of friction, kinetic	0.10
Wear depth at 1,000 hours, in (mm)	0.0045 (0.11 mm)

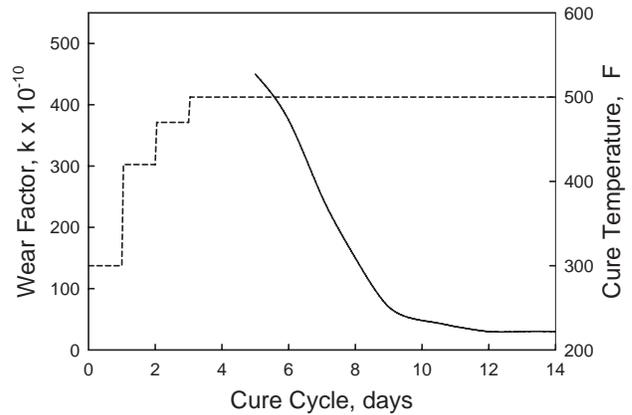
Wear Resistance and Post-Cure

The wear resistance of TORLON parts depends on proper post-cure. A thorough and complete post-cure is necessary to achieve maximum wear resistance. To illustrate the dependence of wear resistance on post-cure, a sample of TORLON 4301 was post-cured through a specified cycle* and tested for wear resistance at various points in time. The results of that test and the cure cycle are shown in Figure 46. In this case, the Wear Factor, K, reached a minimum after eleven days, indicating achievement of maximum wear resistance.

The length of post-cure will depend on part configuration, thickness, and to some extent on molding conditions. Very long exposure to 500°F (260°C) is not detrimental to TORLON parts. The suitability of shorter cycles must be verified experimentally.

Figure 46

Extended Cure at 500°F (260°C) Improves Wear Resistance



Cure cycles are a function of part geometry.



Bearing Design

When designing a bearing to be made of TORLON PAI, it is important to remember that adequate shaft clearance is critical. With metal bearings, high clearances tend to result in shaft vibration and scoring. PAI bearings are much more resilient, dampen vibrations, and resist scoring or galling. The bearing inside diameter will be determined by adding the total running clearance to the shaft outside diameter. The total running clearance is the total of the basic clearance, the adjustment for high ambient temperature, and an adjustment for press fit interference if the bearing is press fit.

Figure 47 shows the basic clearance as a function of shaft diameter. If the bearing is to be used at ambient temperatures greater than room temperature, then the factor shown in Figure 48 should be applied. Figure 49 gives the recommended allowance for using a press fit bearing.

To give an example of how to properly size a PAI bearing, consider this hypothetical situation with a shaft diameter of 2 inches (51 mm) and bearing wall thickness of 0.2 inches (5 mm) to operate at an ambient temperature of 150°F (65°C). The PAI bearing is to be press fit into a steel housing. The basic clearance from Figure 47 is 9 mils or 0.009 inches (0.23 mm). The additional clearance for the elevated ambient temperature is obtained by multiplying the factor from Figure 48 (0.0085) by the wall thickness to obtain 0.0017 inches (0.04 mm). The recommended interference for the press fit is 0.005 inches (0.13 mm). Because the inside diameter of the bearing will be decreased by the amount of the interference, that amount is added to the clearance. Therefore the total clearance will be the basic clearance 0.009 in. + the temperature clearance 0.0017 + the interference 0.005 to give 0.0157 in. (0.40 mm). Therefore the inside diameter of the PAI bearing should be 2.0157 inches (51.2 mm).

Figure 47

Basic Bearing Shaft Clearance

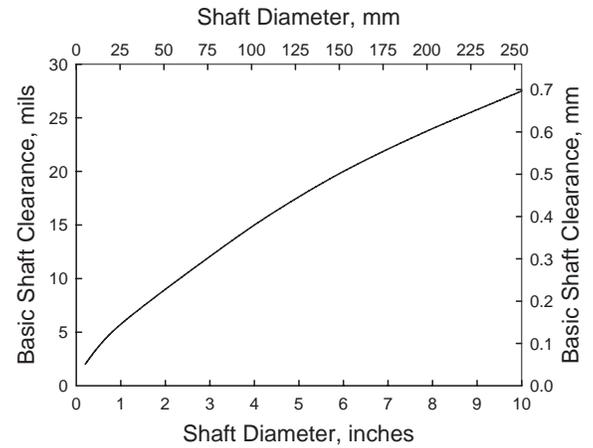


Figure 48

Clearance Factor for Elevated Ambient Temperature

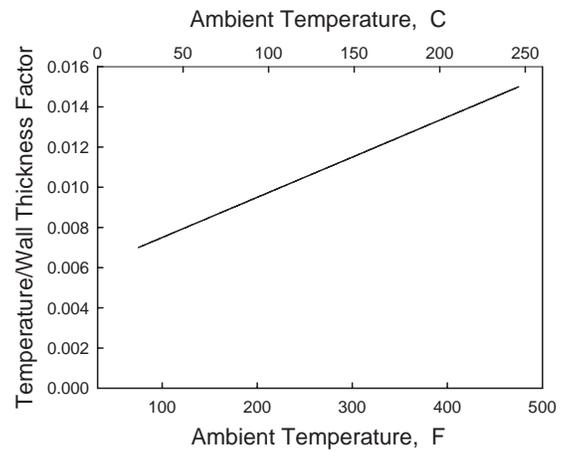
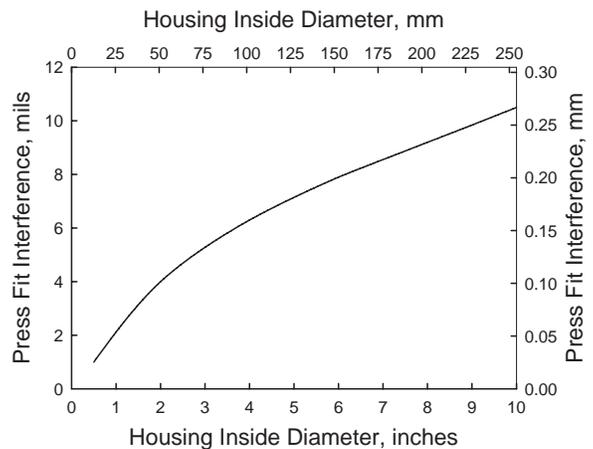


Figure 49

Press Fit Interference



Industry and Agency Approvals

TORLON engineering polymers have been tested successfully against many industry standards and specifications. The following list is a summary of approvals to date, but should not be considered inclusive, as work continues to qualify TORLON polyamide-imide for a myriad of applications.

ASTM D 5204 Standard Classification System for Polyamide-imide (PAI) Molding and Extrusion Materials

TORLON Grade	ASTM D 5204 Designation
4203L	PAI000R03A56316E11FB41
or	PAI011M03
or	PAI021M03
4301	PAI000L15A32232E12FB42
or	PAI012L15
or	PAI022L15
4275	PAI000L23A22133E13FB42
or	PAI012L23
or	PAI022L23
4435	PAI0120
or	PAI0220
5030	PAI000G30A61643E15FB46
or	PAI013G30
or	PAI023G30
7130	PAI000C30A51661FB47
or	PAI013C30
or	PAI023C30

Federal Aviation Administration

TORLON 5030 and 7130 pass FAA requirements for flammability, smoke density, and toxic gas emissions.

Military Specification MIL-P-46179A

This specification was cancelled on July 27, 1994 and ASTM D 5204 was adopted by the Department of Defense. The following cross reference table appears in the adoption notice.

TORLON Grade	Type	Class	ASTM D 5204
4203L	I		PAI000R03A56316E11FB41
4301	II	1	PAI000L15A32232E12FB42
4275	II	2	PAI000L23A22133E13FB42
5030	III	1	PAI000G30A61643E15FB46
7130	IV		PAI000C30A51661FB47

National Aeronautics and Space Administration

NHB8060.1 “Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments that Support Combustion” TORLON 4203L and 4301 have passed the NASA spacecraft materials requirements for non-vacuum exposures per NHB8060.1.

Society of Automotive Engineers-Aerospace Material Specifications

AMS 3670 is the specification for TORLON materials. The specification suggests applications requiring a low coefficient of friction, thermal stability, and toughness up to 482°F (250°C). TORLON 4203L, 4275, 4301, 5030, and 7130 are covered in the detail specifications:

- AMS 3670/1-TORLON 4203L
- AMS 3670/2-TORLON 4275
- AMS 3670/3-TORLON 4301
- AMS 3670/4-TORLON 5030
- AMS 3670/5-TORLON 7130

Underwriters' Laboratories

Vertical Flammability

All TORLON grades have been awarded a 94 V-0 classification. See Table 19 on page 17.

Continuous Use

The Relative Thermal Indices of TORLON 4203L, 4301, and 5030 are shown in Table 9 on page 12.

Structural Design

Material Efficiency—Specific Strength and Modulus

Reducing weight can be the key to lower cost, reduced friction, and decreased energy consumption. When a TORLON engineering polymer replaces metal, the TORLON part can support an equivalent load at significantly lower weight.

The ratio of a material's tensile strength to its density (specific strength) provides information about “material efficiency.” The specific strength of TORLON 5030, for example, is 5.1×10^5 in-lbf/lb (1.3×10^5 J/kg) compared with 3.1×10^5 in-lbf/lb (0.8×10^5 J/kg) for stainless steel. Therefore, a TORLON 5030 part will weigh almost 40% less than a stainless steel part of equivalent strength. Similarly, the specific modulus of a material is of interest when stiffness of the part is crucial to performance.

Comparison of material efficiency data in Table 34 and Figure 50 shows that TORLON PAI can beat the weight of many metal parts.

Table 34

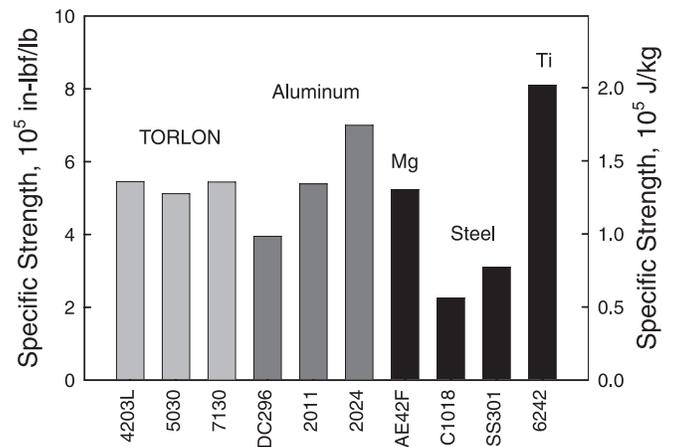
Specific Strength and Modulus of TORLON polymers and Selected Metals

	Specific strength		Specific stiffness	
	10^5 in-lbf/lb	10^5 J/kg	10^7 in-lbf/lb	10^6 J/kg
TORLON 4203L	5.5	1.4	1.4	3.4
TORLON 5030	5.1	1.3	2.7	6.7
TORLON 7130	5.4	1.4	6.0	15.0
Aluminum Alloys, Heat Treated				
Die Casting, A380	3.9	1.0	11.0	26.0
2011	5.4	1.3	10.0	25.0
2024	7.0	1.7	11.0	26.0
Magnesium AE42-F	5.2	1.3	9.8	25.0
Carbon Steel, C1018	2.2	0.6	9.7	24.0
Stainless Steel, 301	3.1	0.8	9.7	24.0
Titanium 6-2-4-2	8.1	2.0	10.0	26.0



Figure 50

Specific Strength of TORLON Resins vs. Metal



Geometry and Load Considerations

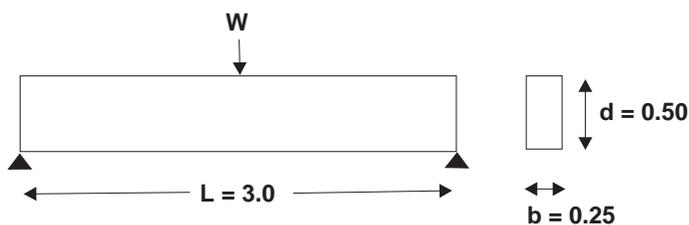
In the early stages of part design, standard stress and deflection formulas should be applied to ensure that maximum working stresses do not exceed recommended limits.

Examples of Stress and Deflection Formula Application

Recommended maximum working stresses for TORLON engineering polymers appear in Table 35 on page 36. To illustrate how these values may be used, the maximum load for a beam made of TORLON 5030 will be calculated under various loading conditions at room temperature. Figure 51 shows the beam dimensions and the calculation of the moment of inertia (I).

Figure 51

Beam used in examples



W = Load, lb

L = Length of beam between supports, in

c = Distance from the outermost point in tension to the neutral axis, in

b = Beam width, in

d = Beam height, in

I = Moment of inertia, in⁴

In this example:

$L = 3.0$ in

$c = 0.25$ in

$b = 0.25$ in

$d = 0.50$ in

$$I = \frac{bd^3}{12} = \frac{(0.25 \text{ in.})(0.50 \text{ in.})^3}{12} = 0.0026 \text{ in}^4$$

M = Load x distance to support, in•lb

Example 1—Short-term loading

The maximum bending stress, S_{\max} , occurs at

$$L/2 \text{ and } M = \frac{WL}{4}$$

$$S_{\max} = \frac{WLc}{4I}$$

Solving for W and substituting the recommended maximum working stress for TORLON 5030 under a short-term load at room temperature:

$$W_{\max} = \frac{4S_{\max}I}{Lc} = \frac{(4)(17800 \text{ psi})(0.0026 \text{ in}^4)}{(3.0 \text{ in.})(0.25 \text{ in.})} = 247 \text{ lb}$$

Therefore, the maximum short-term load for a TORLON 5030 beam at room temperature is approximately 247 pounds.

The maximum deflection for this beam is:

$$Y_{\max} = \frac{WL^3}{48EI} \text{ at } \frac{L}{2}$$

Where E is the flexural modulus of TORLON 5030 obtained from Table 3.

$$Y_{\max} = \frac{(247 \text{ lb})(3.0 \text{ in})^3}{(48)(15.6 \times 10^5 \text{ psi})(0.0026 \text{ in}^4)} = 0.034 \text{ in.}$$

Therefore, the predicted maximum deflection is 0.034 in.

Example 2—Steady load

In this example, the load is long-term. Creep is considered to be the limiting factor. The maximum load which may be applied to the TORLON 5030 beam is:

$$W_{\max} = \frac{4S_{\max}I}{Lc} = \frac{(4)(17000)(0.0026)}{(3.0)(0.25)} = 236 \text{ lb.}$$

To calculate the maximum deflection of the beam under a steady load, the apparent (creep) modulus (E_a) is used rather than the flexural modulus. Because material properties are time dependent, a finite period is selected. In this example, maximum deflection after 100 hours is calculated.

The apparent modulus at 100 hours can be estimated by dividing the steady load recommended maximum working stress from Table 35 by the assumed maximum strain (1.5 percent).

$$E_a = \frac{17000 \text{ psi}}{0.015} = 1.13 \times 10^6 \text{ psi}$$

Substituting:

$$Y_{\max} = \frac{WL^3}{48E_a I} = \frac{(236)(3.0)^3}{(48)(1.13 \times 10^6)(0.0026)} = 0.045 \text{ in.}$$

Maximum deflection at L/2 is predicted to be 0.045 inch.

Example 3-Cyclic load

When materials are stressed cyclically, failures will occur at stress levels lower than the material's ultimate strength due to fatigue. To calculate the maximum cyclic load our beam can handle for a minimum of 10,000,000 cycles:

$$W_{\max} = \frac{4S_{\max} I}{L_c} = \frac{(4)(4550)(0.0026)}{(3.0)(0.25)} = 63 \text{ lb}$$

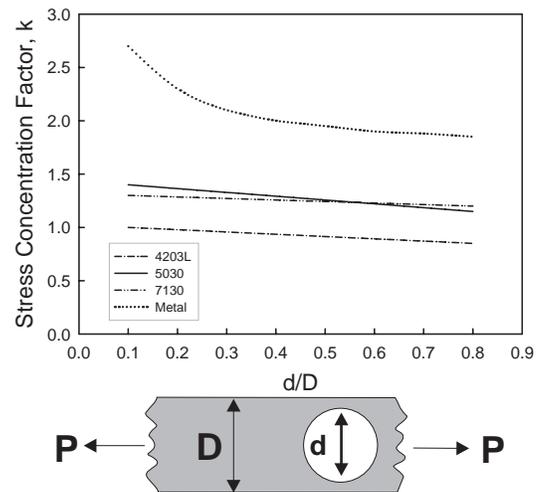
Stress Concentration

Part discontinuities, such as sharp corners and radii, introduce stress concentrations that may result in failure below the recommended maximum working stress. It is, therefore, critical that a part be designed so that the stress field is as evenly distributed as possible.

Circular perforations give rise to stress concentrations, but as Figure 52 demonstrates, TORLON polyamide-imide is less sensitive than metal.

Figure 52

Stress Concentration Factor for Circular Stress Raiser (elastic stress, axial tension)



Maximum Working Stresses for TORLON Resins

End use conditions restrict the allowable working stresses for a structural member. Prototype evaluation is the best method of determining the suitability of TORLON parts. The data summarized in Table 35 are useful early in the design process for use in the engineering equations for the proposed part.

Table 35

Maximum Working Stresses for Injection Molded TORLON Resins

English units (psi)	Temperature, °F	TORLON grade					
		4203L	4301	4275	4435	5030	7130
Short term load	73	17,000	14,000	13,000	9,600	17,800	17,600
	275	10,000	9,800	9,800	7,800	13,900	13,700
	450	5,700	6,400	4,900	4,500	9,800	9,400
Steady load (creep), <1.5% strain, 100 hrs.	73	7,000	10,000	9,500		17,000	17,000
	200	6,500	7,500	7,900		15,000	15,000
	400	5,000	6,000	6,000		10,000	10,000
Cyclic load, 10 ⁷ cycles	73	3,850	3,000	2,800	2,000	4,550	5,250
	275	2,450	2,100	2,100	1,620	3,500	4,200
	450	1,400	1,350	1,050	950	2,450	2,800
SI units (MPa)	Temperature, °C						
Short term load	23	117	96	89	66	122	121
	135	69	67	67	54	96	94
	232	39	44	34	31	67	55
Steady load (creep), <1.5% strain, 100 hrs.	23	48	69	65		117	117
	93	45	52	54		103	103
	204	34	41	41		69	69
Cyclic load, 10 ⁷ cycles	23	26	21	19	14	31	36
	135	17	14	14	11	24	29
	232	10	9	7	6	17	19

Designing with TORLON® Resin

Fabrication Options

TORLON polyamide-imide can be molded using any of three conventional molding techniques; injection, compression and extrusion. Each has advantages and limitations.

Injection Molding

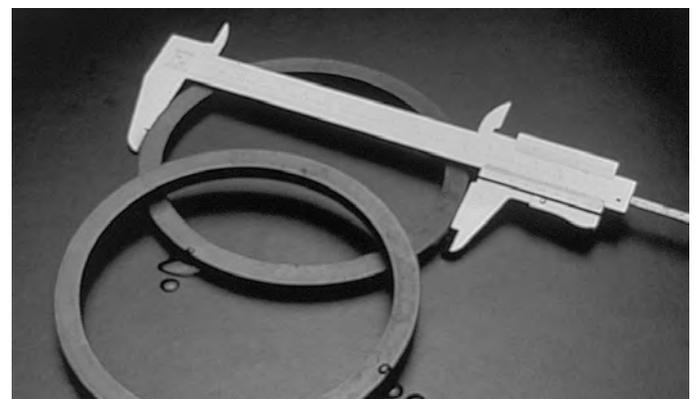
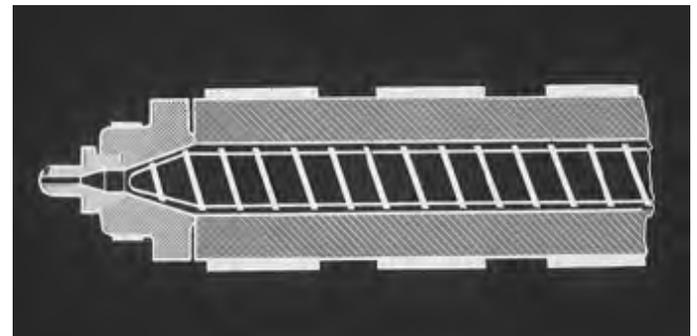
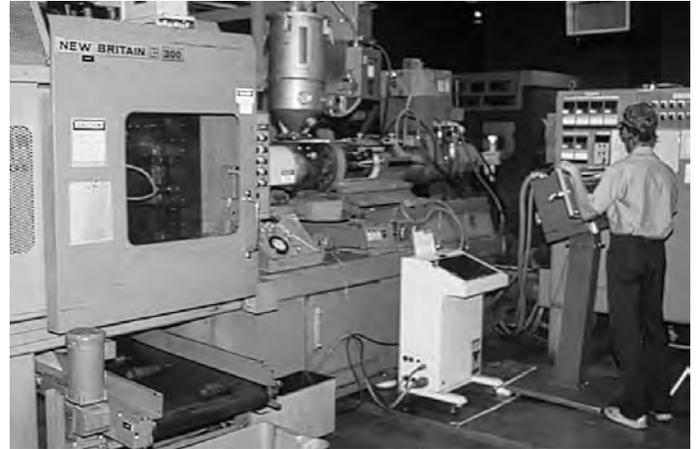
TORLON parts can be injection molded to fine detail. Of the three methods, injection molding produces parts of the highest strength. When a large quantity of complex parts is required, injection molding can be the most economical technique due to short cycle times and excellent replication. Part thickness is limited by the flow length versus thickness relationship of the polymer. Thickness is limited to a maximum of $\frac{5}{8}$ inch (15.9 mm).

Extrusion

TORLON polymers can be extruded into profiles and shapes such as rods, tubing, sheet, film and plates. Small parts with simple geometries can be economically produced by combining extrusion molding and automatic screw machining. TORLON rod and plate stock are available in a variety of sizes. Contact your Solvay Advanced Polymers representative for information on approved sources.

Compression Molding

Large parts over $\frac{5}{8}$ inch (15.9 mm) thick must be compression-molded. Tooling costs are considerably lower compared with other molding techniques. Compression-molded parts will generally be lower in strength than comparable injection-molded or extruded parts, but have lower stresses and are therefore easier to machine. Compression molded rod, OD/ID tube combinations and compression molded plates are available in a variety of sizes and thickness. Contact your Solvay Advanced Polymers representative for information on approved sources.



Post-Curing TORLON Parts

TORLON parts must be post-cured. Optimal properties, especially chemical and wear resistance, are only achieved with thorough post-cure. Best results are obtained when TORLON parts are cured through a cycle of increasing temperature. Cure cycle parameters are a function of the size and geometry of a particular part.

Guidelines for Designing TORLON Parts

TORLON polyamide-imide can be precision molded to fine detail using a wide range of fabricating options. Not only can the designer select a material with outstanding performance, but one which gives him a great deal of design freedom.

The following sections provide guidelines for designing parts with TORLON polyamide-imide.

Wall Section

Whenever feasible, wall thickness should be minimized within the bounds prescribed by the end-use, to shorten cycle time and economize on material. When sections must be molded to thicknesses in excess of 1/2 inch (12.7 mm), parts may incorporate core and rib structures, or special TORLON grades may be used.

For small parts molded with TORLON resin, wall sections generally range from 0.03-0.50 inch (0.8-13 mm), but thicknesses up to 5/8 inch (19.0 mm) are possible with reinforced or bearing grades.

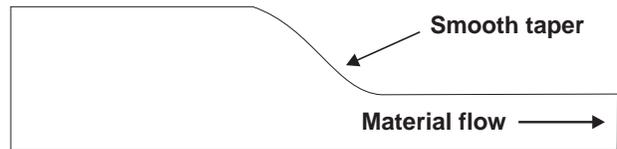
TORLON polyamide-imide has a relatively high melt viscosity, which limits flow length for a given wall thickness. Use of hydraulic accumulators and precise process control reduce the impact of this limitation. Many factors, such as part geometry, flow direction, and severity of flow path changes make it difficult to characterize the relationship between flow length and wall thickness for sections less than 0.050 inch (1.3 mm) thick. We suggest you contact your Solvay Advanced Polymers Technical Representative to discuss the part under consideration.

Wall Transition

Where it is necessary to vary wall thickness, gradual transition is recommended to eliminate distortion and reduce internal stresses. Figure 53 shows the desired method of transition -- a smooth taper. It is better that the material flows from thick to thin sections to avoid molding problems such as sinks and voids.

Figure 53

Gradual Blending Between Different Wall Thicknesses

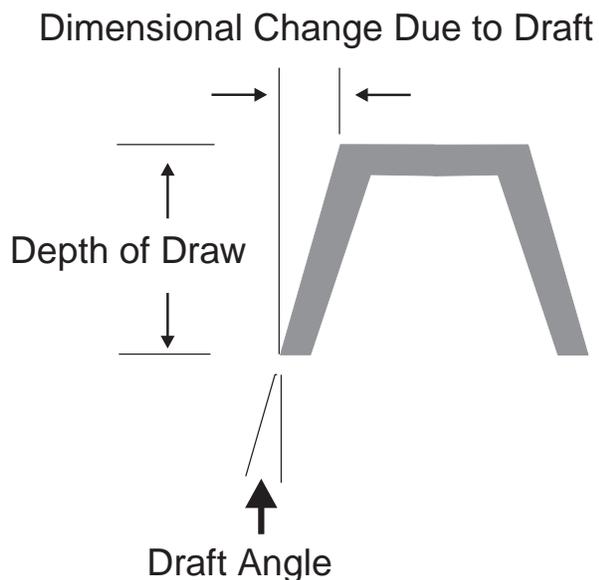


Draft Angle

1/2° to 1° draft should be allowed to facilitate removal of the part from the mold. With TORLON resin, draft angles as low as 1/8° have been used, but such low angles require individual analysis. Draft angle is also dependent on the depth of draw; the greater the depth of draw, the greater the required draft angle (see Figure 54). Part complexity will also affect draft requirements, as will the texture of the finish. A textured finish generally requires 1° per side for every 0.001 inch (0.025 mm) of texture depth.

Figure 54

Draft



Cores

Coring is an effective way to reduce wall thickness in heavy sections. To minimize mold cost, core removal should be parallel to the movement of the platens.

Draft should be added to core design. Blind cores should be avoided, but if necessary, the general guidelines are: for cores less than $\frac{3}{16}$ inch (4.8 mm) diameter, the length should be no greater than twice the diameter; if greater than $\frac{3}{16}$ inch (4.8 mm), length should not exceed three times the diameter. For cored-through holes, length should not exceed six times the diameter for diameters over $\frac{3}{16}$ inch (4.8 mm), and four times the diameter for diameters less than $\frac{3}{16}$ inch (4.8 mm).

Ribs

Ribs can increase the stiffness of TORLON parts without increasing section thickness. The width of the rib at the base should be equal the thickness of the adjacent wall to avoid backfill. Ribs should be tapered for mold release.

Bosses

Bosses are commonly used to facilitate alignment during assembly, but may serve other functions. In general, the outer diameter of a boss should be equal to or greater than twice the inside diameter of the hole, and the wall thickness of the boss should be less than or equal to the adjacent wall thickness.

Undercuts

It is not possible to mold undercuts in TORLON parts unless side pulls are used. To minimize mold costs, undercuts should be avoided. If it is necessary, external undercuts can be accommodated by use of a side pull, but internal undercuts require collapsing or removable cores.

Molded-in inserts

Threads molded into TORLON parts have good pull-out strength, but if greater strength is needed, metal inserts can be molded-in. TORLON resins have low coefficients of thermal expansion, making them excellent materials for applications integrating plastic and metal. For ease of molding, inserts should be situated perpendicular to the parting line and should be supported so they are not displaced during injection of the molten plastic. Inserts should be preheated to the temperature of the mold.

Table 36 defines the ratio of the wall thickness of polymer around the insert to the outer diameter of the insert for common insert materials. Sufficient polymer surrounding the insert is necessary for strength.

Threads

Threads can be molded-in. Both internal and external threads can be molded using normal molding practices to Class 2 tolerance using TORLON resins. Class 3 can be molded using very high precision tooling. In general, it is more economical to machine threads for short runs. Table 39 on page 41 shows the screw holding strength of TORLON threads.

Holes

Holes can serve a variety of functions. Electrical connectors, for example, have numerous small holes in close proximity. Associated with each hole is a weld line which potentially is a weak point. The degree of weakness is related to flow distance, part geometry, and the thickness of the wall surrounding the hole. Because TORLON resins can be molded to close tolerances, and can be molded to thin cross sections without cracking, they are excellent materials for this type of part; however, each application must be considered on an individual basis due to the complexity of design variables.

Table 36

Wall Thickness/Insert O.D. Relationship

Insert material	Ratio of wall thickness to insert o.d.
Steel	1.2
Brass	1.1
Aluminum	1.0

Secondary Operations

Joining

TORLON parts can be joined mechanically or with adhesives.

Mechanical Joining Techniques

The dimensional stability and creep resistance of TORLON polyamide-imide allows it to be readily joined with metal components even in rotating or sliding assemblies.

Snap-fit: Economical and Simple

Snap-fit is an economical and simple method of joining TORLON parts. Although the strain limit must be considered for a snap-fit assembly that will be repeatedly assembled and disassembled, TORLON engineering polymers are excellent for this type of use, due to the superior fatigue strength of polyamide-imide. The high modulus, elongation, and low creep of TORLON resins also make them well suited for snap-fit designs. Snap-in fingers in the locked position should be strain-free, or under a level of stress which can be tolerated by the material. TORLON resins can tolerate up to 10% strain for the unfilled grades, and 5% strain for filled grades. Graphite-fiber-reinforced grades are not suitable for snap-fit assembly.

Threaded Fasteners

Self-tapping Screws

In general, TORLON polyamide-imide is too tough for self-tapping screws. Tapped holes are recommended.

Molded-in Inserts

Metal inserts can be molded into TORLON parts. Preheating the insert to the temperature of the mold is required for best results. While polyamide-imide has low shrink, it is still important to have sufficient material around the insert to distribute the stress induced by shrinkage.

Threaded Mechanical Inserts

Self-threading, self-locking inserts provide a high-strength, low-stress option for joining TORLON parts. These metal inserts have an exterior “locking” feature for anchorage in the TORLON part and allow for repeated assembly and disassembly through the threaded interior. HeliCoil® inserts from HeliCoil Products, division of Mite Corporation, and SpeedSerts® inserts from Tridair Fasteners, Rexnord, Incorporated, are examples of this type of insert.

Table 37 gives the tensile strength of HeliCoil inserts in TORLON 4203L and 5030. It is the axial force required to pull the insert at least 0.020 inch (0.51 mm) out of TORLON specimens .

Table 37

Strength of HeliCoil Inserts

Thread size	Tensile strength				
	#4-40	#6-32	#8-32	#10-32	¼"-20
Engagement, in	0.224	0.276	0.328	0.380	0.500
mm	5.7	7.0	8.3	9.6	12.7
TORLON 4203L					
lb-f	870	1,470	1,840	2,200	2,830
N	3,870	6,540	8,180	9,790	12,600
TORLON 5030					
lb-f	970	1,700	2,140	2,940	5,200
N	4,310	7,560	9,520	13,100	23,100

Molded-in Threads

Both external and internal threads can be molded with TORLON polymer to a Class 2 tolerance. Mating parts with metal fasteners in TORLON threads works well because the thermal expansion of TORLON polyamide-imide is close to that of metal, so there is relatively low thermal stress at the metal-to-plastic interface. Due to the increase in mold cost, it is generally advisable to machine threads for short runs.

Strength of Bolts made of TORLON Resin

Threaded fasteners molded from TORLON engineering polymers are dependable because of the high strength, modulus, and load-bearing characteristics of TORLON engineering polymers. Bolts were injection molded from TORLON 4203L and 5030 then tested* for tensile strength, elongation, and torque limit (Table 38). The bolts were 0.25 inch (6.3 mm) diameter, type 28TPI with class 2A threads.

Table 38

Strength of TORLON Bolts

	Tensile strength		Elongation	Shear torque	
	psi	MPa	%	in-lb	N-m
TORLON 4203L	18,200	125	9.5	28.6	3.2
TORLON 5030	18,400	127	6.6	27.2	3.1

*Tensile strength calculations were based on 0.0364 inch² (0.235 cm²) cross sectioned area. Torque tests were conducted by tightening the bolts on a steel plate with steel washers and nuts. Maximum shear torque was determined using a torque wrench graduated in inch-pounds.

Screw Holding Strength

Metal screws can securely join threaded TORLON parts. Holes for #4-40 screws were drilled and tapped in 0.19 inch (4.8 mm) thick TORLON plaques. Screw pull-out strength determined by ASTM D1761* appears in Table 39

Interference Fits

Interference, or press, fits provide joints with good strength at minimum cost. TORLON engineering polymer is ideal for this joining technique due to its resistance to creep. Diametrical interference, actual service temperature, and load conditions should be evaluated to determine if stresses are within design limits.

Table 39

Screw Holding Strength of Threads in TORLON PAI

	Pull-out strength		Engagement
	lb	kg	threads per hole
TORLON 4203L	540	240	7.5
TORLON 4275	400	180	7.7
TORLON 4301	460	200	7.8

*Crosshead speed was 0.1 inch (2.5 mm) per minute. The span between the plaque and the screw holding fixture was 1.08 inches (27 mm).

Ultrasonic Inserts

Metal inserts can be imbedded in uncured TORLON parts by ultrasonic insertion. Inserts are installed rapidly with strength comparable to that provided by molded-in techniques. A hole is molded slightly smaller than the insert. The metal insert is brought in contact with the TORLON part. Vibration in excess of 18 kHz is applied to the metal insert, creating frictional heat which melts the plastic. High strength is achieved if sufficient plastic flows around knurls, threads, etc.

Other Mechanical Joining Techniques

Because post-cured TORLON parts are extremely tough, some joining techniques will not be suitable. Expansion inserts are generally not recommended; however, each application should be considered on an individual basis.

Bonding with Adhesives

TORLON polyamide-imide parts can be joined with commercial adhesives, extending design options. It is a good practice to consult the adhesive supplier concerning the requirements of your application.

Adhesive Choice

A variety of adhesives including amide-imide, epoxy, and cyanoacrylate can be used to bond TORLON parts. Cyanoacrylates have poor environmental resistance and are not recommended. Silicone, acrylic, and urethane adhesives are generally not recommended unless environment conditions preclude other options. The amide-imide adhesive is made by dissolving 35 parts of TORLON 4000T PAI powder in 65 parts of N-methylpyrrolidone**.

**Warning! NMP is a flammable organic solvent and the appropriate handling procedures recommended by EPA, NIOSH, and OSHA should be followed. Adequate ventilation is necessary when using solvents.

TORLON PAI Grade

TORLON resin grades 4203L, 5030, and 7130 are relatively easy to bond. Bearing grades 4301, 4275, and 4435 have inherent lubricity, and are more difficult to bond. Table 40 compares the shear strengths of these grades bonded with epoxy, cyanoacrylate, and amide-imide adhesives.

Post-cured TORLON bars, 2.5 x 0.5 x 0.125 inch (64 x 13 x 3 mm) were lightly abraded, wiped with acetone, then bonded with a 0.5 inch (13 mm) overlap. The clamped parts were cured per the adhesive manufacturer's recommendations. After seven days at room temperature, bonds were pulled apart with a tensile testing machine at a crosshead speed of 0.05 inches per minute (1.3 mm per minute). If failure occurred outside the bond area, the process was repeated with progressively smaller bond areas, to a minimum overlap of 0.125 inch (3.2 mm).

Table 40

Shear Strength of TORLON PAI to TORLON PAI Bonds

PAI Grade	Epoxy ⁽¹⁾		Cyanoacrylate ⁽²⁾		Amide-imide	
	psi	MPa	psi	MPa	psi	MPa
TORLON 4203L	6,000+	41.4	2,780	19.2	5,000+	34.5
TORLON 4301	2,250	15.5	1,740	12.0	2,890	19.9
TORLON 4275	3,500	24.1	1,680	11.6	3,400	23.4
TORLON 5030	4,780	33.0	3,070	21.2	5,140	35.4
TORLON 7130	6,400+	44.1	3,980	27.4	4,750	32.8
Ease of use 1 = easiest	2		1		3	
Useful temperature range,						
°F	- 67 to 160		- 20 to 210		- 321 to 500	
°C	- 55 to 71		- 29 to 99		- 196 to 260	

(1) Hysol EA 9330. Hysol is a trademark of Dexter Corporation.

(2) CA 5000. Lord Corporation.

Surface Preparation

Bonding surfaces should be free of contaminants, such as oil, hydraulic fluid, and dust. TORLON parts should be dried for at least 24 hours at 300°F (149°C) in a desiccant oven (thicker parts, over ¼ inch (6.3 mm), require longer drying time) to dispel casual moisture prior to bonding. TORLON surfaces should be mechanically abraded and solvent-wiped, or treated with a plasma arc to enhance adhesion.

Adhesive Application

For adhesives other than amide-imide, follow the manufacturer's directions. For amide-imide adhesive: coat each of the mating surfaces with a thin, uniform film of the adhesive. Adhesive-coated surfaces should be clamped under minimal pressure, approximately 0.25 psi (1.7 Pa). The excess adhesive can be cleaned with N-methylpyrrolidone (NMP).**

**Warning! NMP is a flammable organic solvent and the appropriate handling procedures recommended by EPA, NIOSH, and OSHA should be followed. Adequate ventilation is necessary when using solvents.

Curing Procedure

Amide-imide adhesive should be cured in a vented, air-circulating oven. The recommended cycle is 24 hours at 73°F, 24 hours at 300°F, 2 hours at 400°F. The parts should remain clamped until cooled to below 150°F (66°C).

Bond Strength of Various Adhesives

Commercial adhesives were used to bond TORLON parts. The bonds were evaluated for shear strength, which appears in Table 40.

Method of cure, handling, and working life of the adhesive are rated in terms of "ease of use" Useful temperature ranges appear in the manufacturers' literature and will vary with factors such as load and chemical environment.

Bonding TORLON Parts to Metal

TORLON and metal parts can be joined with adhesives. With proper surface preparation and adhesive handling, the resulting bonds will have high strength. In addition, there will be minimal stress at the interface with temperature change. This is because TORLON resins, unlike many other high temperature plastics, have expansion coefficients similar to those of metals.

As mentioned in the preceding section, bond strength depends on adhesive selection, and TORLON grade, as well as proper technique in preparing and curing the bond. Table 41 reports shear strength data for TORLON PAI to aluminum and TORLON PAI to steel bonds. Mechanical abrasion alone may not be adequate for preparing steel surfaces — chemical treatment of the steel is recommended when service temperature requires the use of amide-imide adhesive.

Table 41

Shear Strength of TORLON PAI to Metal Bonds

Shear Strength—Aluminum 2024 to TORLON PAI Bonds

	Epoxy ⁽¹⁾		Cyanoacrylate ⁽²⁾		Amide-imide	
	psi	MPa	psi	MPa	psi	MPa
TORLON 4203L	4000	27.6	1350	9.3	5050+	34.8+
TORLON 4301	2500	17.2	1450	10.0	4950+	34.1+
TORLON 4275	2450	16.9	750	5.2	4350+	30.0+
TORLON 5030	3900	26.9	3250	22.4	6050+	41.7+
TORLON 7130	4000	27.6	3750	25.9	6400+	44.1+

Shear Strength—Cold Rolled Steel to TORLON PAI Bonds

	Epoxy ⁽¹⁾		Cyanoacrylate ⁽²⁾		Amide-imide	
	psi	MPa	psi	MPa	psi	MPa
TORLON 4203L	3050	21.0	2200	15.2	1450	10.0
TORLON 4301	3700	25.5	2050	14.1	1850	12.7
TORLON 4275	3150	21.7	2450	16.9	1900	13.1
TORLON 5030	4650	32.1	2100	14.5	2400	16.5
TORLON 7130	4550	31.4	2450	16.9	1100	7.6

Ease of use 1= easiest

2

1

3

Useful temperature range,

°F

- 67 to 160

- 20 to 210

- 321 to 500

°C

-55 to 71

- 29 to 99

- 196 to 260

*This test used TORLON bars 2.5 x 0.5 x 0.125 inches (64 x 13 x 3 mm); steel strips of similar size were cut from cold rolled steel, dull finished panel; and aluminum strips were cut from 2024 alloy panels.

(1) Hysol EA 9330. Hysol is a trademark of Dexter Corporation.

(2) CA 5000. Lord Corporation.

Guidelines for Machining Parts Made From TORLON Resin

Molded shapes and extruded bars manufactured from TORLON polyamide-imide can be machined using the same techniques normally used for machining mild steel or acrylics. Machining parameters for several typical operations are presented in Table 42.

Parts made from TORLON resin are dimensionally stable, and do not deflect or yield as the cutting tool makes its pass. All TORLON grades are very abrasive to standard tools, and high-speed tools should not be used.

Carbide-tipped tools may be used, but diamond-tipped or insert cutting tools are strongly recommended. These tools will outlast carbide-tipped tools and provide a strong economic incentive for production operations, despite a relatively high initial cost. Thin sections or sharp corners must be worked with care to prevent breakage and chipping. Damage to fragile parts can be minimized by using shallow cuts during finishing operations. The use of mist coolants to cool the tool tip and to help remove chips or shavings from the work surface is recommended. Air jets or vacuum can be used to keep the work surface clean.

Parts machined from injection-molded blanks may have built-in stresses. To minimize distortion, parts should be machined symmetrically, to relieve opposing stresses.

Machined Parts Should be Recured.

Parts designed for friction and wear-intensive service, or which will be subjected to harsh chemical environments, should be recured after machining to insure optimum performance. If such a part has been machined to greater than $\frac{1}{16}$ inch (1.6 mm) depth, recuring is strongly recommended.

Table 42

Guidelines for Machining Parts Made From TORLON Resin

Turning

Cutting speed, fpm	300-800
Feed, in/rev	0.004-0.025
Relief angle, degrees	5-15
Rake angle, degrees	7-15
Cutting depth, in	0.025

Circular Sawing

Cutting, fpm	6000-8000
Feed, in/rev	fast & steady
Relief angle, degrees	15
Set	slight
Rake angle, degrees	15

Milling

Cutting speed, fpm	500-800
Feed, in/rev	0.006-0.035
Relief angle, degrees	5-15
Rake angle, degrees	7-15
Cutting depth, in	0.035

Drilling

Cutting speed, rpm	300-800
Feed, in/rev	0.003-0.015
Relief angle, degrees	0
Point angle, degrees	118

Reaming

Slow speed, rpm	150
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Technical Service

Our expert technical staff is ready to answer your questions related to designing, molding, finishing or testing TORLON parts. We respect proprietary information and will consult with you on a confidential basis.

The latest design, fabrication, and testing equipment available to our service engineers supplements their years of practical experience with applications of TORLON polymers. Using a computer-aided design workstation, our engineers can forecast the cost and performance of your proposed part and offer suggestions for efficient molding. Solvay Advanced Polymers can also provide rod, sheet, film, plate, ball, disc, and tube stock shapes for making prototype parts.

The availability of these services can be a tremendous help as you evaluate TORLON polyamide-imide for your engineering resin needs.

Whatever type of process you are considering, our personnel and facilities can help you achieve consistent quality and more profitable products. Call us to discuss your ideas.

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Centrifugal Compressor Labyrinth Seals

TORLON® polyamide-imide resins produce labyrinth seals that are more corrosion resistant than Aluminum and can be fitted to smaller clearances. Smaller clearances mean higher efficiency and greater through-put without increasing energy input. Better corrosion resistance means more productive time between maintenance shutdowns.



Automotive Drivetrain Thrust Washers

TORLON® polyamide-imide resin drive train thrust washers in automotive applications have superior impact strength, wear resistance, and chemical resistance.

Diesel Engine Thrust Washers

TORLON® polyamide-imide thrust washers absorb and dissipate impact energy in truck engines. They offer low friction and wear, high pressure and velocity limits, excellent mechanical properties and heat resistance.



Health and Safety Information

Material Safety Data Sheets (MSDS) for products of Solvay Advanced Polymers are available upon request from your sales representative or by e-mailing us at advancedpolymers@solvay.com. Always consult the appropriate MSDS before using any of our products.

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