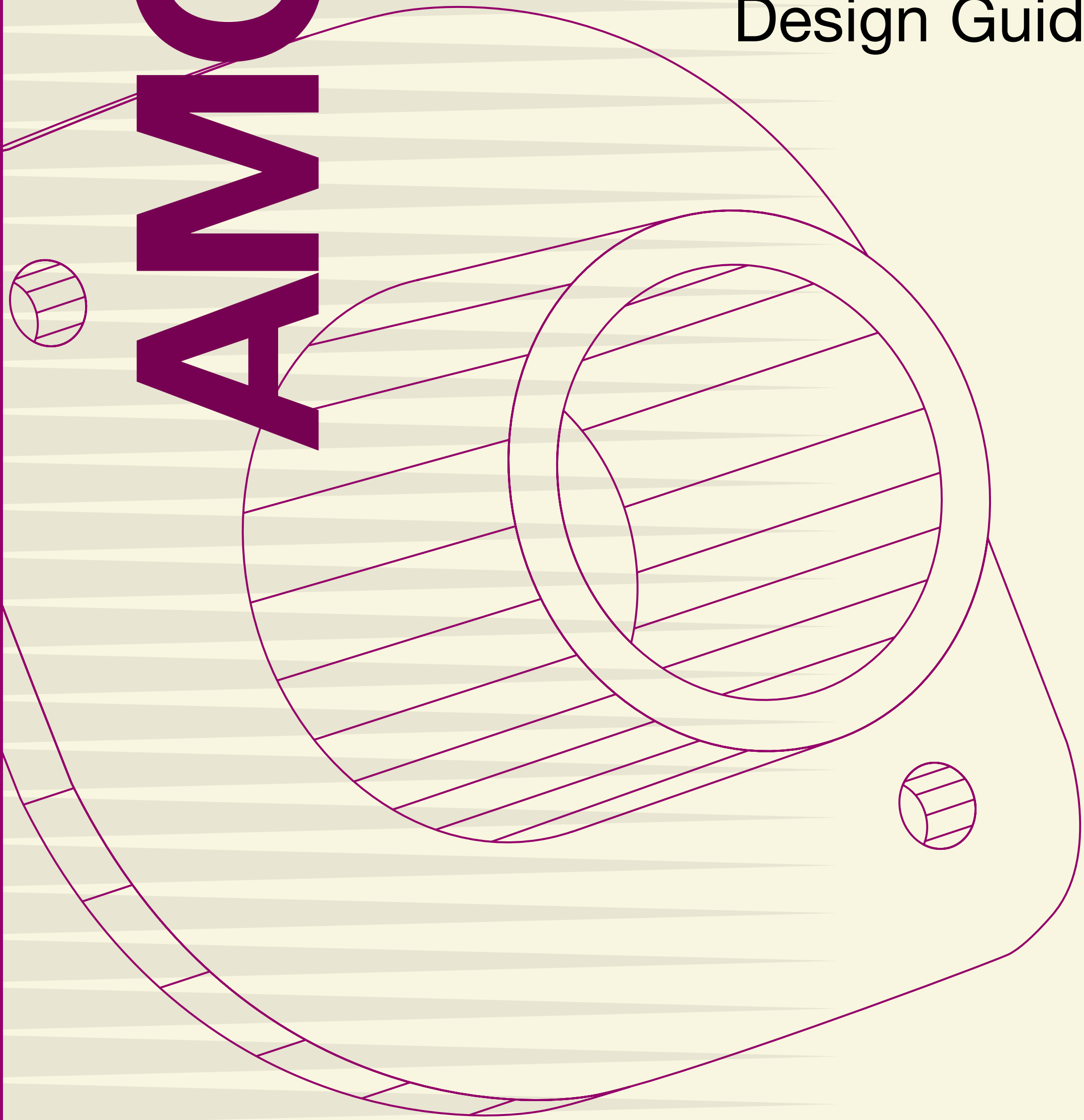
AMODEL

design

AMODEL®
Polyphthalamide
Design Guide



Solvay
Advanced Polymers

Abbreviations used in this Manual

Abbreviation	Meaning
ABS	acrylonitrile-butadiene-styrene
ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
Btu	British thermal unit
CLTE	coefficient of linear thermal expansion
CTI	comparative tracking index
DAM	"dry, as molded"
DSC	differential scanning calorimetry
EMI	electromagnetic interference
FD	flow direction
GF	glass filled
GR	glass reinforced
HDT	heat deflection (distortion) temperature
HS	heat stabilized
HVATR	high voltage arc tracking rate
HWI	hot wire ignition
Hz	Hertz
IR	infrared
ISO	International Organization for Standardization
kpsi	kilo (1000) pounds per square inch
MF	mineral filled
NBS	National Bureau of Standards
PEEK	polyetheretherketone
PET	polyethylene terephthalate
PLC	Performance Level Class (UL 746A)
PPA	polyphthalamide
PPS	polyphenylene sulfide
psi	pounds per square inch
RFI	radio frequency interference
RH	relative humidity
RTI	relative thermal index
SI	International System of Units
TD	transverse direction
TMA	thermomechanical analysis
UL	Underwriters Laboratories Inc.
UV	ultraviolet radiation

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INTRODUCTION

Solvay Advanced Polymers has a broad line of engineering thermoplastics that offer exceptional value combined with high performance properties. The product line includes ACUDEL™ polyphenylsulfone blends, AMODEL® polyphthalamide, IXEF® polyarylamide, KADEL® polyketone, MINDEL® modified polysulfones, PRIMEF® polyphenylene sulfide, RADEL® A polyethersulfone, RADEL® R polyphenylsulfone, TORLON® polyamide-imide, UDEL® polysulfone, and XYDAR® liquid crystal polymers.

AMODEL polyphthalamide (PPA) resins were commercialized in 1991. Although the polyphthalamide resin technology can produce both semi-crystalline and amorphous polymers, this manual deals with the semi-crystalline resins based on the polymer designated AMODEL A-1000 polyphthalamide.

The semi-crystalline grades of AMODEL PPA resins have excellent mechanical properties, outstanding dimensional stability, exceptional elevated thermal performance, and good processing characteristics. AMODEL resins bridge the cost/performance gap between the high-volume, moderate-performance engineering resins, such as thermoplastic polyesters and nylons, and the low-volume, high-cost specialty thermoplastics, such as polyetheretherketone (PEEK).

AMODEL resins are available in a wide variety of compounds designed to meet specific application requirements in the automotive, electrical and electronic, industrial, wear and anti-friction, power tool, and lawn and garden industries. Because of their desirable balance of properties, AMODEL resins will continue to find acceptance in a broad range of applications.

This manual concentrates on the grades of AMODEL resin developed and designed for fabrication by the injection molding process.

The goal of this manual is to provide an easily used technical reference of the properties of the AMODEL PPA family of thermoplastic resins. It includes a discussion regarding the design of components to be made from these materials, and recommendations for processing them. This manual is provided to assist users of engineering plastics, design engineers, component designers, and fabricators with their development of the most cost/effective AMODEL PPA component in the shortest possible time.

SURFACE MOUNT RIGHT-ANGLE LEDs FOR SMT PACKAGES

Surface mount right-angle circuit board indicators using high intensity LEDs by Dialight Corporation for diagnostic and indicator applications use AMODEL PPA for the LED and assembly housings.

Instead of forming the leads of through-hole LEDs, Dialight bends the light instead, using new high-intensity LEDs with a combination reflective prism and wide angle lens.

AMODEL PPA is capable of withstanding IR reflow as well as VPS assembly operations at temperatures up to 500°F (260°C). It meets this thermal requirement, molds easily, and also provides good adhesion with the epoxy lens, according to Dialight.

Chemistry

AMODEL resins are classified in the general chemical family known as polyamides. Polyamides may be produced by the reaction of a difunctional organic acid with a difunctional amine, or the self-condensation of either an ω-amino acid or a lactam.

Polyamides can be produced from a wide variety of acids and amines, and a number of polyamides are commercially important. A naming convention for polyamides has evolved. The convention is to name the polyamide using the number of carbon atoms in the monomers with the diamine component first. Thus, a polyamide made from hexamethylene diamine and adipic acid is called polyamide 6,6 or nylon 6,6, and one made from hexamethylene diamine and dodecanedioic acid would be nylon 6,12.

When an aromatic diacid is used instead of an aliphatic diacid, the nomenclature is modified to reflect the isomeric form of the aromatic diacid, and the term polyphthalamide may be used to distinguish these polymers from those of solely aliphatic raw materials.

Polyamide 6,T produced by the condensation of hexamethylene diamine with terephthalic acid, has long been recognized for its excellent dimensional stability, low moisture absorption, high strength, and heat resistance. The fundamental problem preventing its commercialization has been that its high crystalline melting point of 698°F (370°C) is above its thermal decomposition temperature. Therefore, it cannot be processed by most conventional melt processing techniques, such as injection molding or extrusion. In addition, its melting point, among other factors, complicates the polymerization process.

The basic polyamide 6,T technology has been modified by adding comonomers to produce the AMODEL family of polyphthalamide (PPA) resins which are composed of proprietary compositions of matter. These comonomers lower the melting point of polyamide 6,T while retaining a fast crystallization rate. This results in an injection molding resin with an excellent balance of processing and thermal/mechanical performance. One particular composition, which is used as the compounding base for the current product line, has been designated AMODEL A-1000 resin.

Weber Charcoal Grill Has AMODEL PPA Vent Handle

The Weber Performer™ charcoal grill uses AMODEL PPA to make cool work of opening or closing the damper vent for the desired “doneness” of the food being cooked.

Rotary vent handles are molded by GAIM Engineering, Bensonville, Illinois in AMODEL A-1133 HS resin with UV additive protection. The 33% glass-filled heat-stabilized material has a 574°F (301°C) heat deflection temperature plus high flexural modulus and high tensile strength, along with low moisture absorption. It replaced a conventional nylon material which could not withstand the heat, according to a Weber spokesman.

Crystallinity

Thermoplastics are often divided into two classes, amorphous and semi-crystalline. One of the major differences between amorphous and semi-crystalline polymers is the way their properties change in response to changes in temperature. Figure shows a typical response of modulus to temperature change for amorphous and semi-crystalline polymers.

When the temperature is raised, the modulus of amorphous polymers generally decreases slowly until the glass transition temperature (Tg) is reached. At temperatures above the Tg, the modulus decreases rapidly. Therefore, amorphous thermoplastics are rarely used at temperatures higher than their glass transition temperature.

In the case of semi-crystalline polymers, the modulus also gradually decreases with increasing temperature. At or near the glass transition temperature, the modulus decreases rapidly to a lower but still useful level. Continuing to increase the temperature causes the modulus to remain at or near this new level (the crystalline plateau) until the melting point temperature (Tm) is reached. At Tm, the modulus decreases rapidly again. Semi-crystalline polymers are often used at temperatures above their glass transition temperatures, but below their melting points, particularly when they are modified with glass fibers and/or mineral fillers.

When semi-crystalline polymers are processed, the amount of crystallinity can be affected by processing conditions. For example, AMODEL A-1000 PPA based products require mold surface temperatures of at least 275°F (135°C) for development of the maximum amount of crystallinity during injection molding. The degree of crystallinity is directly proportional to the height of the crystalline plateau.

Above the Tm, a semi-crystalline polymer melts, changing from the solid state to the liquid state.

The thermal capability of a semi-crystalline polymer is defined to a large extent by its Tg and Tm, as these values indicate the temperature ranges where the polymer has high stiffness (below Tg), moderate stiffness (between Tg and Tm), or no useful stiffness (above Tm).

Figure 1. Typical Change in Modulus with Temperature

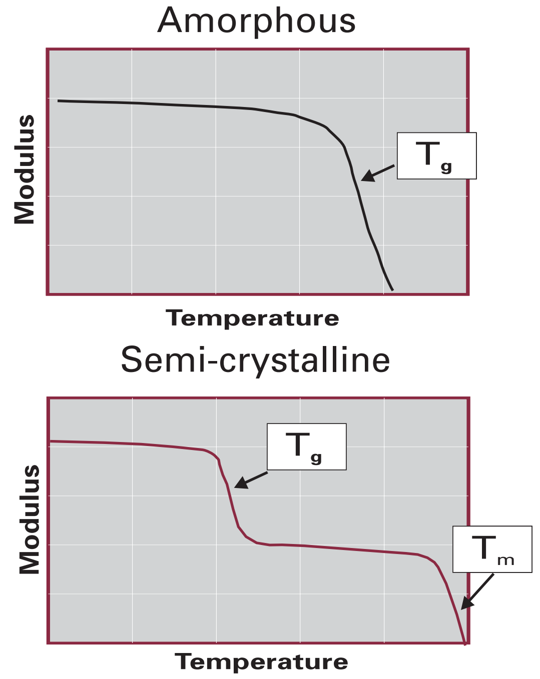


Table 1 gives the glass transition and melting temperatures for AMODEL polyphthalamide. Because adsorbed moisture reduces the glass transition temperature, both the “dry, as molded” and 50% RH equilibrium values are given.

AMODEL A-1000 base resin, which is semi-crystalline and aromatic, has excellent chemical resistance to a wide variety of environments.

Table 1.
Glass Transition and Melting Point Temperatures of AMODEL A-1000 PPA

Relative Humidity	Glass Transition Temperature		Melting Temperature	
	°F	°C	°F	°C
“dry, as molded”	261	127	590	310
50% RH	198	92	590	310

Moisture Effects

Like other polymers, AMODEL A-1000 resin absorbs moisture from the atmosphere. When an AMODEL resin component reaches equilibrium with a 100% relative humidity (RH) atmosphere, the increase in weight due to moisture absorption will be roughly 5 to 6 percent of the polyphthalamide resin weight.

Figure 2 compares the glass transition temperatures of AMODEL A-1000 resin and nylon 6,6 at a range of moisture contents. These materials absorb moisture at different rates and have different maximum moisture adsorption amounts. The most useful and practical comparison is achieved by plotting the T_g versus the equilibrium moisture content at various relative humidities.

Comparing dry nylon 6,6 to dry AMODEL resin, AMODEL resin has a T_g advantage of about 115°F (64°C). If the comparison is made at the 50% RH equivalent moisture content, the T_g advantage of AMODEL resin is about 160°F (89°C). The exceptional dimensional stability and property retention of AMODEL polyphthalamide is due largely to the higher T_g and the fact that the T_g remains well above room temperature, even at the moisture content appropriate for 100% RH. The T_g of nylon 6,6, on the other hand, falls to 5°F (-15°C) at moisture contents consistent with equilibria at 50 to 60% RH. These effects are discussed in detail beginning on page 44.

Figure 3 compares the dimensional change of AMODEL A-1000 resin to that of nylon 6,6 after being immersed in water at 73°F (23°C). Results shown are for 0.125 in. (3.2 mm) thick plaques. After one year (about 8,800 hours), the dimensional change of the nylon resin is approximately three times that of the PPA resin.

Not only do polyphthalamides absorb less moisture than typical nylons (polyamides), they do so much more slowly. The diffusion coefficient for water in AMODEL A-1000 resin is approximately 20% of that for nylon 6,6 at 73°F (23°C).

Figure 2. Glass Transition Temperature vs. Moisture Content

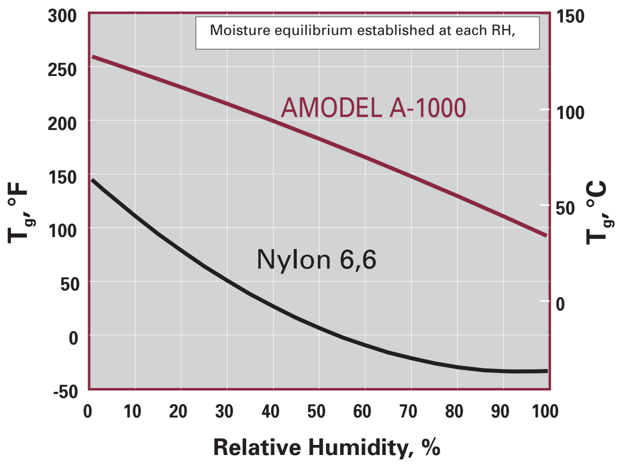
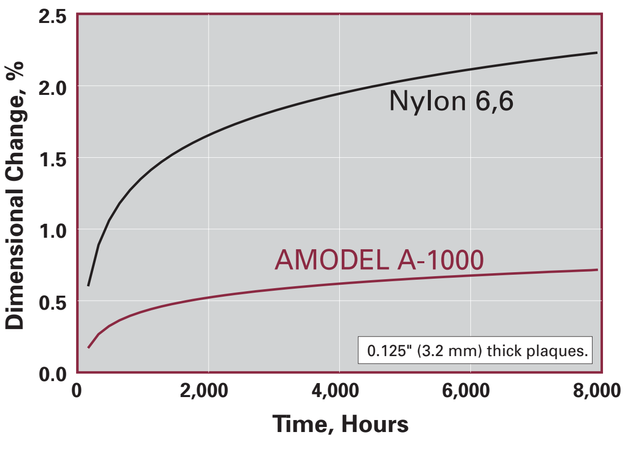
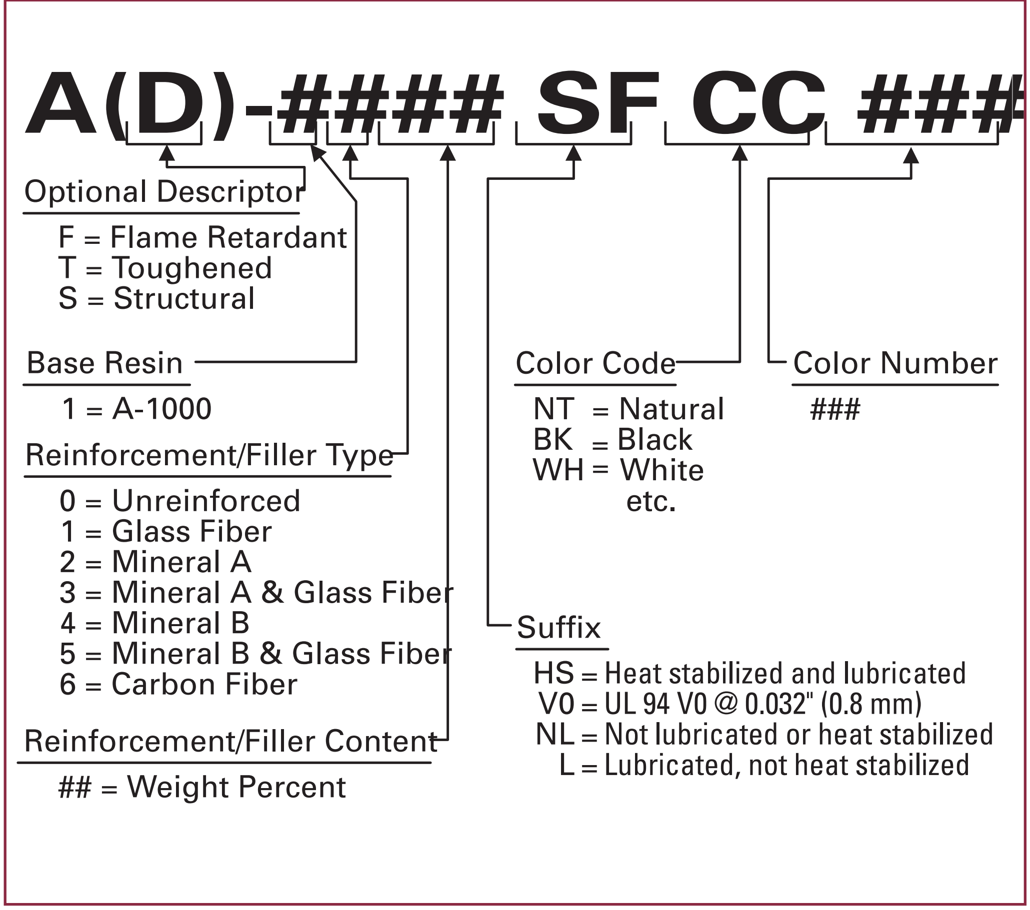


Figure 3. Dimensional Change vs. Water Immersion Time



Nomenclature

Figure 4. AMODEL Resin Grade Designations



AMODEL PPA resins are available in neat, impact modified, glass fiber reinforced, mineral filled, and flame retardant compositions. The grade designations used for AMODEL PPA resins are designed to communicate important compositional information. The nomenclature system is illustrated in Figure 4.

Product Group

The AMODEL PPA grade designations start with the letter "A", except those in the ET resin series.

Descriptor (Optional)

The optional descriptor may be "F" for flame retardant, "T" for toughened, or "S" for structural.

Base Resin

Currently, all commercial grades of AMODEL resin are based on the semi-crystalline polymer designated A-1000.

Suffix

The suffixes convey additional information about the additive packages used.

Color

The base polymer is translucent white due to its crystallinity. Specific product natural color will vary depending on the additives used. A variety of colors can be provided.

The following examples illustrate the nomenclature system for AMODEL resins:

AMODEL AF-1133 V0 resin is flame retardant (Descriptor "F"), based on A-1000 polymer (First digit "1"), glass fiber reinforced (Second digit "1"), at 33% by weight (Third and fourth digits "33"), and U.L. recognized as V0 (Suffix "V0") at 0.032 inch (0.8 mm).

AS-1145 HS is a structural grade, based on A-1000, has 45% glass fiber reinforcement, heat stabilized and lubricated.

ET-1000 HS is an unreinforced, impact modified A-1000 grade that is heat stabilized and lubricated.

Product Selection

AMODEL resins offer improved performance when compared to many other engineering polymers because they have higher strength, stiffness, melt and glass transition temperatures. Performance of AMODEL resins is further enhanced through the use of fillers, reinforcements, and other additives.

A product selection guide is given in Table 2 to facilitate your selection of the proper grade of AMODEL resin for an application.

Table 2.
Product Selection Guide - The product families and their characteristics

Product Family	General Description
Glass Fiber Reinforced	These resins cost effectively maximize strength and stiffness properties and are typically used in applications requiring structural integrity at elevated temperatures.
Mineral-Glass Filled	These materials offer stiffness and thermal performance approaching glass reinforced products with better dimensional stability and lower cost.
Flame Retardant	These grades are specially formulated for flame retardance, rated 94 V0 at 0.032 in (0.8 mm), rated 94-5V at 0.062 in. (1.6 mm), and are vapor phase and IR reflow solderable. Both glass fiber reinforced and mineral-glass filled versions are available.
Unreinforced Impact Modified	These "supertough" resins have notched Izods greater than 15 ft-lb/in. (800 J/m) and combine superior impact performance with good strength and stiffness at both low and high temperatures.
Mineral Filled	Mineral filled grades provide an excellent surface finish for vacuum metallizing and chrome plating applications.

Selecting Products by Application Requirements

Key Application Requirements	Product Family	AMODEL Grades	Representative Potential Applications
Strength and Stiffness	Glass Fiber Reinforced	AS-1133 HS AS-1145 HS AS-4133 HS*	Mechanical fasteners Motor end frames Pump housings Automotive sensors
Stiffness and Dimensional Stability	Mineral-Glass Filled	A-1340 HS AS-1566 HS	Downhole oil field components Lawn mower grills Automotive connectors Power tool drivers Automotive engine parts
Flame Resistance, Strength, Stiffness, and Dimensional Stability	Flame Retardant	AF-1133 VO AF-1550 VO	Electric motor brush holders Distribution and control contactors
		AF-4133 V0* AFA-4133 V0* AFA-6133 V0*	Connectors Dip switches Other surface mount components
High Impact Resistance	Unreinforced Impact Modified	AT-1001 L ET-1001 HS	Pump and fan impellers Oil field equipment Safety shoe tips Sporting goods components

* Molds with high crystallinity in water-cooled molds.

TYPICAL PROPERTY TABLES

Typical Properties

The typical property data contained in the following short term property tables fall within the normal range of product properties. These data are typical values. Actual properties of individual batches will vary within specification limits.

These values should not be used to establish specification limits. Neither should they be used alone as the basis for part design.

Accelerated Moisture Conditioning

Because polyamides absorb moisture, and absorbed moisture affects properties, it is customary to list the properties “dry, as molded” and at the moisture content appropriate for equilibrium with 50% RH. In the case of AMODEL polyphthalamides, the resins absorb moisture so slowly, determination of properties at moisture equilibrium levels is very time consuming.

Accelerated conditioning methods were used to bring the test specimens to the approximate equilibrium moisture content. To obtain the equivalent of 50% RH, test specimens were boiled in an aqueous solution containing 80 grams of potassium acetate per 100 grams of water until constant weight was achieved. To obtain the equivalent of 100% RH conditions, test specimens were boiled in water until constant weight was achieved.

These procedures were developed empirically to give the same moisture uptake as samples that were placed in a constant humidity chamber until equilibrium was achieved.

For example, AMODEL AS-1133 HS resin gains about 1.8% and 3.9% moisture, when conditioned to approximate equilibria at 50% and 100% RH respectively.

Because the temperatures involved in this conditioning are between 212° and 266°F (100° and 130°C), some annealing takes place. For this reason, the 50% and 100% RH modulus values are sometimes a few percent higher than the “dry, as molded” values given in the tables.

In addition, exposure to the aqueous conditioning media at these relatively high temperatures combined with the long exposure time — usually 72 hours for 0.125 inch (3.2 mm) thick specimens — results in some hydrolysis of the glass/resin matrix interface. In many cases, the properties that are dependent on glass/resin adhesion, such as tensile strength, notched Izod, etc., are about 10% lower than would have been obtained had the samples been allowed to condition to 50% or 100% RH in air at 73°F (23°C). As a result, the reported values in these cases are conservative.

Table 3.
Typical Properties of Unreinforced AMODEL Resins - SI Units

Property	ASTM Method	Units	ET-1001 HS		AT-1001 L	
			DAM	50% RH	DAM	50% RH
Mechanical						
Tensile Strength	D 638	MPa				
23°C			76	62	62	52
Tensile Elongation at Yield	D 638	%				
23°C			6	6	6	6
Tensile Elongation at Break	D 638	%				
23°C			30	30	30	30
Tensile Modulus	D 638	GPa	2.4	2.3	1.9	2.0
Flexural Strength	D 790	MPa	128	110	97	79
Flexural Modulus	D 790	GPa	2.6	2.6	2.2	2.1
Notched Izod Impact	D 256	J/m				
23°C			960	960	1,065	1,175
-40°F					750	
Penetration Impact (Dynatup®[1]) at 23°C	D 3763					
Maximum Load		N	5,600		4,900	
Energy to Maximum Load		J	43		41	
Total Energy Absorbed		J	64		54	
Penetration Impact (Dynatup®[1]) at -23°C						
Maximum Load		N	6,500		5,600	
Energy to Maximum Load		J	48		41	
Total Energy Absorbed		J	66		54	
Rockwell Hardness	D 785	R	120	110		
Taber Abrasion, CS-17 Wheel, 1000 g		mg/1000 cycles	13.5	10.9		
Thermal						
Heat Deflection Temperature	D 648	°C				
at 1.8 MPa			120		120	
Melting Point	D 3418	°C	310		310	
General						
Specific Gravity	D 792		1.15		1.11	
Moisture Absorption, 24 hr	D 570	%	0.65		0.75	
Mold Shrinkage	D 955	%				
Flow Direction			1.5-2.0		1.7-2.2	
Transverse Direction			1.5-2.0		1.9-2.1	

Refer to page 7 for general information regarding the use of this table.

[1] "Dynatup" is a registered trademark of General Research Corporation.

Table 4.
Typical Properties of Unreinforced AMODEL Resins - U.S. Customary Units

Property	**ASTM Method**	**Units**	**ET-1001 HS**		**AT-1001 L**	
			DAM	50% RH	DAM	50% RH
Mechanical						
Tensile Strength	D 638	psi				
73°F			11,000	9,000	9,000	7,500
Tensile Elongation at Yield	D 638	%				
73°F			6	6	6	6
Tensile Elongation at Break	D 638	%				
73°F			30	30	30	30
Tensile Modulus	D 638	kpsi	350	340	275	290
Flexural Strength	D 790	psi	18,500	16,000	14,000	11,400
Flexural Modulus	D 790	kpsi	380	380	320	300
Notched Izod Impact	D 256	ft-lb/in				
73°F			18	18	20	22
-40°F					14	
Penetration Impact (Dynatup®) at 73°F	D 3763					
Maximum Load		lbs	1,260		1,100	
Energy to Maximum Load		ft-lbs	32		30	
Total Energy Absorbed		ft-lbs	47		40	
Penetration Impact (Dynatup®) at -10°F						
Maximum Load		lbs	1,460		1,260	
Energy to Maximum Load		ft-lbs	34		30	
Total Energy Absorbed		ft-lbs	49		40	
Rockwell Hardness	D 785	R	120	110		
Taber Abrasion, CS-17 Wheel, 1000 g		mg/1000 cycles	13.5	10.9		
Thermal						
Heat Deflection Temperature	D 648	°F				
at 264 psi			248		248	
Melting Point	D 3418	°F	590		590	
General						
Specific Gravity	D 792		1.15		1.11	
Moisture Absorption, 24 hr	D 570	%	0.65		0.75	
Mold Shrinkage	D 955	%				
Flow Direction			1.5-2.0		1.7-2.2	
Transverse Direction			1.5-2.0		1.9-2.1	

Refer to page 7 for general information regarding the use of this table.

Table 5.
Typical Properties of Mineral and Mineral-Glass Filled AMODEL Resins - SI Units

Property	**ASTM Method**	**Units**	**A-1240 L**		**A-1340 HS**		**AS-1566 HS**
			DAM	50% RH	DAM	50% RH	DAM
Mechanical							
Tensile Strength	D 638	MPa	107	93	174	130	207
Tensile Elongation	D 638	%	1.6	1.2	2.2	1.8	1.7
Tensile Modulus	D 638	GPa	9.0	8.3	11	11	20.0
Flexural Strength	D 790	MPa	196	172	262	233	290
Flexural Modulus	D 790	GPa	7.6	6.9	10.6	10.8	18.6
Shear Strength	D 732	MPa	96	93	91	85	
Compressive Strength (13x13x25 mm)	D 695	MPa	179	166	228	208	
Poisson's Ratio			0.29		0.38		
Izod Impact	D 256	J/m					
Notched			48	31	43	43	64
Un-notched			530				590
Rockwell Hardness	D 785	R	125		125		
Thermal							
Heat Deflection Temperature	D 648	°C					
at 1.8 MPa			154		275		271
at 0.45 MPa			260		290		
Continuous Use Temperature	D 3045	°C					
5,000 hr.					150		
20,000 hr.					130		
Melting Point	D 3418	°C	310		310		
Flammability (3.2 mm bar)	UL-94		HB		HB		
Coefficient of Thermal Expansion	E 831	10^{-5} m/m°C					
0° to 100°C FD[1]			3.4		2.9		1.1
TD[2]			4.0		4.6		3.8
160° to 250°C FD[1]			7.9		1.9		
TD[2]			9.5		9.2		
Electrical							
Volume Resistivity	D 257	ohm-cm	9×10^{15}	2×10^{15}	1×10^{16}	2×10^{15}	2×10^{16}
High Voltage Arc Resistance	D 495	sec	125	120	150	130	
Comparative Tracking Index	D 3638	volts	550	550	550	550	
Dielectric Constant	D 150						
at 100 Hz			4.2	4.4	4.5	4.7	
at 1 MHz			4.0	4.0	4.3	4.3	4.7
Dissipation Factor	D 150						
at 100 Hz			0.006	0.007	0.005	0.008	
at 1 MHz			0.017	0.019	0.017	0.022	0.010
General							
Specific Gravity	D 792		1.53		1.54		1.78
Moisture Absorption, 24 hr	D 570	%	0.14		0.16		
Mold Shrinkage	D 955	%					
Flow Direction			1.0	0.7	0.4	0.3	0.3
Transverse Direction			1.0	0.7	0.7	0.6	0.5

[1] FD = Flow direction, [2] TD = Transverse direction
Refer to page 7 for general information regarding the use of this table.

Table 6.
Typical Properties of Mineral and Mineral-Glass Filled AMODEL Resins - U.S. Customary Units

	ASTM		**A-1240 L**		**A-1340 HS**		**AS-1566 HS**
Property	**Method**	**Units**	DAM	50% RH	DAM	50% RH	DAM
Mechanical							
Tensile Strength	D 638	psi	15,500	13,500	25,200	18,800	30,000
Tensile Elongation	D 638	%	1.6	1.2	2.2	1.8	1.7
Tensile Modulus	D 638	kpsi	1,300	1,200	1,600	1,600	2,900
Flexural Strength	D 790	psi	28,500	25,000	38,100	33,700	42,000
Flexural Modulus	D 790	kpsi	1,100	1,000	1,540	1,570	2,700
Shear Strength	D 732	psi	13,900	13,500	13,200	12,300	
Compressive Strength (0.5x0.5x1")	D 695	psi	26,000	24,100	33,000	30,100	
Poisson's Ratio			0.29		0.38		
Izod Impact	D 256	ft-lb/in					
Notched			0.90	0.59	0.8	0.8	1.2
Un-notched			10				11
Rockwell Hardness	D 785	R	125		125		
Thermal							
Heat Deflection Temperature	D 648	°F					
at 264 psi			310		527		520
at 66 psi			500		554		
Continuous Use Temperature	D 3045	°F					
5,000 hr.					302		
20,000 hr.					266		
Melting Point	D 3418	°F	590		590		
Flammability (1/8" bar)	UL-94		HB		HB		
Coefficient of Thermal Expansion	E 831	10^{-5} in/in°F					
32° to 212°F FD[1]			1.9		1.6		0.6
TD[2]			2.2		2.6		2.1
320° to 480°F FD[1]			4.4		1.1		
TD[2]			5.3		5.1		
Electrical							
Volume Resistivity	D 257	ohm-cm	9×10^{15}	2×10^{15}	1×10^{16}	2×10^{15}	2×10^{16}
High Voltage Arc Resistance	D 495	sec	125	120	150	130	
Comparative Tracking Index	D 3638	volts	550	550	550	550	
Dielectric Constant	D 150						
at 100 Hz			4.2	4.4	4.5	4.7	
at 1 MHz			4.0	4.0	4.3	4.3	4.7
Dissipation Factor	D 150						
at 100 Hz			0.006	0.007	0.005	0.008	
at 1 MHz			0.017	0.019	0.017	0.022	0.010
General							
Specific Gravity	D 792		1.53		1.54		1.78
Moisture Absorption, 24 hr	D 570	%	0.14		0.16		
Mold Shrinkage	D 955	%					
Flow Direction			1.0	0.7	0.4	0.3	0.3
Transverse Direction			1.0	0.7	0.7	0.6	0.5

[1] FD = Flow direction, [2] TD = Transverse direction
Refer to page 7 for general information regarding the use of this table.

Table 7.
Typical Properties of Glass Reinforced AMODEL Resins - SI Units

Property	ASTM Method	Units	A-1133 HS (AS-1133 HS)		A-1145 HS (AS-1145 HS)		AS-4133 HS	
			DAM	50% RH	DAM	50 % RH	DAM	50 % RH
Mechanical								
Tensile Strength	D 638	MPa	221	193	259	228	200	172
Tensile Elongation	D 638	%	2.5	2.1	2.6	2.1	2.5	2.2
Tensile Modulus	D 638	GPa	13.1	13.1	17.2	17.2	11.7	11.7
Flexural Strength	D 790	MPa	317	254	362	294	290	241
Flexural Modulus	D 790	GPa	11.4 (10.3)	11.4 (10.3)	13.8	13.8	11.0	11.0
Shear Strength	D 732	MPa	101	89	108	92	90	76
Compressive Strength	D 695	MPa						
Specimen 6 x 13 x 25 mm			241 (276)	217 (247)	314	302		
Specimen 13 x 13 x 25 mm			193		207		179	172
Poisson's Ratio			0.41		0.41		0.41	
Izod Impact	D 256	J/m						
Notched			80(85)	60(75)	112(120)	100	80	70
Rockwell Hardness	D 785	R	125		125			
Thermal								
Heat Deflection Temperature	D 648	°C						
at 1.8 MPa			285		287		300	
at 0.45 MPa			297		301		320	
Continuous Use Temperature	D 3045	°C						
5,000 hr.			185		185			
20,000 hr.			165		165			
Melting Point	D 3418	°C	310		310		327	
Flammability (3.2 mm bar)	UL-94		HB		HB		HB	
Coefficient of Thermal Expansion	E 831	10^{-5} m/m°C						
0° to 100°C FD [1]			2.4		1.5		2.2	
TD [2]			6.0		5.0		5.9	
160° to 250°C FD [1]			1.5		1.0		1.5	
TD [2]			13.0		10.0		12.1	
Electrical								
Volume Resistivity	D 257	ohm-cm	1 x 10^{16}	2 x 10^{15}	1 x 10^{16}	2 x 10^{15}	2 x 10^{16}	5 x 10^{14}
High Voltage Arc Resistance	D 495	sec	140	120	145	125		
Comparative Tracking Index	D 3638	volts	550	550	550	550	>600	>600
Dielectric Constant	D 150							
at 60 Hz			4.4	4.7	4.6	4.9	3.8	4.3
at 1 MHz			4.2	4.3	4.4	4.5	3.6	3.4
Dissipation Factor	D 150							
at 60 Hz			0.005	0.009	0.005	0.009	0.004	0.020
at 1 MHz			0.017	0.022	0.016	0.021	0.012	0.019
General								
Specific Gravity	D 792		1.48(1.46)		1.56		1.45	
Moisture Absorption, 24 hr	D 570	%	0.21		0.12		0.29	
Mold Shrinkage	D 955	%						
Flow Direction			0.4	0.0	0.2	0.1	0.5	
Transverse Direction			0.8	0.2	0.6	0.1	1.0	

[1] FD = Flow direction, [2] TD = Transverse direction
Refer to page 7 for general information regarding the use of this table.

Table 8.
Typical Properties of Glass Reinforced AMODEL Resins - U.S. Customary Units

Property	ASTM Method	Units	A-1133 HS AS-1133 HS		A-1145 HS AS-1145 HS		AS-4133 HS	
			DAM	50% RH	DAM	50 % RH	DAM	50 % RH
Mechanical								
Tensile Strength	D 638	psi	32,000	28,000	37,500	33,000	29,000	25,000
Tensile Elongation	D 638	%	2.5	2.1	2.6	2.1	2.5	2.2
Tensile Modulus	D 638	kpsi	1,900	1,900	2,500	2,500	1,700	1,700
Flexural Strength	D 790	psi	46,000	36,900	52,600	42,700	42,000	35,000
Flexural Modulus	D 790	kpsi	1,650 (1,500)	1,650 (1,500)	2,000	2,000	1,600	1,600
Shear Strength	D 732	psi	14,700	12,900	15,600	13,300	13,000	11,000
Compressive Strength	D 695	psi						
Specimen 0.25 x 0.5 x 1"			35,000 (40,000)	31,500 (35,800)	45,500	43,800		
Specimen 0.5 x 0.5 x 1"			28,000		30,000		26,000	25,000
Poisson's Ratio			0.41		0.41		0.41	
Izod Impact	D 256	ft-lb/in						
Notched			1.5(1.6)	1.1(1.4)	2.1(2.2)	1.9	1.5	1.3
Rockwell Hardness	D 785	R	125		125			
Thermal								
Heat Deflection Temperature	D 648	°F						
at 264 psi			545		549		572	
at 66 psi			567		574		608	
Continuous Use Temperature	D 3045	°F						
5,000 hr.			365		365			
20,000 hr.			327		329			
Melting Point	D 3418	°F	590		590		620	
Flammability (1/8" bar)	UL-94		HB		HB		HB	
Coefficient of Thermal Expansion	E 831	10^{-5} in/in°F						
32° to 212°F FD[1]			1.3		0.8		1.2	
TD[2]			3.3		2.8		3.3	
320° to 480°F FD[1]			0.8		0.6		0.8	
TD[2]			7.2		5.6		6.7	
Electrical								
Volume Resistivity	D 257	ohm-cm	1×10^{16}	2×10^{15}	1×10^{16}	2×10^{15}	2×10^{16}	5×10^{14}
High Voltage Arc Resistance	D 495	sec	140	120	145	125		
Comparative Tracking Index	D 3638	volts	550	550	550	550	>600	>600
Dielectric Constant	D 150							
at 60 Hz			4.4	4.7	4.6	4.9	3.8	4.3
at 1 MHz			4.2	4.3	4.4	4.5	3.6	3.4
Dissipation Factor	D 150							
at 60 Hz			0.005	0.009	0.005	0.009	0.004	0.020
at 1 MHz			0.017	0.022	0.016	0.021	0.012	0.019
General								
Specific Gravity	D 792		1.48(1.46)		1.56		1.45	
Moisture Absorption, 24 hr	D 570	%	0.21		0.12		0.29	
Mold Shrinkage	D 955	%						
Flow Direction			0.4	0.0	0.2	0.1	0.5	
Transverse Direction			0.8	0.2	0.6	0.1	1.0	

[1] FD = Flow direction, [2] TD = Transverse direction
Refer to page 7 for general information regarding the use of this table.

Table 9.
Typical Properties of Flame Retardant AMODEL Resins - SI Units

Property	**ASTM Method**	**Units**	**AF-1133 V0**		**AF-1550 V0**		**AFA-4133 V0**	**AFA-6133 V0**
			DAM	50% RH	DAM	50% RH	DAM	DAM
Mechanical								
Tensile Strength	D 638	MPa	179	169	145	116	165	170
Tensile Elongation	D 638	%	1.8		1.3	1.0	1.6	1.7
Tensile Modulus	D 638	GPa	13.8	13.8	16.5	16.5		
Flexural Strength	D 790	MPa	257	230	214	177	221	224
Flexural Modulus	D 790	GPa	13.1	13.1	14.1	14.1	13.2	13.2
Izod Impact	D 256	J/m						
Notched			80	53	64	59	85	85
Un-notched			460		386			
Rockwell Hardness	D 785	R	125					
Thermal								
Heat Deflection Temperature	D 648	°C						
at 1.8 MPa			273		263	243	295	277
Continuous Use Temperature	D 3045	°C						
5,000 hr.			190					
20,000 hr.			170					
Melting Point	D 3418	°C	310				325	310
Flammability (0.8 mm) bar	UL-94		V0		V0		V0	V0
Coefficient of Thermal Expansion	E 831	10^{-5} m/m°C						
0° to 100°C FD[1]			2.0					
TD[2]			3.9					
Electrical								
Dielectric Strength, 1.6 mm	D 149	kV/mm	24.8		25.8		24.5	24.0
Volume Resistivity	D 257	ohm-cm	3×10^{15}		4×10^{16}		1×10^{15}	1×10^{15}
High Voltage Arc Resistance		sec(PLC)[3]	>300 (0)		>300 (0)			
Comparative Tracking Index	D 3638	volts(PLC)	550 (1)		500 (1)			
Dielectric Constant	D 150							
at 100 Hz			4.0		4.3	4.7		
at 1 MHz			4.9		4.3	4.6	4.2	4.1
Dissipation Factor	D 150							
at 100 Hz			0.009		0.005	0.018		
at 1 MHz			0.008		0.012	0.026	0.010	0.011
General								
Specific Gravity	D 792		1.71		1.82		1.68	1.68
Moisture Absorption, 24 hr	D 570	%	0.18		0.12			
Mold Shrinkage	D 955	%						
Flow Direction			0.2	0.0	0.3		0.3-0.5	0.3-0.4
Transverse Direction			0.4	0.0	0.3		0.4-0.7	0.5-0.7

[1] FD = Flow direction, [2] TD = Transverse direction

[3] PLC = Performance Level Class

Refer to page 7 for general information regarding the use of this table.

Table 10.
Typical Properties of Flame Retardant AMODEL Resins - U.S. Customary Units

Property	ASTM Method	Units	AF-1133 V0		AF-1550 V0		AFA-4133 V0	AFA-6133 V0
			DAM	50% RH	DAM	50% RH	DAM	DAM
Mechanical								
Tensile Strength	D 638	psi	26,000	24,500	21,000	16,900	24,000	24,700
Tensile Elongation	D 638	%	1.8		1.3	1.0	1.6	1.7
Tensile Modulus	D 638	kpsi	2,000	2,000	2,400	2,400		
Flexural Strength	D 790	psi	37,300	33,400	31,000	25,700	32,100	32,500
Flexural Modulus	D 790	kpsi	1,900	1,900	2,040	2,040	1,920	1,910
Izod Impact	D 256	ft-lb/in						
Notched			1.5	1.0	1.2	1.1	1.6	1.6
Un-notched			8.7		7.3			
Rockwell Hardness	D 785	R	125					
Thermal								
Heat Deflection Temperature	D 648	°F						
at 264 psi			523		505	470	563	590
Continuous Use Temperature	D 3045	°F						
5,000 hr.			374					
20,000 hr.			338					
Melting Point	D 3418	°F	590		590		617	590
Flammability (1/32") bar	UL-94		V0		V0		V0	V0
Coefficient of Thermal Expansion	E 831	10^{-5} in/in°F						
32 to 212°F FD [1]			1.1					
TD [2]			2.2					
Electrical								
Dielectric Strength, 1/16"	D 149	V/mil	610		635		600	590
Volume Resistivity	D 257	ohm-cm	3×10^{15}		4×10^{16}		1×10^{15}	1×10^{15}
High voltage Arc Resistance		sec(PLC)[3]	>300 (0)		>300 (0)			
Comparative Tracking Index	D 3638	volts(PLC)	550 (1)		500 (1)			
Dielectric Constant	D 150							
at 100 Hz			4.0		4.3	4.7		
at 1 MHz			4.9		4.3	4.6	4.2	4.1
Dissipation Factor	D 150							
at 100 Hz			0.009		0.005	0.018		
at 1 MHz			0.008		0.012	0.026	0.010	0.011
General								
Specific Gravity	D 792	g/cc	1.71		1.82		1.68	1.68
Moisture Absorption, 24 hr	D 570	%	0.18		0.12			
Mold Shrinkage	D 955	%						
Flow Direction			0.2	0.0	0.3		0.3-0.5	0.3-0.4
Transverse Direction			0.4	0.0	0.3		0.4-0.7	0.5-0.7

[1] FD = Flow direction, [2] TD = Transverse direction
[3] PLC = Performance Level Class
Refer to page 7 for general information regarding the use of this table.

DOWN-HOLE OIL PRODUCTION SUCKER ROD GUIDES

In reciprocating pump oil production, sucker rod friction and wear is a major cost and down-time problem. Imagine inserting a piece of spaghetti down a straw without touching the sides! That "straw" can extend down 4,000 to 6,000 feet!

To help solve the wear problem, plastic sucker rod guides - or spacers - are used to keep the rod off the tubing. They must attach tightly, without slipping. They need chemical resistance, dimensional stability, friction and wear properties, fatigue resistance and thermal properties. Cost is also an important consideration.

A variety of plastics and fillers/reinforcements have been used for this application, including nylon 6,6 and polyphenylene sulfide (PPS). Recently, AMODEL PPA has been introduced to fill the cost-performance gap between the engineering polymers and the high-cost specialty resins.

Guideco Corporation, headquartered in Houston, introduced their Guidel™ sucker rod guides molded of AMODEL PPA in 1992. Their testing program shows that AMODEL PPA has better practical toughness and mechanical properties than PPS or nylon 6,6. All have similar chemical resistance. But where abrasion is the problem, AMODEL resin is comparable to nylons and vastly superior to PPS. It is more resistant to wear than PPS, and significantly less abrasive to steel. It also withstands higher temperatures without loss of stiffness - a problem with the nylons.

MECHANICAL PROPERTIES

The mechanical properties of a material are of fundamental importance to engineers when designing a part. The designer must match the mechanical properties of the candidate materials to the performance requirements of the application in order to achieve an optimum part design.

The challenge facing the design engineer familiar only with designing with metals is the fact that the mechanical properties of polymeric materials are much more time and temperature dependent. Also, while polymers generally don't corrode, their properties may be adversely affected by environmental factors such as ultraviolet radiation, humidity, or exposure to chemicals.

AUTOMOTIVE TRANSMISSION STUB TUBES

Ford Motor Company's Transmission Div., Livonia, Michigan, selected AMODEL PPA resin for two different transmission stub tube configurations. One is for automatic four-speed overdrive small truck and larger car transmissions. The other has provision for an electronic transmission fluid level sensor.

AMODEL resin was selected after both polyetherimide and nylon 6,6 failed to withstand service temperatures up to 550°F (288°C) [due to proximity of the exhaust system], a Ford spokesperson pointed out.

For transmission components, AMODEL resins have excellent chemical resistance and are superior to conventional nylons in mechanical, thermal and friction-wear properties for thrust washers, bearing retainers, accumulator and servo parts.

To design successfully with polymeric materials, the designer must consider not only the short-term mechanical properties, those typically listed on the material supplier's data sheets, but also the time, temperature, and environmental behavior of the material.

To assist the designer, the material properties listed in this manual have been grouped into short-term or instantaneous and long-term or time-dependent properties.

Short-term Mechanical Properties

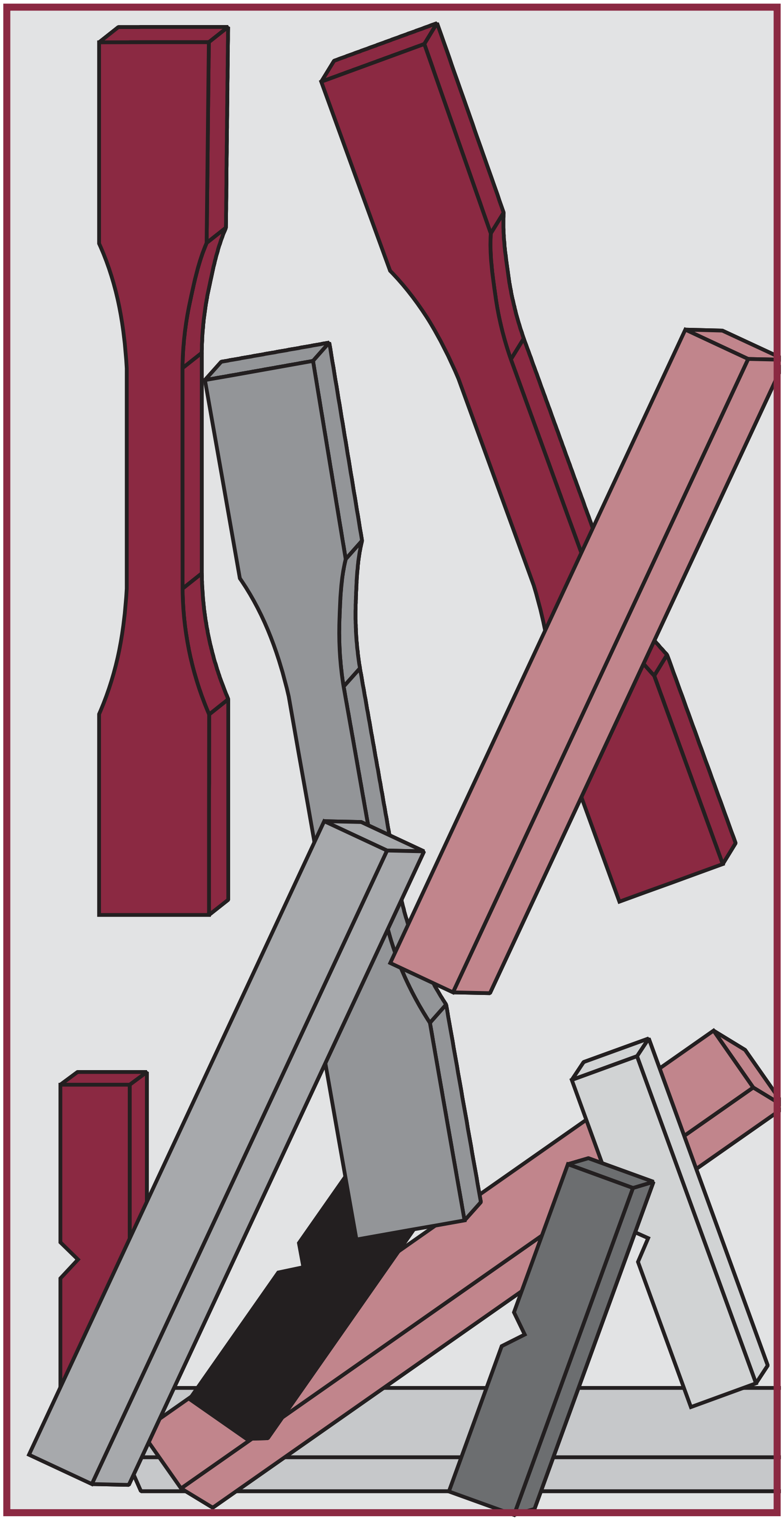
Short-term mechanical properties typically include tensile strength and modulus, flexural strength and modulus, notched Izod impact, compressive strength, shear strength, and surface hardness. These properties are usually reported at room temperature, and other temperatures as appropriate. Moisture content may also be specified, often using the Relative Humidity (RH) convention.

The data sheets provided by the material suppliers typically list short-term properties, and their primary utility is for comparing similar materials.

The utility of short-term mechanical properties in design is limited. Typically, the properties are measured using molded test specimens that have been specifically designed to produce reproducible results, under carefully controlled environmental conditions, using specified loading rates. These measurements often provide the highest value obtainable for any property and material.

Actual components often contain stress concentrations, weld lines, or other features that may reduce strength. The strength of a material in an actual component may also be reduced, or in rare cases enhanced, by reinforcing fiber orientation, amount of crystallinity, or thermal history. In addition, short-term properties do not provide any guidance regarding time-related effects or the influence of chemical environments.

A more complete discussion of the use of these data in design can be found in the “Design Information” section beginning on page 77.



Tensile Properties

Tensile properties are determined by clamping each end of a test specimen in the jaws of a testing machine that applies a unidirectional axial force to the specimens at a specified rate in accordance with ASTM method D 638, *Standard Test Method for Tensile Properties of Plastics*. The force required to separate the jaws divided by the minimum cross-sectional area of the test specimen is defined as the tensile stress. The test specimen will elongate as a result of the stress being applied. The amount of elongation divided by the original length of the test specimen is the strain.

When the applied stress is plotted against the resulting strain, a curve similar to that shown in Figure 5 for AMODEL ET-1000 HS resin is obtained. The curve of a ductile metal would have a similar shape.

The initial portion of the stress/strain curve is of special interest because its slope relates to the stiffness or modulus of the material as shown in Figure 6. This figure shows that the strain is directly proportional to stress up to a certain amount of stress. This region is know as the “Hookean” or elastic region. The maximum stress level that results in a proportional amount of strain is known as the proportional limit.

The tensile or elastic modulus is the slope of the stress/strain curve when a specimen is subjected to a tensile loading. Since the stress/strain plot is non-linear above the proportional limit, some conventions have been developed to standardize the measurements and reduce the variability in test results. One method uses the slope of a line drawn tangent to the curve. Another method utilizes the slope of a secant drawn through the origin and some arbitrarily designated strain level, usually 1%. The tangent method was used for the data presented in this brochure. Therefore, estimates of strain based upon these moduli will be low at higher stress levels.

Ductile polymers undergo a “yield” prior to rupture. At this point, the material undergoes additional elongation without an increase in stress. The stress level at which yield occurs is often referred to as tensile strength at yield. The elongation achieved at this point is called the elongation at yield or yield strain. As the test proceeds, the specimen is elongated until rupture occurs. The stress level at this point is called tensile strength at break or ultimate tensile strength. The test method used for determining tensile properties, ASTM D 638, defines tensile strength as the greater of measured stresses which could be either the stress at yield or the stress at rupture.

Figure 5. Typical Stress/Strain Curve AMODEL ET-1000 HS

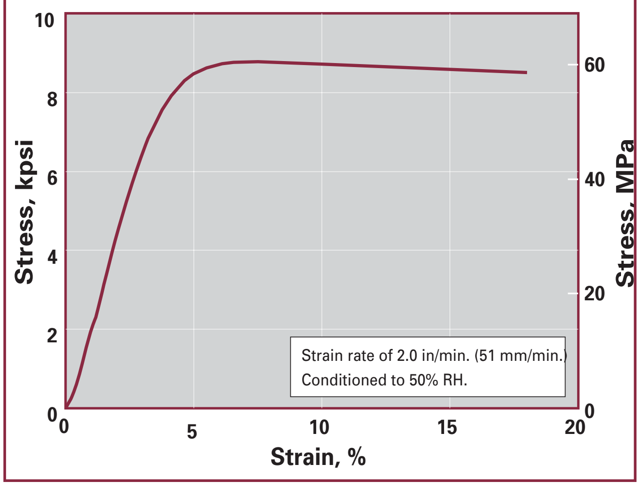
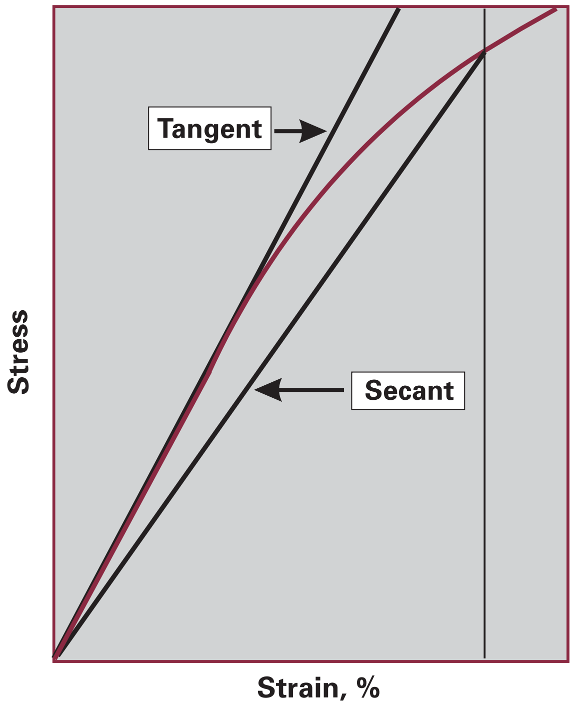


Figure 6. Stress/Strain Curve Secant vs. Tangent Modulus



Tensile Properties of Toughened AMODEL Resin

Table 11 shows the tensile strength and elongation of AMODEL ET-1000 HS resin, a toughened grade, at -40°F (-40°C) and 73°F (23°C). This behavior is typical of most plastics; that is, the strength typically decreases and the elongation at break increases with increasing temperature.

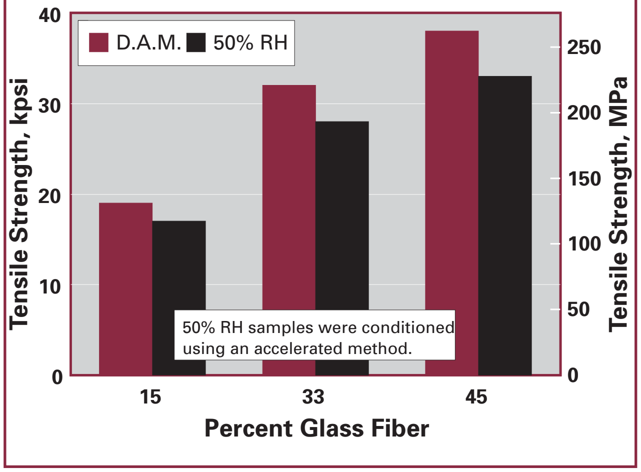
Table 11.
Tensile Properties of AMODEL ET-1000 HS Resin

Tensile Property	**AMODEL ET-1000 HS** DAM	**AMODEL ET-1000 HS** 50% RH
Strength, ksi (MPa)		
at -40°F (-40°C)	16.0 (110)	14.0 (96)
at 73°F (23°C)	10.0 (69)	9.1 (63)
Elongation at Yield, %		
at -40°F (-40°C)	9	9
at 73°F (23°C)	6	6
Elongation at Rupture, %		
at -40°F (-40°C)	12	11
at 73°F (23°C)	20	18

Tensile Properties of Glass Reinforced AMODEL Resins

Figure 7 shows the room temperature tensile strength of the glass fiber reinforced grades of AMODEL resin, both “dry, as molded” (DAM) and conditioned to 50% RH. The tensile strength increases with glass fiber content, which is typical of semi-crystalline thermoplastics.

Figure 7. Tensile Strength of Glass Reinforced AMODEL Resins



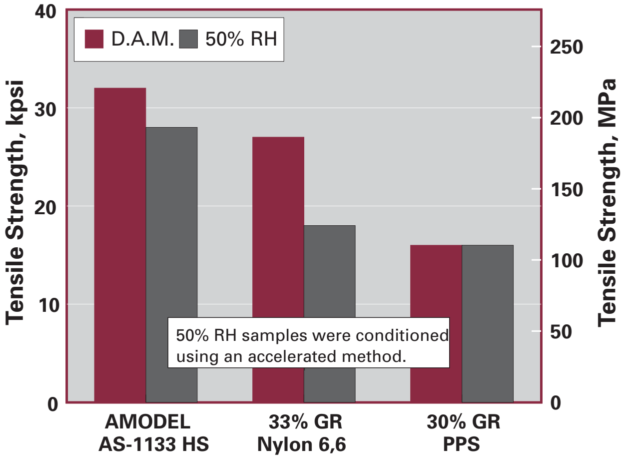
50% RH samples were conditioned using an accelerated method.

Strength Comparison of Glass Reinforced Resins

Figure 8 presents a comparison of the tensile strength of 33% glass fiber reinforced AMODEL resin to that of glass reinforced nylon 6,6 and polyphenylene sulfide when tested "dry, as molded" and conditioned to 50% RH.

Comparing the materials “dry, as molded”, the AMODEL resin is about 15% stronger than the comparable nylon grade. Comparing the materials conditioned to 50% RH, the AMODEL resin is about 35% stronger. The typical 30% glass reinforced PPS resins have between 50 and 60% the strength of a comparable AMODEL resin.

Figure 8. Tensile Strength Comparison Glass Reinforced Resins



50% RH samples were conditioned using an accelerated method.

Tensile Strength at Elevated Temperature

Like other engineering materials, the tensile strength of AMODEL resins decrease with increasing temperatures and higher moisture contents.

Figure 9 shows the tensile strength of "dry, as molded" glass fiber reinforced AMODEL resins at temperatures from roughly -30° to 350°F (-34° to 177°C). At 300°F (149°C), the tensile strength of these resins is about 40 percent of the room temperature value. Since the 45 percent glass fiber reinforced grade has the highest strength at room temperature, it also has the highest strength at elevated temperature.

The effect of elevated temperature on the tensile strength of these materials conditioned to 50% RH is shown in Figure 10. The temperature range used for testing these materials was limited to about 200°F (93°C) because exposing the conditioned test specimens to higher temperatures long enough to achieve thermal equilibrium results in the loss of some of the absorbed moisture, invalidating the test.

Comparing the room temperature tensile strength of "dry, as molded" versus 50% RH conditioned materials shows that moisture conditioning reduces the strength by approximately 15 percent. Comparing the strengths at 150°F (66°C) shows a strength reduction of about 30 percent due to moisture.

Figures 11 and 12 show the results of similar testing using mineral filled and glass fiber reinforced/mineral filled AMODEL resins.

Figure 9. Tensile Strength vs. Temperature Glass Reinforced AMODEL Resins "dry, as molded"

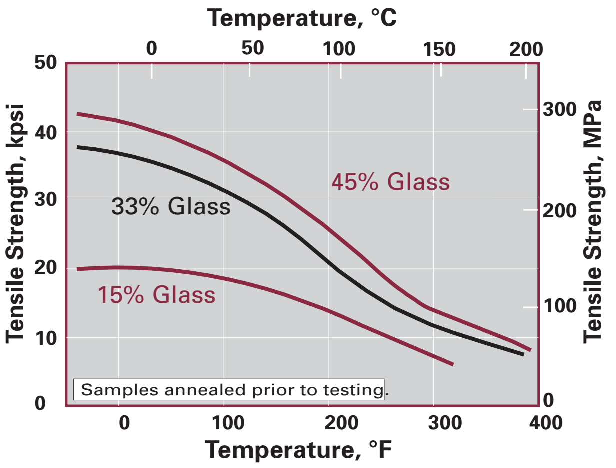


Figure 10. Tensile Strength vs. Temperature Glass Reinforced AMODEL Resins Conditioned to 50% RH

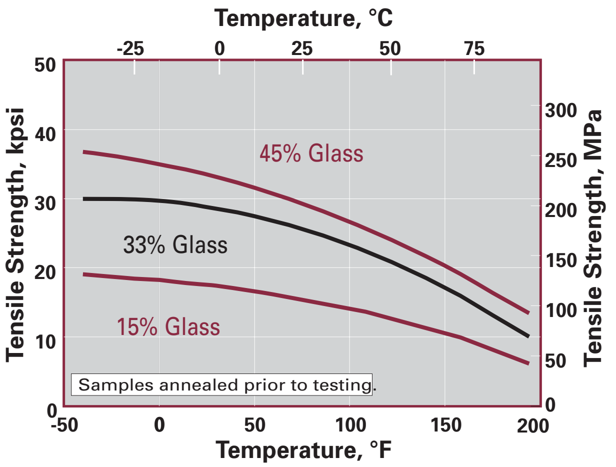


Figure 11. Tensile Strength vs. Temperature Mineral and Glass/Mineral Filled AMODEL Resins - "dry, as molded"

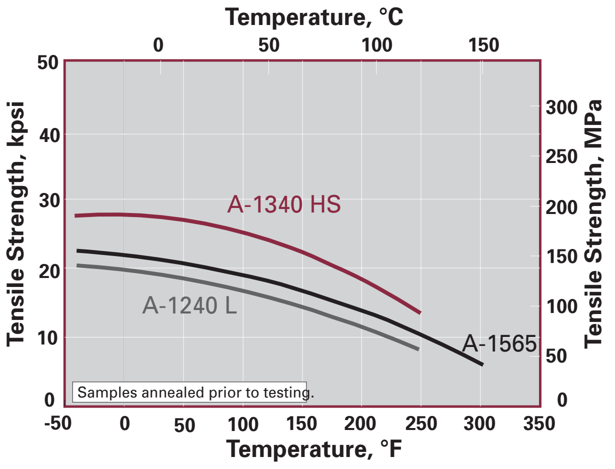
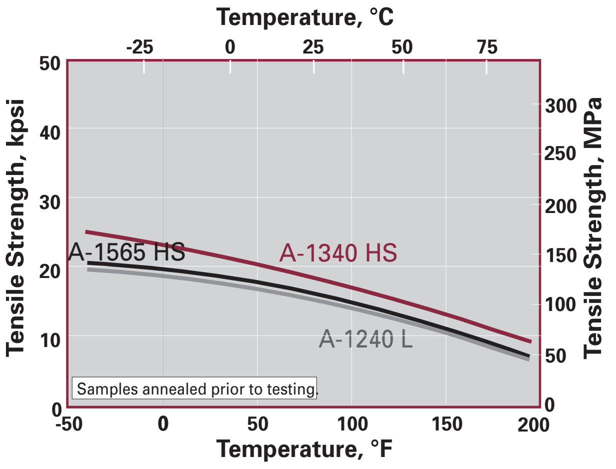


Figure 12. Tensile Strength vs. Temperature Mineral and Glass/Mineral Filled AMODEL Resins - Conditioned to 50% RH



Elevated Temperature Tensile Strength Comparison

Figure 13 shows the tensile strength of AMODEL AS-1133 HS resin and 33% glass fiber reinforced nylon 6,6 resin when tested "dry, as molded" over the temperature range -50° to 600°F (-45° to 316°C). AMODEL polyphthalamide has a clear tensile strength advantage over the competitive resin at temperatures up to about 300°F (149°C).

Figure 14 compares the tensile strength of AMODEL AS-1133 HS resin with that of a 33% glass fiber reinforced nylon 6,6 resin as a function of temperature, in both cases, using specimens conditioned to 50% relative humidity. The tensile strength of conditioned AMODEL resin is higher than that of conditioned nylon 6,6 resin at temperatures up to 212°F (100°C).

Figure 13. Tensile Strength vs. Temperature Comparison of GR AMODEL Resin and GR Nylon 6,6 "dry, as molded"

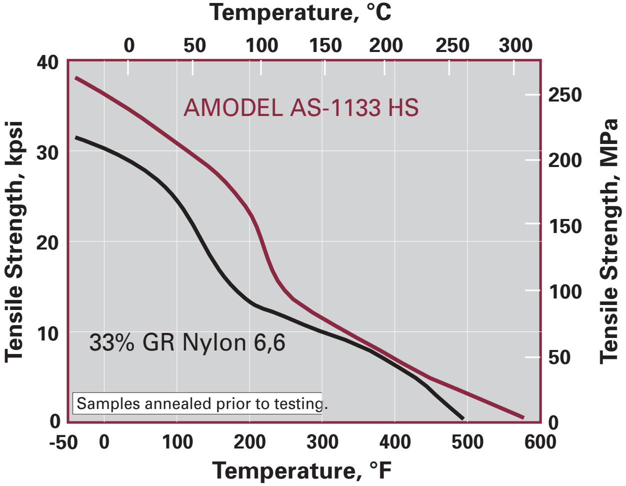
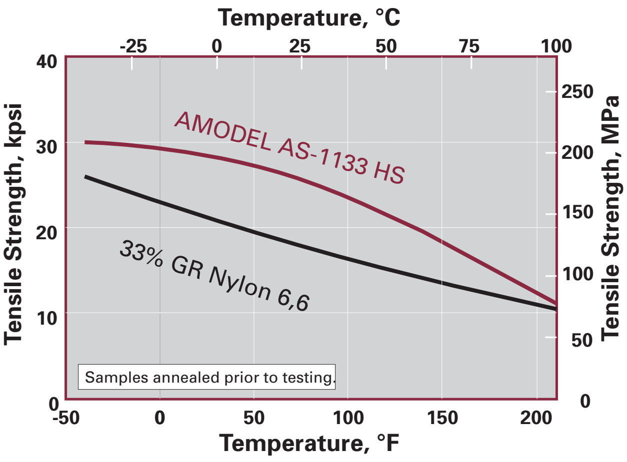


Figure 14. Tensile Strength vs. Temperature Comparison of GR AMODEL Resin and GR Nylon 6,6 Conditioned to 50% RH



Flexural Properties

Flexural properties of thermoplastic materials are determined in accordance with ASTM D 790, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, using the 3 point loading method, *Test Method I*, as shown in Figure 15. In this method, an injection molded test specimen, typically 5.0 x 0.50 x 0.125 inch (127 x 12.7 x 3.2 mm), is suspended on two supports and a vertical load is applied to the top of the test specimen at a point midway between the supports. The test specimen will deform or bend as a result of the load. In this test, the test specimen simultaneously undergoes tensile loading of the outer fiber of the lower surface and compressive loading of the upper surface.

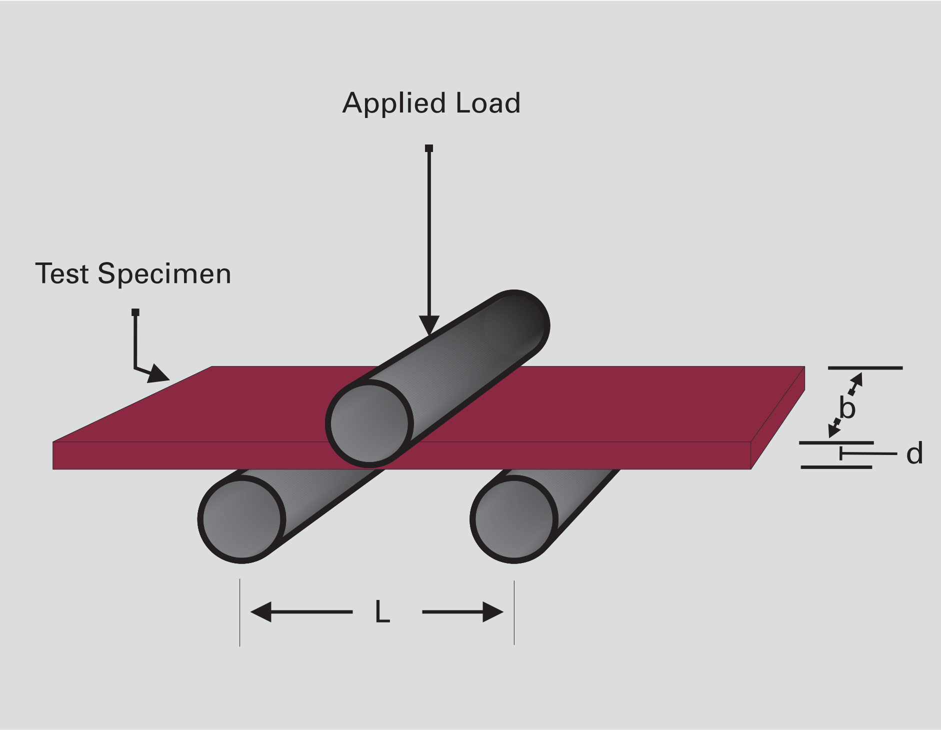
The specimen is deflected until rupture occurs or the maximum fiber strain of 5% is reached. The flexural strength is defined as the maximum fiber stress at the moment of rupture.

The flexural modulus of elasticity is the ratio, within the elastic limit, of the stress in the outermost fiber of the object being stressed to corresponding strain. As in tensile testing, the modulus is calculated from the slope of the load deflection curve in the linear “Hookean” region.

Flexural testing provides information about the relative strength and stiffness of materials when subjected to bending loads. The material with the higher flexural strength can endure higher bending loads without fracture. Parts produced from a material with a higher flexural modulus will deflect less when subjected to a bending load than parts made of a lower modulus material.

Glass fibers and mineral additives increase the flexural modulus of AMODEL PPA compared to the unfilled resin. The resultant higher modulus may be desirable in many applications.

Figure 15. Flexural Test Appartus



Calculation of Flexural Strength

Flexural strength is calculated in accordance with beam theory in which the following equation is used to determine the maximum fiber stress:

$$\sigma = \frac{3PL}{2bd^2}$$

where:

σ = stress in the outer fiber at midspan

P = load at rupture

L = support span

b = beam width

d = beam depth

Flexural Strength of Unreinforced Toughened AMODEL Resin

Table 12 shows the flexural strength and modulus of the unreinforced AMODEL ET-1000 HS polyphthalamide.

Table 12.
Flexural Properties of AMODEL ET-1000 HS Resin

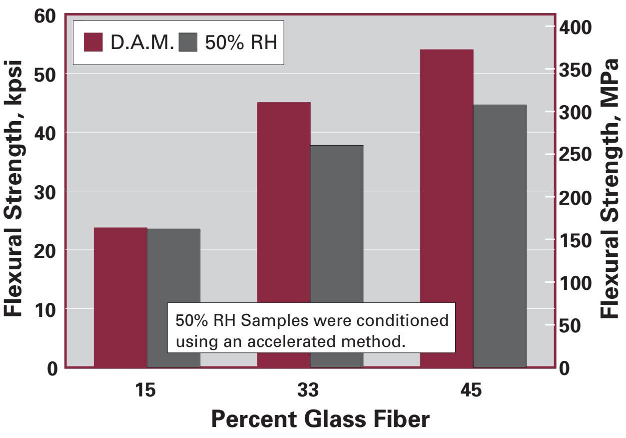
	AMODEL ET-1000 HS	
Flexural Property	DAM	50% RH
Flexural Strength, kpsi (MPa)	15.8 (109)	12.4 (85)
Flexural Modulus, kpsi (GPa)	330 (2.28)	313 (2.16)

Flexural Strength of Glass Reinforced Resins

Like tensile strength and modulus, the flexural strength and modulus of a plastic material can be increased by adding specially treated glass fibers into the plastic resin. Treatment of the glass fibers can produce a strong chemical bond between the plastic and the glass that enhances both tensile and flexural properties over a wide range of environmental conditions. As the amount of glass fiber reinforcement is increased in the plastic, both the flexural strength and modulus increase.

Figure 16 shows the room temperature flexural strength of the glass fiber reinforced grades of AMODEL resin "dry, as molded" and conditioned to 50% RH.

Figure 16. Flexural Strength of Glass Reinforced AMODEL Resins

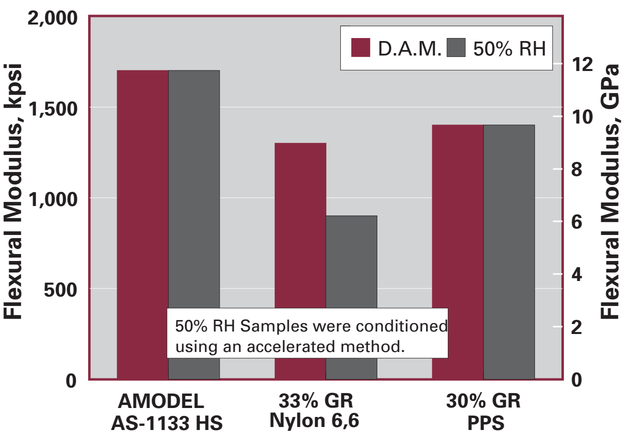


50% RH Samples were conditioned using an accelerated method.

Comparison of Flexural Modulus of GR Resins

Figure 17 compares the flexural modulus of 33% glass fiber reinforced AMODEL resin with that of nylon 6,6 and polyphenylene sulfide tested "dry, as molded" and conditioned to 50% RH. This graph shows that AMODEL PPA has a higher modulus than both the nylon and the polyphenylene sulfide. AMODEL PPA also retains its modulus when conditioned to 50% RH, while the modulus of the nylon resin declines significantly.

Figure 17. Flexural Modulus Comparison of 33% Glass Reinforced Resins



50% RH Samples were conditioned using an accelerated method.

Flexural Strength at Elevated Temperature

Figure 18 shows the relationship between the flexural strength of glass fiber reinforced AMODEL resins that have been tested when “dry, as molded” and the test temperature.

Figure 19 shows this relationship for the flexural strength of glass fiber reinforced AMODEL resins that have been conditioned to 50% RH. As these two figures demonstrate, increasing the glass fiber content in AMODEL PPA increases its flexural strength at all temperatures shown.

Figure 20 shows the flexural strength of mineral filled and mineral/glass reinforced AMODEL PPA resins tested “dry, as molded” versus temperature.

Figure 21 shows the flexural strength of mineral filled AMODEL resins that have been conditioned to 50% RH versus temperature.

Figure 18. Flexural Strength vs. Temperature Glass Reinforced AMODEL Resins “dry, as molded”

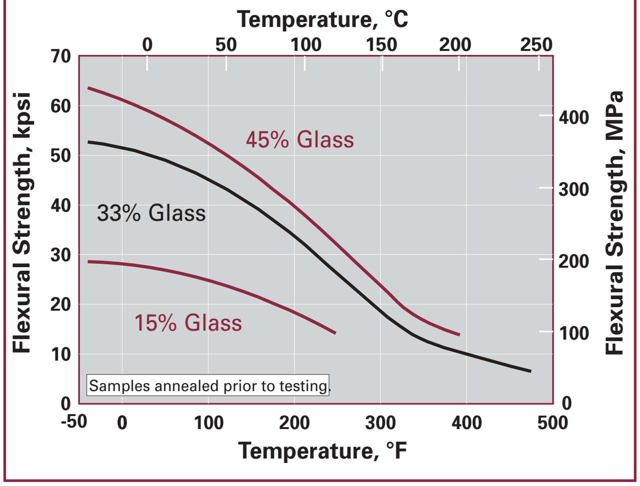


Figure 19. Flexural Strength vs. Temperature Glass Reinforced AMODEL Resins Conditioned to 50% RH

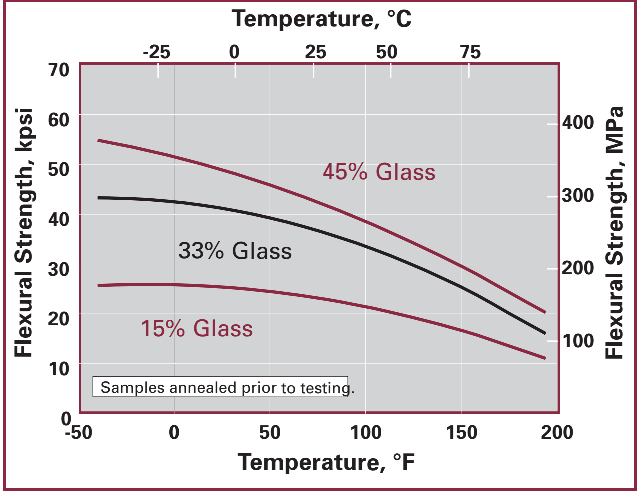


Figure 20. Flexural Strength vs. Temperature Mineral, Mineral/Glass Filled AMODEL Resins “dry, as molded”

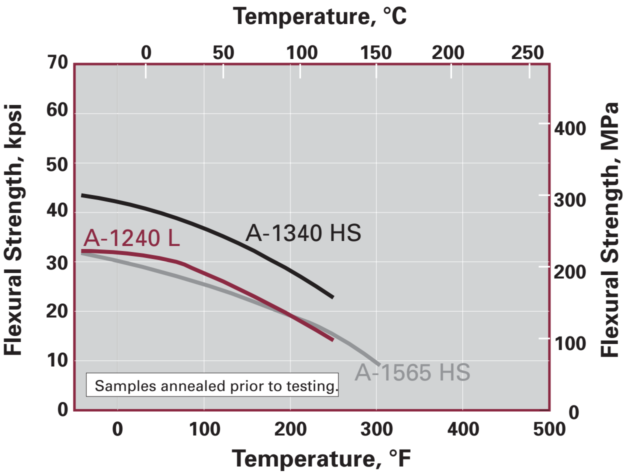
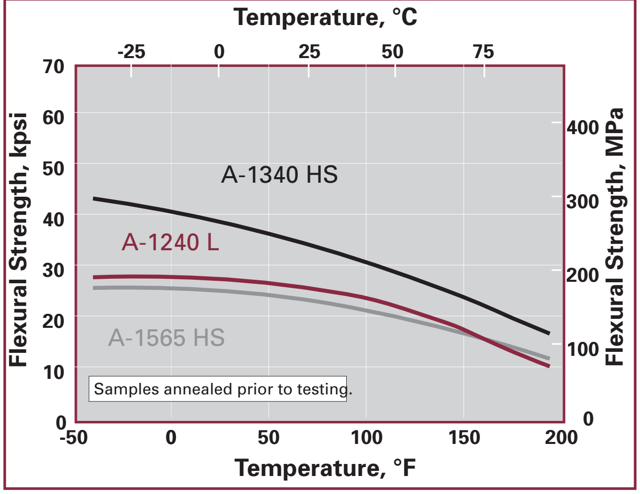


Figure 21. Flexural Strength vs. Temperature Mineral, Mineral/Glass Filled AMODEL Resins Conditioned to 50% RH



Flexural Modulus at Elevated Temperature

Figure 22 shows the flexural modulus of glass fiber reinforced AMODEL resins tested "dry, as molded" versus temperature.

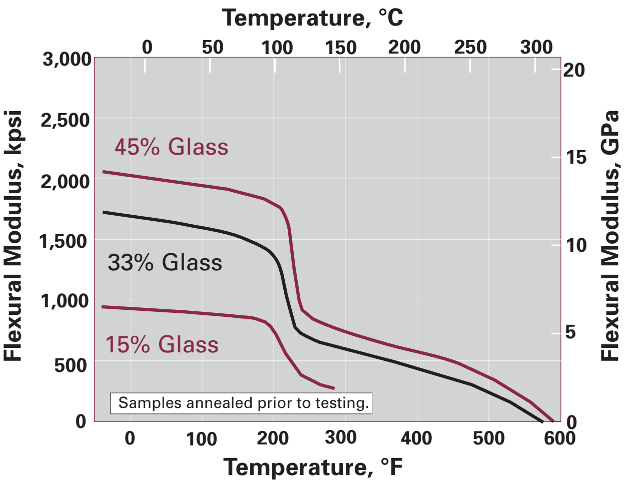
Figure 23 shows the flexural modulus versus temperature plots for glass fiber reinforced AMODEL resins tested after being conditioned to 50% relative humidity. As these two figures demonstrate, increasing the glass fiber content in AMODEL PPA increases in the flexural modulus at all temperatures shown.

Figure 24 shows the modulus of mineral filled and mineral/glass reinforced AMODEL resins tested "dry, as molded" conditions as a function of test temperature.

Figure 25 shows the modulus of mineral filled AMODEL resins conditioned to 50% RH versus temperature.

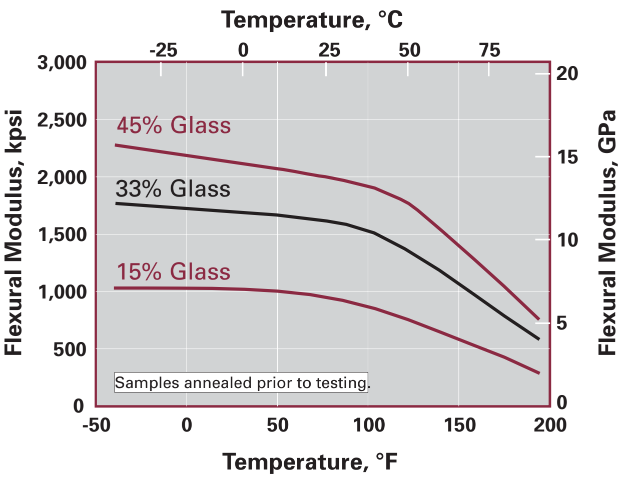
In some instances, the modulus actually increases upon conditioning. This is due to the relieving of molded-in stresses in the test part and/or additional annealing that occurs during the accelerated moisture conditioning step which is done at a temperature above the T_g of the material.

Figure 22. Flexural Modulus vs. Temperature
Glass Reinforced AMODEL Resins
"dry, as molded"



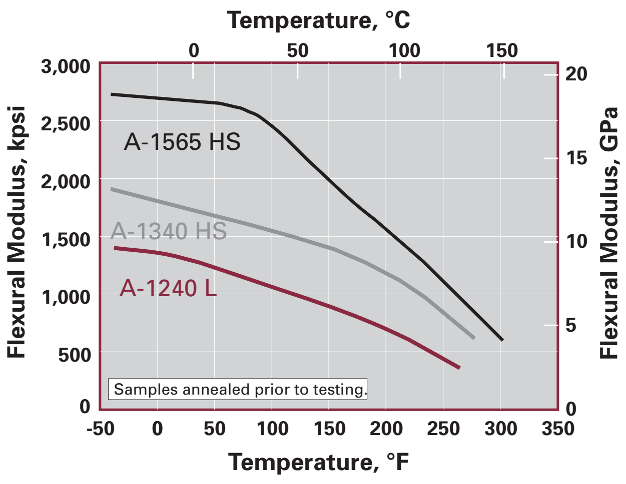
Samples annealed prior to testing.

Figure 23. Flexural Modulus vs. Temperature
Glass Reinforced AMODEL Resins
Conditioned to 50% RH



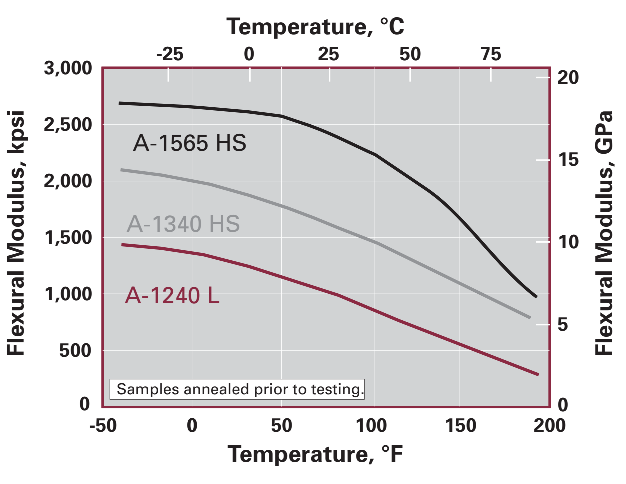
Samples annealed prior to testing.

Figure 24. Flexural Modulus vs. Temperature
Mineral, Mineral/Glass Filled AMODEL Resins
"dry, as molded"



Samples annealed prior to testing.

Figure 25. Flexural Modulus vs. Temperature
Mineral, Mineral/Glass Filled AMODEL Resins
Conditioned to 50% RH

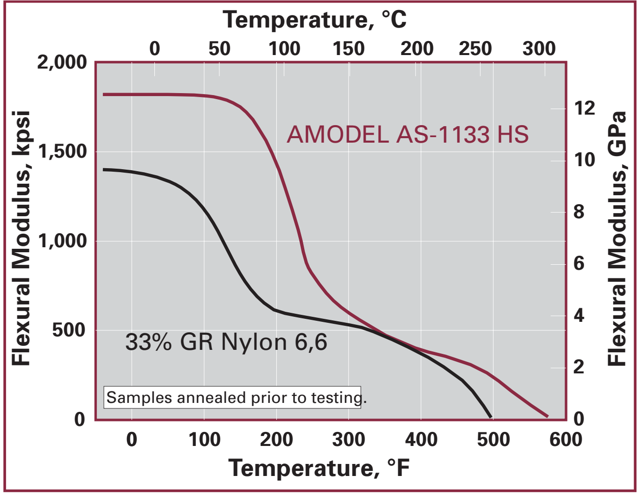


Samples annealed prior to testing.

Elevated Temperature Flexural Moduli Comparison to Nylon 6,6

Figure 26 shows a comparison between the flexural modulus of AMODEL AS-1133 HS resin with the flexural modulus of a 33% glass reinforced nylon 6,6 when tested under "dry, as molded" conditions. The AMODEL resin is clearly stiffer than the nylon resin at all temperatures up to 300°F (149°C).

Figure 26. Flexural Modulus vs. Temperature Comparison of GR AMODEL and GR Nylon 6,6 Resins "dry, as molded"

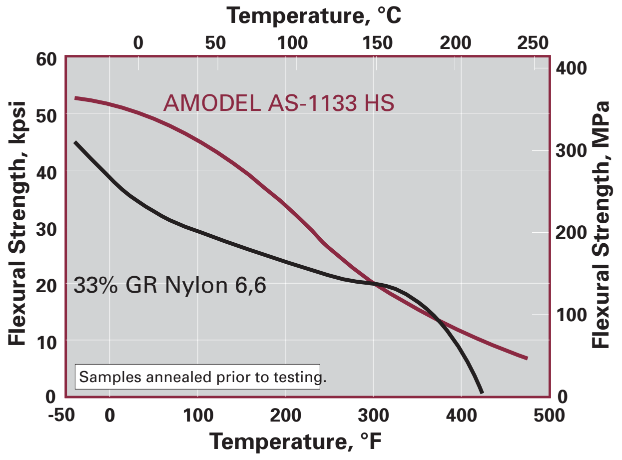


Samples annealed prior to testing.

Elevated Temperature Flexural Strength Comparison to Nylon 6,6

Figure 27 compares the flexural strength of AMODEL AS-1133 HS resin with that of 33% glass reinforced nylon 6,6 as a function of temperature when tested under "dry, as molded" conditions. The AMODEL resin has clearly higher strength at temperatures below 300°F (149°C).

Figure 27. Flexural Strength vs. Temperature Comparison of GR AMODEL and GR Nylon 6,6 "dry, as molded"



Samples annealed prior to testing.

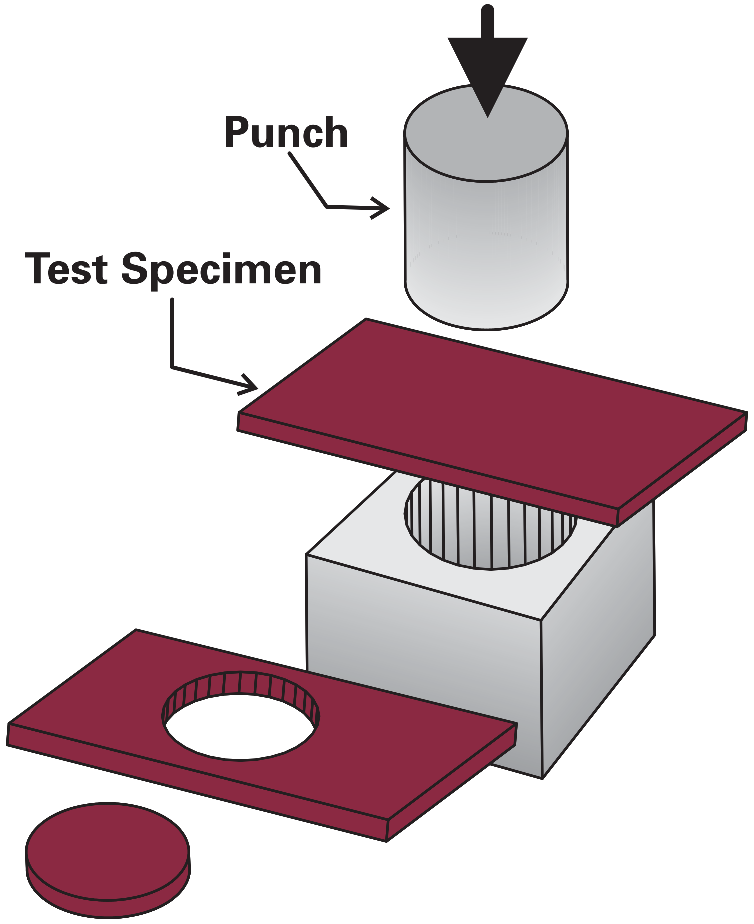
Shear Properties

Shear strength is the resistance to yield or fracture of two planes moving relative to one another in the direction of load. Shear strength can also be defined as the maximum load required to shear the specimen being tested in such a manner that the moving plane has completely cleared the stationary plane.

Shear strength values are important in designing structural components because in actual applications the maximum stress on a component is often a shear stress.

Shear strength was determined in accordance with ASTM D 732, *Standard Test Methods for Shear Strength of Plastics by Punch Tool*. In this test, a plaque molded from the material to be tested is placed on a plate with a circular hole in it. A circular punch whose diameter is slightly smaller than the hole in the plate is pushed through the molded plaque, punching out a circular disc. The maximum stress is reported as the shear strength, and is calculated by dividing the load required to shear the specimen by the sheared area, which is calculated by multiplying the circumference of the hole by the thickness of the plaque.

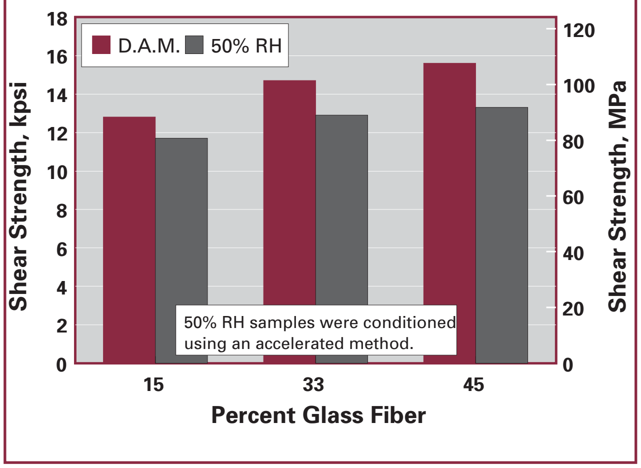
Figure 28. Shear Strength Test Apparatus



Shear Strength of AMODEL GR Resins

Figure 29 shows the shear strength of the glass fiber reinforced grades of AMODEL resin tested “dry, as molded” and conditioned to 50% RH. While increasing the glass content does cause the shear strength to increase, the change is considerably smaller than is the case with the tensile and/or flexural strengths. (Refer to Figure 7 on page 20 and Figure 16 on page .)

Figure 29. Shear Strength of Glass Reinforced AMODEL Resins

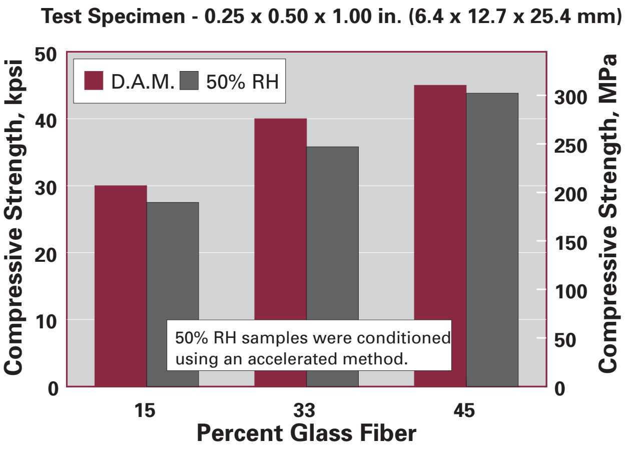


50% RH samples were conditioned using an accelerated method.

Compressive Properties

Compressive strength and modulus are measured in accordance with ASTM D 695, *Standard Test Methods for Compressive Properties of Rigid Plastics*. The test specimen is molded from the material to be tested and then placed between parallel plates. These plates then exert a compressive force on the specimen, while the force and the distance between the parallel plates is monitored. The compressive strain is given by the change in the distance between the plates. The stress at failure, calculated by dividing the force by the cross-sectional area, is the compressive strength, and the slope of the stress/strain curve is the compressive modulus.

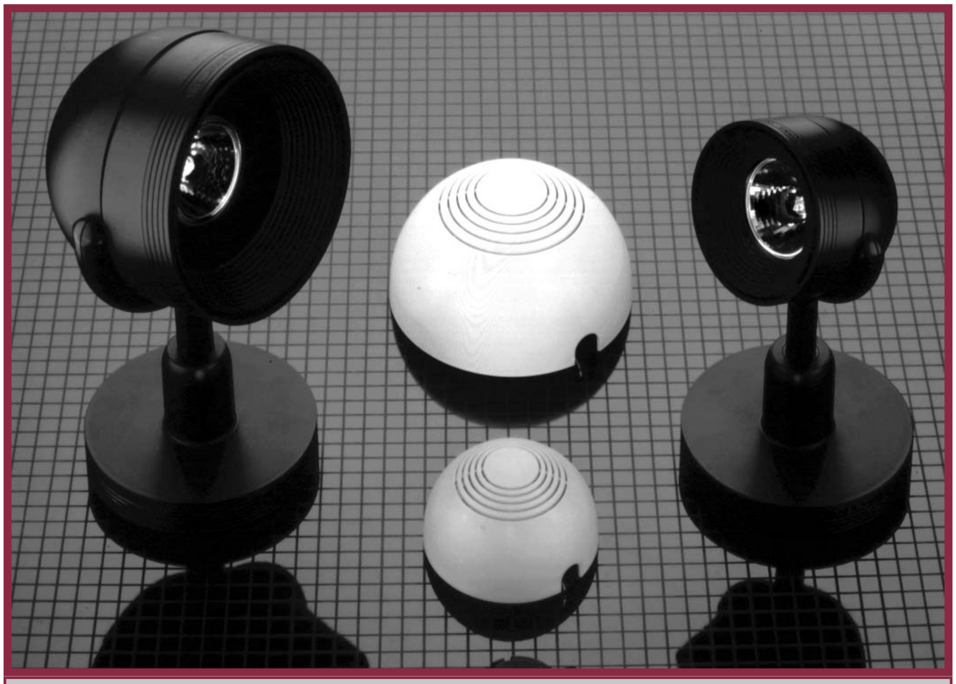
Figure 30. Compressive Strength of Glass Reinforced AMODEL Resins



50% RH samples were conditioned using an accelerated method.

In classical mechanical analysis, tension and compression differ only in algebraic sign. While this relationship is true for many metals, polymers typically have poorer strength in compression than tension.

AMODEL PPA resins have exceptional compressive strength as shown in Figure 30. This graph shows the compressive strength of the glass fiber reinforced grades of AMODEL resin when tested "dry, as molded" and conditioned to 50% RH.



GLASS-FILLED AMODEL PPA SELECTED FOR HALOGEN LAMP HOUSING COMPONENTS

Halloform GmbH has introduced a new concept in miniaturized, low-voltage, high-intensity halogen lamp designs for architectural, artistic and decorative uses. They include spot, mini-flood, reflecting, ceiling and recessed models.

Glass-filled AMODEL polyphthalamide was selected for housing components, providing cost-effective design flexibility. It accepts metallic chrome and gold-toned coatings as well as many organic paint coatings, and withstands processing and service temperatures as high as 356°F (180°C).

The engineering thermoplastic is easy to process, molds with minimum flash and without tool abrasion, according to engineers with the German lighting fixture manufacturer.

Compressive Properties at Elevated Temperature

The measured compressive strength versus temperature for AMODEL AS-1133 HS resin is shown in Figure 31.

The compressive strength at 73°F (23°C) shown in Figure 31 is lower than the value reported in Figure 30 for AMODEL AS-1133 HS resin (40,000 psi). The difference in the values is due to the different size of the test specimens used in these two tests. The values in Figure 30 were determined using specimens with a 0.25 inch x 0.5 inch (6.4 mm x 12.7 mm) cross section, while the values in Figure 31 were determined using specimens with a 0.5 inch x 0.5 inch (12.7 mm x 12.7 mm) cross section. When the thinner specimen is molded, the glass fibers are oriented in the direction of stress application to a higher degree than with the thicker specimens. More glass fiber orientation in the direction of stress application yields higher compressive strength.

Figure 32 shows the compressive modulus of AMODEL AS-1133 HS resin tested "dry, as molded" versus temperature. Above the glass transition temperature of AMODEL AS-1133 HS resin [261°F (127°C)], there is a decrease in the compressive modulus of the resin. This is due to the greater mobility of the polymer chains at these temperatures.

Figure 31. Compressive Strength vs. Temperature AMODEL AS-1133 HS Resin

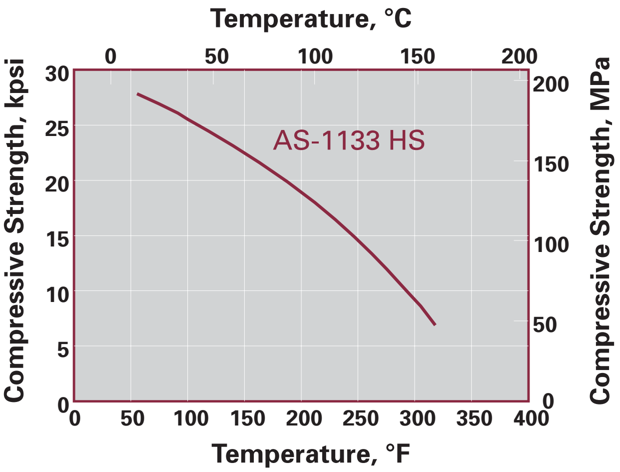
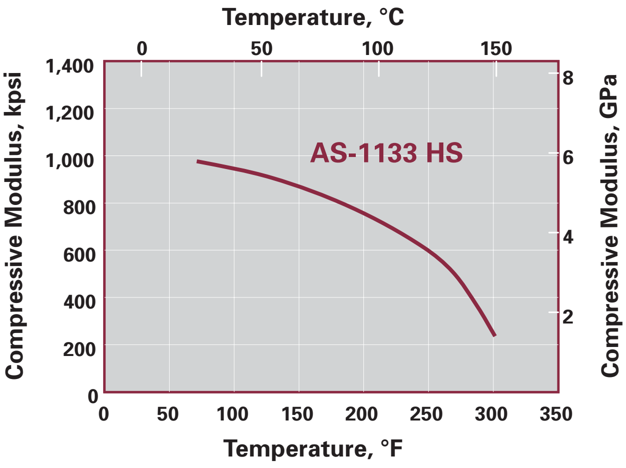


Figure 32. Compressive Modulus vs. Temperature AMODEL AS-1133 HS Resin



Impact Properties

Because polymers are viscoelastic, their properties depend upon the rate at which a load is applied. When the loading rate is rapid, the part is said to be subjected to impact loading. If a plastic part is to survive an impact without damage, it must be able to absorb the kinetic energy transferred by the collision.

The ability of a plastic part to absorb energy is a function of its shape, size, thickness, and the type of plastic used to make the part. The impact resistance testing methods most frequently used may not adequately provide the designer with information that can be used analytically. These tests are most useful for determining relative impact resistance and comparing the notch sensitivities of materials. The results may not adequately predict practical toughness in actual applications, and prototype testing is highly recommended.

The impact test used most frequently by the plastics industry is ASTM D 256, *Standard Test Methods for Impact Resistance of Plastics and Electrical Insulating Materials*. This test is commonly referred to as the “Izod impact test”, after the name associated with the specimen in *Test Method A* of the standard. Izod impact testing is a measure of the effect of sharp corners in a part on its ability to withstand impact rather than a measure of the part’s practical toughness.

Because of the limitations of ASTM D 256, other tests of impact resistance are sometimes used. One such method is ASTM D 3763, *Standard Test Method for High-Speed Puncture Properties of Plastics Using Load and Displacement Sensors*. This method is commonly referred to as “falling dart”, “drop weight”, or Dynatup® impact testing[1]. This test, or the similar but not instrumented test ASTM D 3029, *Standard Test Methods for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Tup (Falling Weight)*, better characterize the practical toughness of polymers.

ENGINE COOLING BLOWER MOTOR END PLATE

AMODEL PPA resin replaced a conventional nylon as the end frame material for an engine cooling blower motor for improved strength and stiffness. The customer is Delco Chassis Division, General Motors Corporation. AMODEL A-1133 HS resin meets Delco’s long-term thermal stability requirements at temperatures as high as 349°F (176°C), while providing excellent creep resistance and high stiffness properties over a wide range of temperatures and humidities.

The molder, Webster Plastics, Webster, NY, reports that the part molds easily and meets the close dimensional requirements. It also withstands Delco’s vibration and thermal shock test requirements.

Compared with conventional nylons, AMODEL PPA offers improved durability, strength and stiffness for valve covers and intake manifolds, as well as motor end frames.

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[1] "Dynatup" is a registered trademark of General Research Corporation.

Izod Impact Properties

ASTM D 256, *Impact Resistance of Plastics and Electrical Insulating Materials*, is the impact test most widely used by the plastics industry. In this test, a test specimen, as illustrated in Figure 33, with a notch of specified radius cut in its edge is struck by a swinging pendulum. After the impact, the pendulum continues to swing, but with less energy due to the collision. The amount of energy lost is reported as the Izod impact strength in units of foot-pounds per inch (ft-lbs/in) or Joules per meter (J/m) of notch width.

Occasionally this test is run using test specimens without a notch or with the notch facing away from the swinging pendulum. The difference between the energy required to break an unnotched and a notched specimen gives an indication of the relative effect of sharp corners on the impact resistance of a part. The effect of sharp corners is commonly referred to as the "notch sensitivity".

A quantitative method of evaluating the sensitivity of the impact strength of a material to sharpness of notch is to conduct a series of Izod impact tests with test specimens with notches of various radii. Figure 34 shows the results of such an experiment for AMODEL ET-1000 resin and polycarbonate. Polycarbonate, whose behavior is typical for amorphous resins, is extremely sensitive to notch radius and may perform poorly when sharp scratches or notches are cut into a part. In contrast, AMODEL ET-1000 HS resin is relatively insensitive to notch radius.

As shown in Figure 35, AMODEL ET-1000 HS resin has a notched Izod impact strength equal to or superior to other plastics known for their performance in this test.

Figure 33. Izod Impact Test Specimen

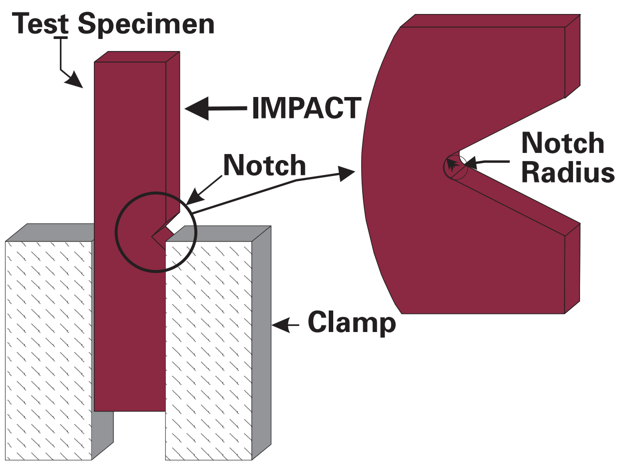


Figure 34. Effect of Notch Radius on Izod Impact

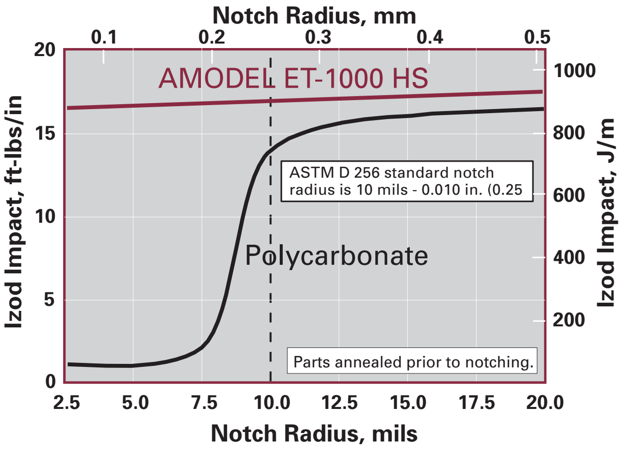
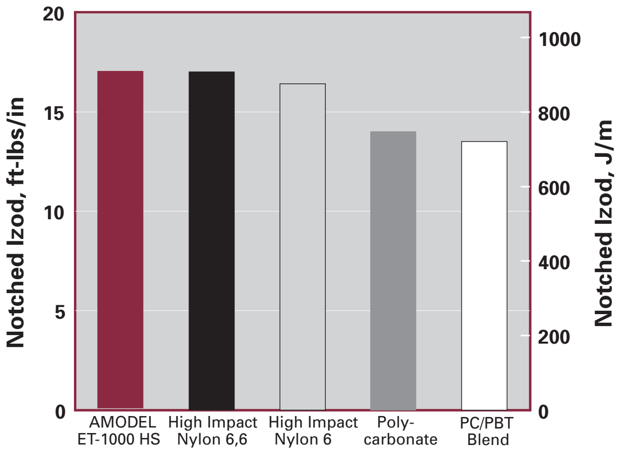


Figure 35. Izod Impact Resistance of Unreinforced Resins



Low Temperature Impact Strength of Toughened AMODEL Resins

As the ambient temperature decreases, plastic materials tend to become stiffer. Impact strength values also tend to decrease accordingly.

Figure 36 shows the notched Izod impact values of AMODEL ET-1000 HS and AMODEL AT-1000 NL resins at temperatures down to -50°F (-46°C). These data show that AMODEL PPA resins have good low temperature impact resistance.

Falling Weight Impact Properties

The practical toughness of AMODEL polyphthalamide resins was compared to impact-modified polyamides, using ASTM D 3763, an instrumented falling weight impact test.

In this test, an injection molded specimen is clamped down over a 3 inch (76 mm) diameter hole and a weighted plunger is dropped from a predetermined height to give it a predetermined impact velocity. The plunger assembly consists of a 0.500 inch (12.7 mm) diameter steel rod with a hemispherical end. The plunger assembly is attached to a load cell which measures the energy needed to cause a sample to fail.

Specimens can fail in either a brittle or a ductile mode. In a ductile failure mode, the specimen is permanently deformed to the shape of the plunger, but remains in one piece after the penetration by the plunger.

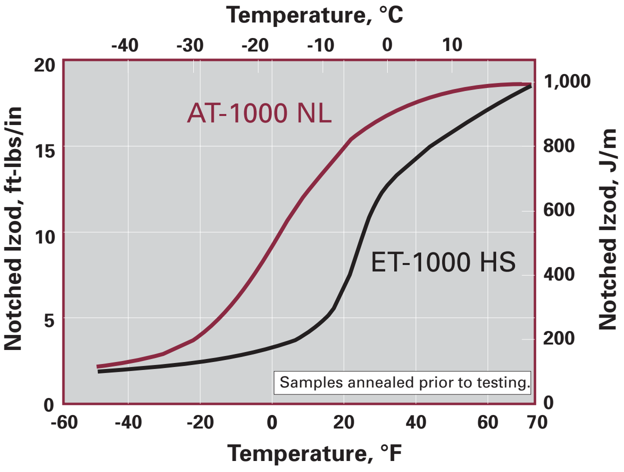
AMODEL ET-1000 HS and AMODEL AT-1000 NL resins fail in a ductile manner.

In a brittle failure mode, the specimen does not have sufficient ductility to be deformed without failure, and therefore breaks into two or more pieces when impacted by the plunger. The glass reinforced, glass/mineral reinforced, and mineral filled AMODEL resins all fail in a brittle manner.

This method is preferred to ASTM D 3029, because although the impact values obtained are similar in nature to the "stair step" falling weight impact test, the instrumented test results are obtained via a computerized data reduction technique and fewer samples are required.

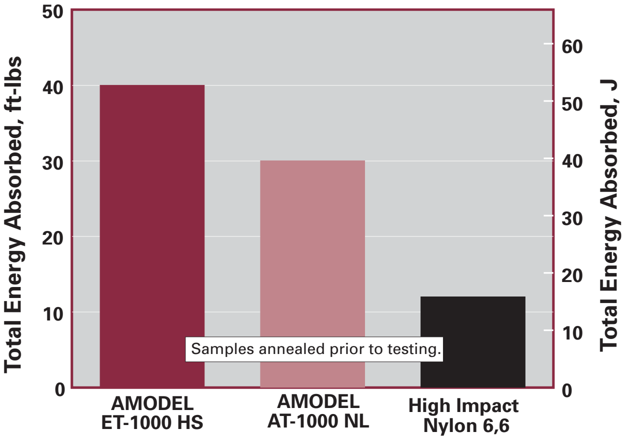
Figure 37 shows the instrumented falling weight impact resistance of neat AMODEL ET–1000 HS and AMODEL AT-1000 NL resins compared to a toughened nylon 6,6 conducted at room temperature.

Figure 36. Izod Impact vs. Temperature Toughened AMODEL Resins



Samples annealed prior to testing.

Figure 37. Falling Weight Impact Resistance of Unreinforced Resins



Samples annealed prior to testing.

Poisson’s Ratio

Poisson’s ratio is a measure of the strain characteristics imposed on a material transverse to the applied load.

Poisson’s ratio is the ratio of lateral strain to longitudinal strain within the proportional limit. To illustrate, consider a cylindrical bar subjected to tensile stress, the length (L) increases and simultaneously its diameter (D) decreases.

In this case, Poisson’s ratio (υ) would be calculated by:

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

Most plastic materials have a Poisson’s ratio between 0.3 and 0.5.

Table 13 gives the Poisson’s ratios for various AMODEL formulations at 73°F (23°C),”dry, as molded”.

Table 13.
Poisson’s Ratio for AMODEL Products

AMODEL PPA Grade	Poisson’s ratio, υ
ET-1000 HS	0.40
A-1115 HS	0.41
AS-1133 HS	0.41
AS-1145 HS	0.41
A-1230 L	0.31
A-1240 L	0.29
A-1340 HS	0.38
A-1440 HS	0.40
A-1540 HS	0.38

Long-term Mechanical Properties

If an engineered component is to perform properly throughout its design life, the design engineer must consider the long-term effects of stress, as well as property changes due to environmental factors. To assess the time related effects of stress on the behavior of polymeric materials, creep and fatigue properties are measured. A wide variety of environmental factors can affect the performance of an engineered component and this subject is discussed in detail in the section entitled "Environmental Resistance" starting on page 63. However, certain environmental factors are so pervasive that it was deemed appropriate to consider them in this section. These are the effects of moisture absorption and long-term exposure to high ambient temperatures.

This section will present data generated to assist the design engineer with his analysis of design life requirements. The data in this section includes:

- Creep modulus in tension, flexure, and compression modes;
- Tensile creep rupture;
- Fatigue endurance;
- Property changes due to moisture absorption;
- Dimensional changes due to moisture absorption; and
- Property changes due to long-term exposure to elevated temperatures.

AMODEL PPA RESIN FOR GAS TANK ROLLOVER VALVE

Fuel tank rollover safety valves manufactured by GT Products, Inc. are being improved by changing to AMODEL polyphthalamide resin.

Rollover valves are both an emissions and a safety protection liquid-discriminating device. They operate partially submerged in gasoline in the vehicle fuel tanks. When upset by a rollover or submerged in liquid fuel, the valve is designed to shut off the passageway out of the fuel tank and prevent liquid fuel from entering the fuel vapor delivery line. AMODEL PPA resin meets all of GT Products' requirements for this application.

Creep

When a material is subjected to stress, an immediate strain occurs. For small strains, this strain is proportional to the stress and calculable from the appropriate modulus. If the application of stress continues for an extended period of time, additional strain may be observed. This behavior is referred to as creep and the additional strain as creep strain.

While creep is observed in metals, the phenomenon is more important with plastics. Their lower modulus means that at the same stress level, the magnitude of the strain is larger and a higher proportion of ultimate strain. In general, the closer the strain is to ultimate strain, the more likely significant creep is.

Creep can occur in tension, compression, or flexural modes. Therefore, to evaluate creep properties, strain is measured as a function of time while a specimen is subjected to a constant tensile, compressive or flexural load at specified environmental conditions. The procedure followed is described in ASTM D 2990, *Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics*.

The normal progression of creep occurs in these three stages:

1. A rapid initial deformation.
2. Continued deformation at a slow and constant rate.
3. Yield followed by rupture for ductile materials, or rupture for non-ductile materials.

The significance of data from creep tests is that they can be used to calculate the time dependent creep strain and creep modulus for use in stress calculations and to determine the safe stress levels for specific time and temperature conditions. If the creep tests are conducted until failure occurs at various stress levels, a creep rupture curve can be produced.

Further discussion of the influence of creep on part design, including an example, can be found on page 88.

Definitions pertaining to creep:

Creep strain: The total strain, at any given time, produced by an applied stress.

Stress: The ratio of the applied load to the initial cross-sectional area of the test piece in tension or compression. When a part is in flexure, the magnitude of stress is the maximum stress in the part's outer fibers due to the applied flexural load.

Creep or apparent modulus: The ratio of the initial applied stress to creep strain.

Tensile Creep

Tensile creep was measured at four temperatures: 73°F (23°C); 149°F (65°C); 212°F (100°C); and 302°F (150°C). Test specimens were 0.125 inch (3.2 mm) thick injection molded *ASTM D 638 Type I* tensile bars. Samples were placed under test in the "dry, as molded" condition. The environment of 73°F (23°C) and 50% RH was maintained throughout the test. The samples tested at the three elevated temperatures were placed in air circulating ovens with make-up air drawn from a room held at 73°F (23°C) and 50% RH. Strains were measured with dial gauges. When the test temperature was 149°F (65°C) or higher, the dial gauges were connected to the samples by invar alloy rods.

Although the strain is measured, the results are typically presented as the apparent modulus, which is calculated by dividing the strain by the applied stress. The apparent modulus is the value design engineers use in their mechanical design calculations when designing components that must perform when subjected to sustained load.

The results of the tensile creep testing are shown in Figures 38 to 41. At 73°F (23°C), the apparent modulus of AMODEL AS-1133 HS resin seems to decline rapidly after 1000 hours. This decline is primarily due to moisture absorption. Nevertheless, the apparent moduli of AMODEL AS-1133 HS resin is higher than that of the GR nylon 6,6 at room temperature, at 149°F (65°C), and at 212°F (100°C). At 302°F (150°C) the two materials exhibit similar creep behavior.

Figure 38. Comparison of Apparent Moduli of GR Resins at 73°F (23°C) and 5,000 psi (34 MPa).

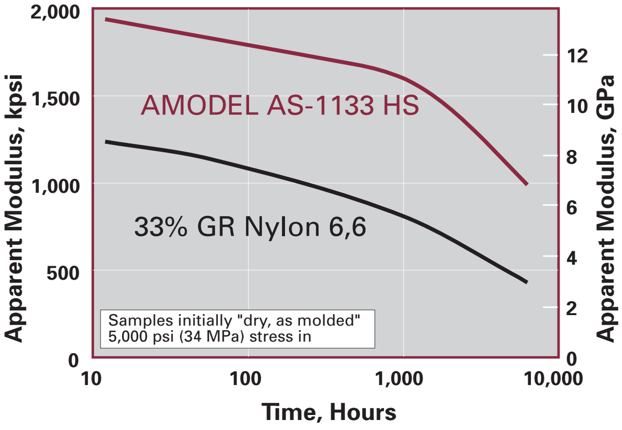


Figure 39. Comparison of Apparent Moduli of GR Resins at 149°F (65°C) and 6,000 psi (41 MPa).

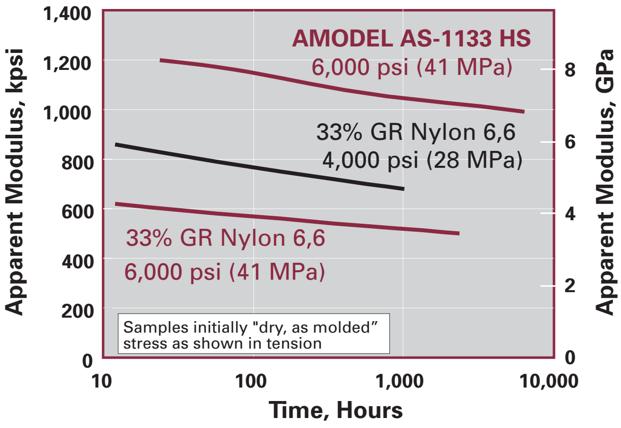


Figure 40. Comparison of Apparent Moduli of GR Resins at 212°F (100°C) and 2,000 psi (14 MPa).

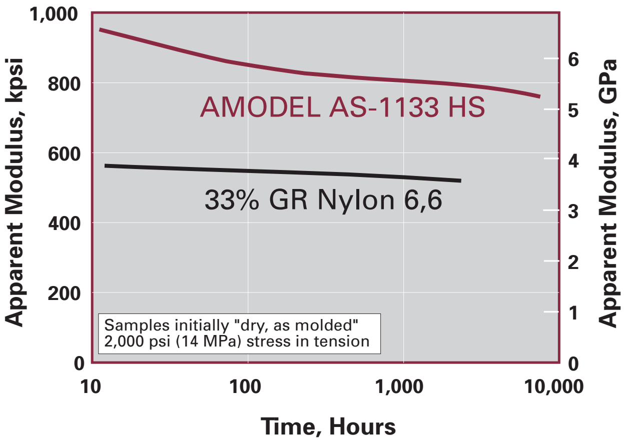
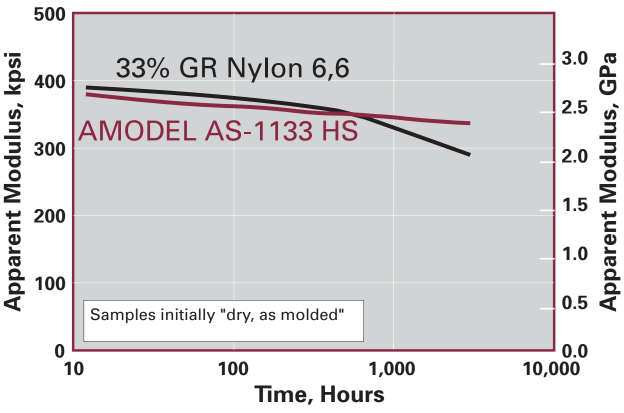


Figure 41. Comparison of Apparent Moduli of GR Resins at 302°F (150°C) and 3,000 psi (21 MPa).



Isochronous Stress/Strain Curves

Another format for presenting creep data is through the use of isochronous (equal time) stress versus strain curves. To prepare an isochronous curve, plot the stresses and the resultant strains for a single time interval and draw a smooth curve through the points. Repeat this process for each time interval.

This method has the advantage of providing a concise summary of a large amount of data. The apparent modulus at any point can be calculated by dividing the stress by the indicated strain. (Please note that the figures show strain expressed in percent; actual strain is the plotted value divided by 100.)

Figure 42 shows the isochronous stress/strain curves in tension for AMODEL AS-1133 HS resin at 73°F (23°C).

The isochronous curves for this resin at 149°F (65°C) is shown in Figure 43, at 212°F (100°C) in Figure 44, and at 302°F (150°C) in Figure 45.

Over this range of stresses the behavior is linear viscoelastic.

Figure 42. Isochronous Stress/Strain Curves AMODEL AS-1133 Resin at 73°F (23°C)

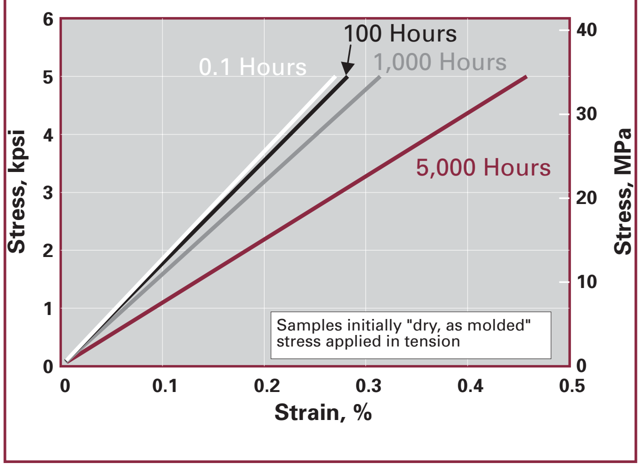


Figure 43. Isochronous Stress/Strain Curves AMODEL AS-1133 Resin at 149°F (65°C)

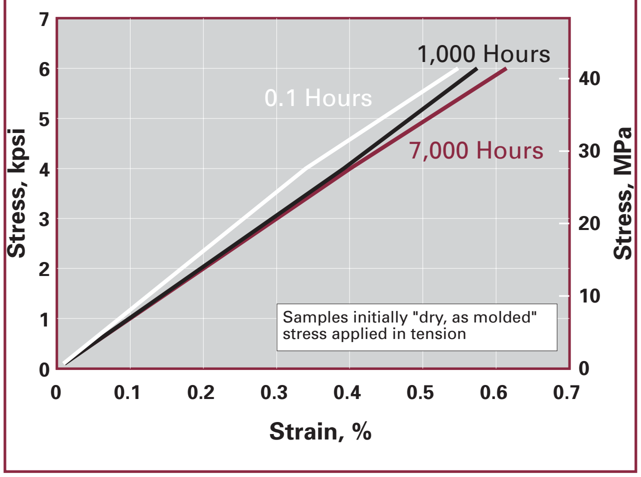


Figure 44. Isochronous Stress/Strain Curves AMODEL AS-1133 Resin at 212°F (100°C)

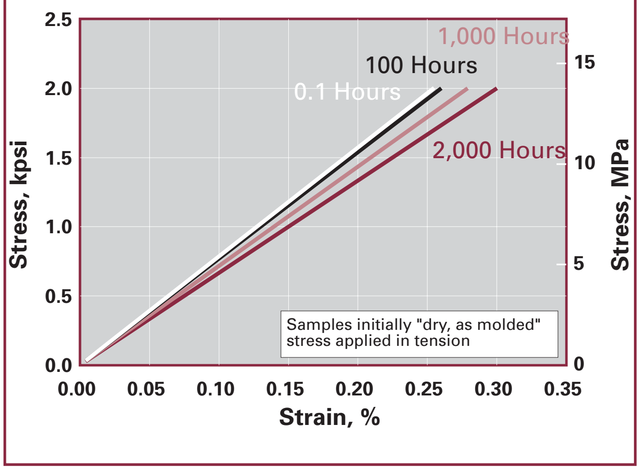
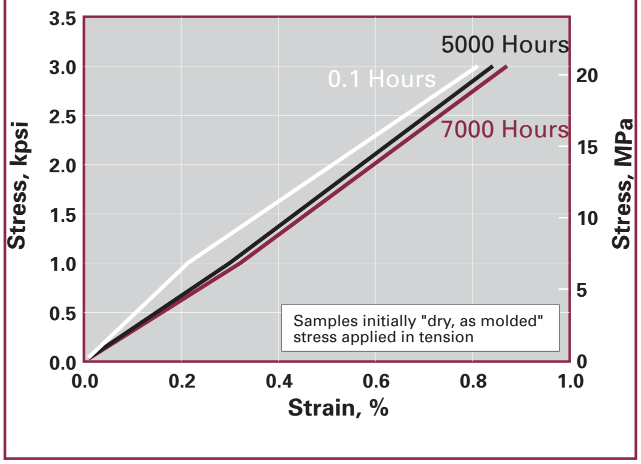


Figure 45. Isochronous Stress/Strain Curves AMODEL AS-1133 Resin at 302°F (150°C)



Tensile Creep Rupture

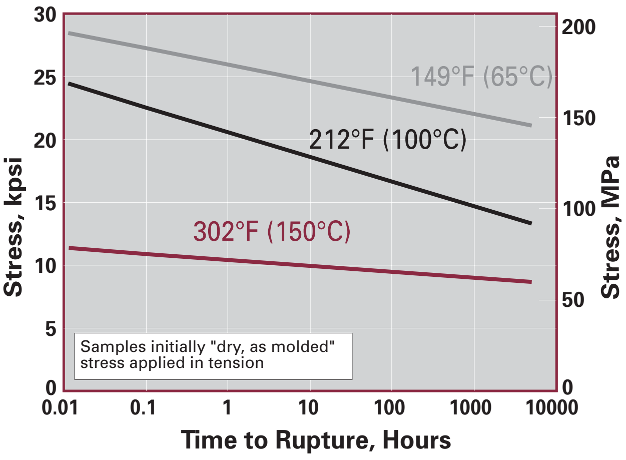
Creep rupture is defined as a failure or rupture that occurs as a result of a sustained load. Because the stress level at which rupture occurs due to sustained load is lower than the short-term strength, creep rupture can be the limiting design property.

The objective of tensile creep rupture testing is to determine the time required for a sustained load to produce a rupture. A plot of stress versus the time to rupture is commonly known as a “creep rupture envelope”. Because the strength of a material varies with temperature, a “creep rupture envelope” can be generated for each temperature of concern.

Creep rupture envelopes were developed in accordance with ASTM D 2990. Tensile specimens were 0.125 inch (3.2 mm) thick injection molded *ASTM D 638 Type I* tensile bars. The environments were the same as in the tensile creep testing above. The samples were loaded in tension using pneumatically actuated bellows to maintain indicated stress levels.

The tensile creep rupture envelopes for AMODEL AS-1133 HS resin are shown in Figure 46 at 149°, 212°, and 302°F (65°, 100° and 150°C).

Figure 46. Tensile Creep Rupture
AMODEL AS-1133 Resin



Using a Creep Rupture Envelope

The value of the creep rupture envelope is that it can be used as an indication of the viability or the safety factor of a design.

For example, if the life requirement of an application is given as 1,000 hours at a sustained stress of 5,000 psi (34 MPa) at a temperature of 150°F (65°C) without rupture. Examination of the creep rupture curves in Figure show that AMODEL AS-1133 HS resin will endure over 20,000 psi (138 MPa) for 1,000 hours at 150°F (65°C).

Therefore, the design can be judged viable with a safety factor of about 4 with regard to creep rupture. This conclusion is only valid for creep rupture. Other factors may affect the suitability of the design.

Flexural Creep

Flexural creep was determined in a three-point bending mode with a two inch (50.8 mm) span, as shown in Figure 15 on page 23, according to ASTM D 2990.

Test specimens were 5.0 x 0.5 x 0.125 inch (127 x 12.7 x 3.2 mm) injection molded bars placed on test "dry, as molded". The environment was maintained at 50% relative humidity and 73°F (23°C). Stress levels were predetermined from flexural strength versus temperature curves and chosen to be 25-35% of the ultimate strength of the material at the test temperature.

Creep resistance can be predicted to a large extent by the relationship of the service temperature to the material's glass transition temperature. Typically, creep resistance is good at service temperatures much lower than T_g, and becomes poorer as service temperature approaches T_g. Therefore, it is not surprising that AMODEL resins have creep resistance superior to many traditional semi-crystalline thermoplastics. For example, AMODEL A-1000 resin has a glass transition temperature of 261°F (127°C) as determined by Differential Scanning Calorimetry (ASTM D 3418). The corresponding T_g for nylon 6,6 is 149°F (65°C). At all temperatures up to its T_g, AMODEL resins do have superior creep resistance.

Figure 47 compares the apparent flexural modulus of AMODEL AS-1133 HS and A-1240 L resins to a 33% glass reinforced nylon 6,6. While the AS-1133 HS resin is clearly superior to the glass reinforced nylon, even the mineral filled grade – AMODEL A-1240 resin – has an effectively higher creep modulus after 1000 hours under load.

Figure 48 compares the apparent flexural modulus of AMODEL ET-1000 HS resin with that of unreinforced and impact modified grades of nylon 6,6 at 181°F (83°C) and 2,000 psi (14 MPa).

Flexural Creep Stress/Strain Calculations

Outer fiber stress (σ) and strain (ε) were determined from elastic beam theory:

$$\varepsilon = \frac{6\,Y\,d}{L^2}$$

$$\sigma = \frac{3\,P\,L}{2\,b\,d^2}$$

where:

P = the point load applied at mid-span
Y = the measured mid-span deflection
d = the sample thickness
b = the sample width
and L = the span.

Figure 47. Apparent Flexural Modulus vs. Time
GR Resins at 10,000 psi (69 MPa), 73°F (23°C)

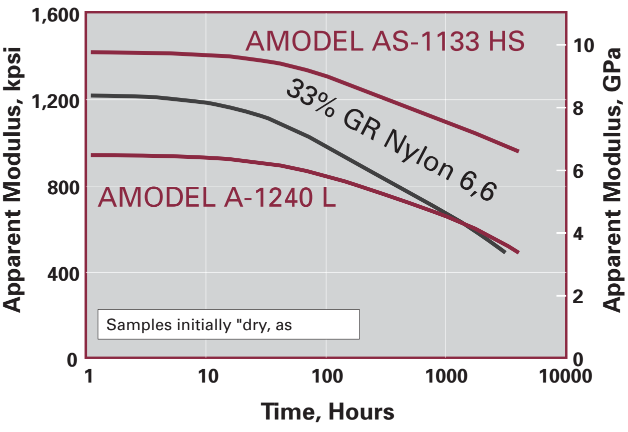
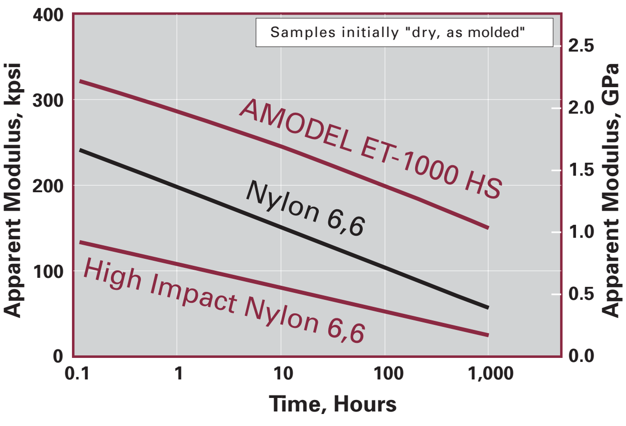


Figure 48. Apparent Flexural Modulus vs. Time
Unreinforced Resins
at 2,000 psi (14 MPa), 181°F (83°C)



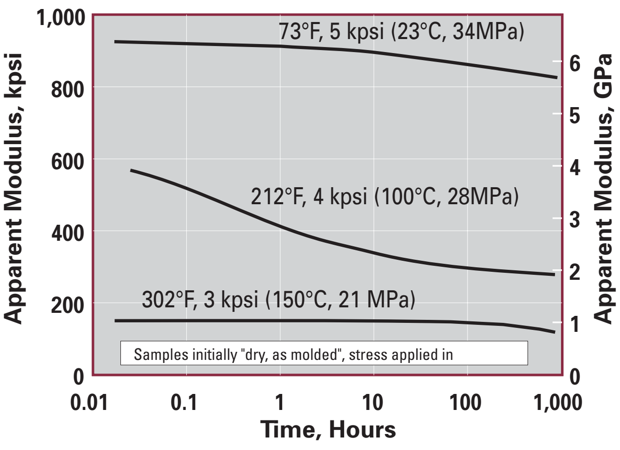
Compressive Creep

Compressive creep was determined according to ASTM D 2990. Test specimens were 0.5 x 0.5 x 1.0 inch (12.7 x 12.7 x 25.4 mm) injection molded bars. The ends of the bars were machined until they were parallel to each other within 0.001 inch (0.025 mm) and perpendicular to the axis. Displacement was monitored with bonded strain gauges. As in the flexural creep experiments, the stress levels were chosen to be less than 35% of the compressive strength at the temperature of the test.

Figure 49 shows the compressive creep moduli of AMODEL AS-1133 HS resin at 73°, 212°, and 302°F (23°, 100°, and 150°C). These moduli are lower than the flexural creep moduli given in Figure 47. This is due to less fiber orientation in the direction of the induced strain.

In most applications where AMODEL resin will be loaded in a compressive manner, the load will be applied in the direction transverse to flow direction and consequently the fiber orientation. Therefore, the apparent moduli presented here are representative of the material's performance in typical applications.

Figure 49. Apparent Compressive Modulus vs. Time AMODEL AS-1133 Resin



Fatigue Resistance

When a material is stressed cyclically, failure or rupture will occur at stress levels much lower than its short-term ultimate strength. Examples of cyclic stress would include components subjected to severe vibration, components of reciprocating or rotating devices where loading is cyclic, and mechanical devices such as gears where load is a function of position.

This phenomenon is well known in metals. Metallurgists have defined the term “Fatigue Endurance Limit” to represent the maximum cyclical stress that a material can be subjected to without failure. Normally, this stress level corresponds to the highest stress level that does not cause failure in 10 million (10^7) cycles.

While the term “Fatigue Endurance Limit” is sometimes used in design discussions involving plastic materials, the response of plastics to cyclic stress is more complex than the response of metals, and the term is not strictly applicable. Fatigue data is typically presented by plotting stress versus number of cycles at rupture. A smooth curve is calculated that represents the best fit to the data. For component design purposes, this S - N (stress - number of cycles) curve provides strength values appropriate for the components required life.

When designing a component that will be subjected to cyclic loading, the establishment of fatigue strength requirements is desirable. However, analysis of the fatigue strength requirements is complicated by a large number of factors that may influence them. Some of these factors are:

the shape of the component;

stress concentration factors;

the rate of load application;

any temperature change caused by load application;

type of stress induced by load , that is, tensile, compressive, or shear, etc.;

environmental factors, such as, chemicals, radiation, ambient temperature;

residual stresses;

the duty cycle; and

the desired component life.

A thorough understanding of all these factors is difficult. The best way of evaluating a material for a component subject to dynamic stresses is still prototype testing. At best, the designer can make a rough estimate using fatigue (S - N) diagrams as shown in Figures 50 and 51.

Fatigue Strength of AMODEL Resin

When measuring and/or comparing the fatigue strength of plastic materials, it is critical to specify the mode (tensile, compressive, or flexural), the frequency, and the stress profile.

The fatigue strength of AMODEL resins was determined in accordance with ASTM test method D 671 *Flexural Fatigue of Plastics by Constant-Amplitude-of-Force*. This method uses a cantilever beam configuration with a constant deflection. The results shown in Figure 50 were generated at a frequency of 32 Hz. Prior to testing, parts were conditioned to 50% RH. Failure was defined when the stress level decayed to 90% of its initial value.

The flexural fatigue behavior for glass reinforced AMODEL resins is compared to other glass reinforced thermoplastics in Figure 50. The AMODEL resins resist higher cyclic loads longer than all of the competitive resins.

Figure 51 gives the fatigue behavior of AMODEL AS-1145 HS resin at 230° and 338°F (110° and 170°C). As expected, raising the temperature reduces the amount of cyclic stress that can be endured.

A good example of an application involving cyclical stress is a gear. As the driving gear causes the driven gear to rotate, each tooth is subject to stress. This is then followed by a period of time at low or zero stress. In designing a gear tooth, the appropriate strength criteria is the fatigue endurance limit of the material at the operating conditions of the gear.

Figure 50. Flexural Fatigue of Glass Reinforced Resins at 73°F (23°C) and 32 Hz

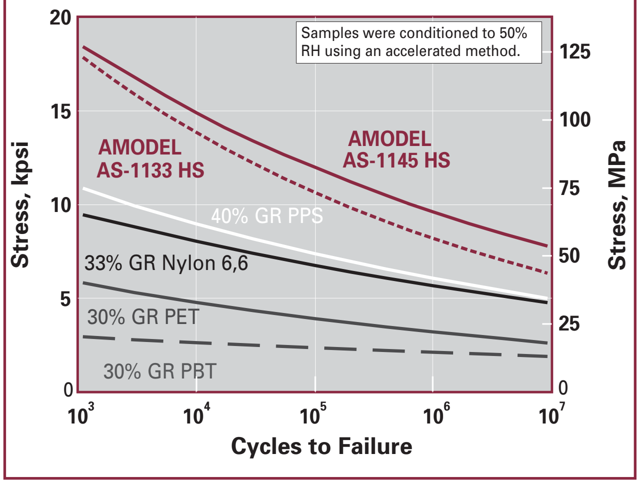
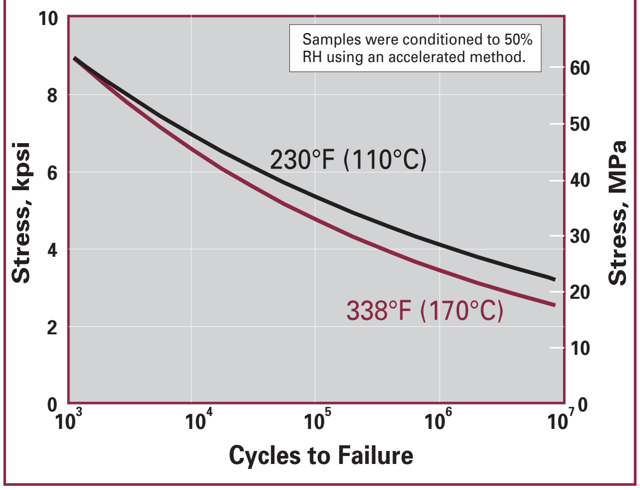


Figure 51. Flexural Fatigue of AMODEL AS-1145 Resin vs. Temperature



Moisture Effects

As with most thermoplastic resins, parts made from AMODEL resins can absorb moisture from the atmosphere. AMODEL polyphthalamides absorb less moisture than aliphatic polyamides such as nylon 6,6 and nylon 6. As a result, the dimensions, strength, and stiffness of AMODEL parts will be less affected by the absorption of moisture than nylon parts. Since moisture is ubiquitous, knowledge of the effects of moisture on the properties of a material is critical to the design engineer trying to meet end use requirements.

Absorption Amount

Water absorption is a reversible process. At each specified relative humidity and temperature, a resin will absorb moisture until an equilibrium is established. At equilibrium, a polymer absorbs moisture at the same rate it releases moisture, achieving a constant weight. Figure 52 compares the increase in weight due to moisture absorption of AMODEL AS-1133 HS to that of 33% glass reinforced nylon 6,6 at room temperature and specified relative humidities. The 33% glass reinforced nylon 6,6 absorbs significantly more moisture than AMODEL AS-1133 HS resin.

Effect of Moisture on Strength and Stiffness

Figure 53 compares the tensile strength of AMODEL AS-1133 HS resin to that of 33% glass reinforced nylon 6,6 at 73°F (23°C) and specified moisture content. The tensile strength of the AMODEL resin is superior to that of the nylon "dry, as molded" and the difference increases with higher moisture levels.

Figure 54 compares the flexural modulus of AMODEL AS-1133 HS resin to that of a 33% glass reinforced nylon 6,6 at 73°F (23°C) and various moisture contents. The modulus of the AMODEL resin is higher "dry, as molded" and remains relatively constant. The modulus of the nylon resin drops rapidly with increasing moisture level.

Figure 52. Comparison of Moisture Absorption Amount of GR AMODEL and Nylon 6,6 Resins

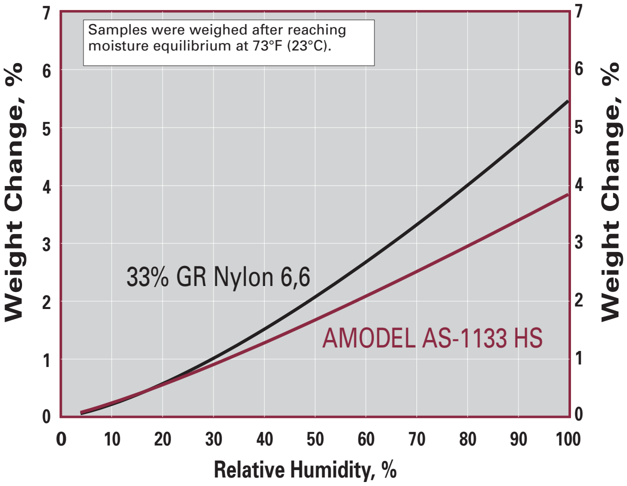


Figure 53. Comparison of Tensile Strength of GR AMODEL and Nylon 6,6 Resins at Various Moisture Contents.

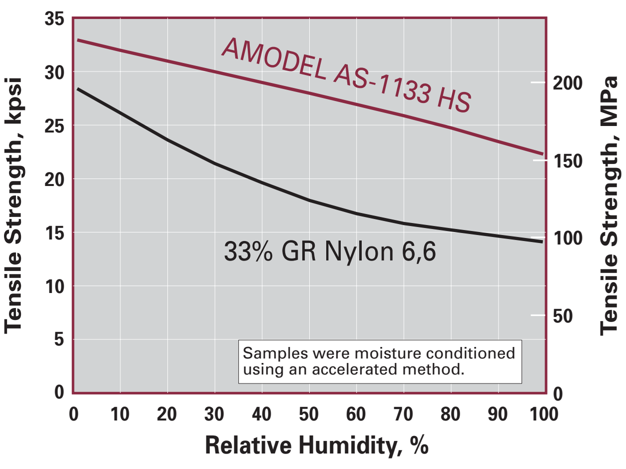
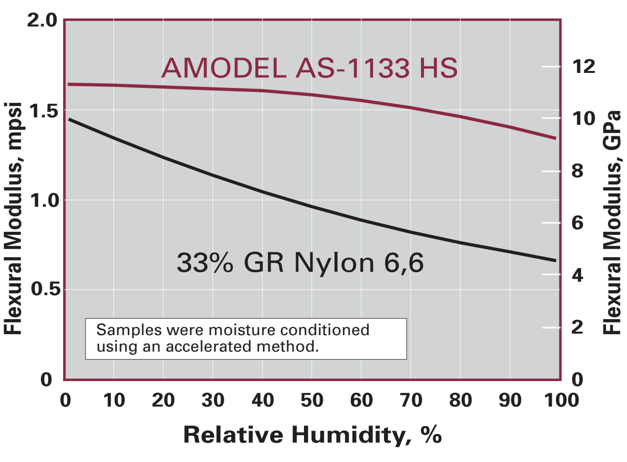


Figure 54. Comparison of Flexural Modulus of GR AMODEL and Nylon 6,6 Resins at Various Moisture Contents



Dimensional Change due to Moisture

To evaluate the effect of moisture absorption on part dimensions, plaques 4 x 4 x 1/8th in. (102 x 102 x 3.6 mm) were molded, measured, and then placed into environments at room temperature, 73°F (23°C), and either 50% or 100% relative humidity. Periodically the plaques were removed and measured. The direction of flow during the molding process was noted and data for both the flow direction and transverse to flow was reported. The dimensional change was calculated by subtracting the initial length from the final length, dividing the result by the original length, and multiplying the result by 100 to express the change in percent.

Figures 55 through 57 show the results of this testing for three grades of AMODEL resin. Even at 100% relative humidity, the dimensions continue to change for a considerable length of time. These graphs show that after one year, the rate of change has greatly diminished but the dimensions are still changing. The magnitude of the dimensional change is relatively small (less than 0.6%), but could be important is applications requiring extremely good dimensional stability.

Figure 55. Dimensional Change vs. Time
AMODEL AS-1133 HS Resin

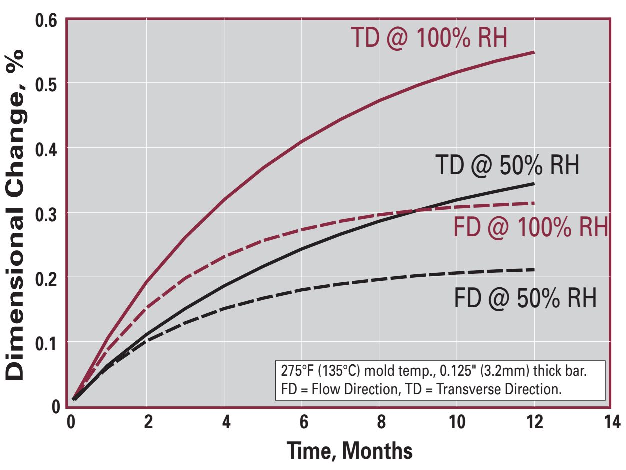


Figure 56. Dimensional Change vs. Time
AMODEL A-1340 HS Resin

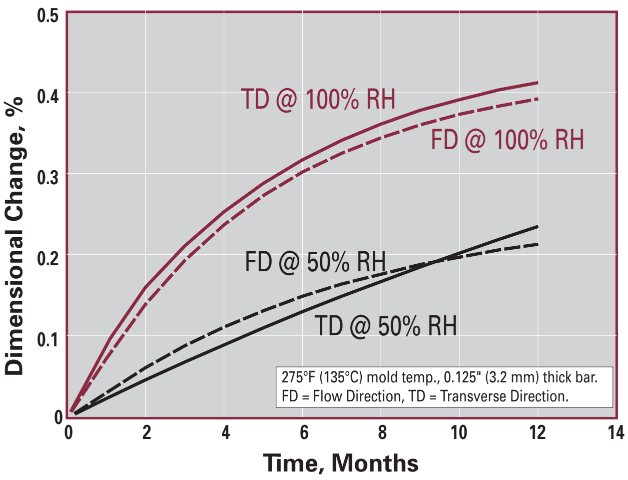
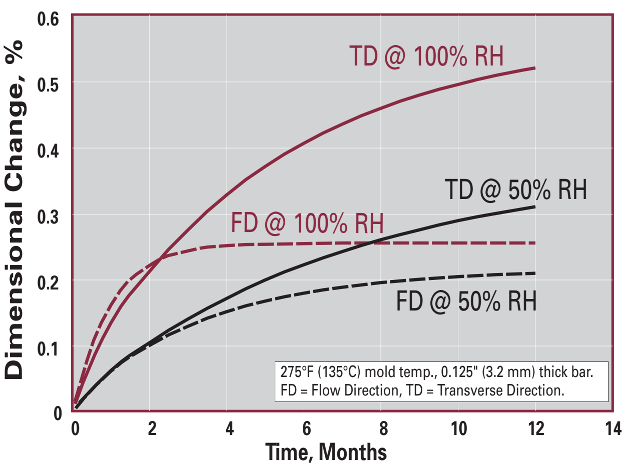


Figure 57. Dimensional Change vs. Time
AMODEL AF-1133 V0 Resin



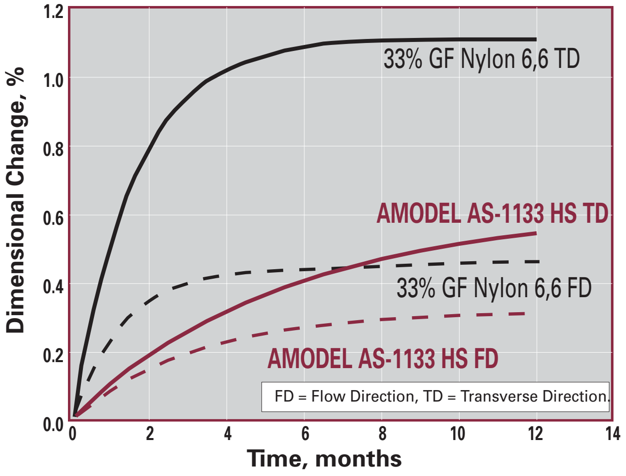
Dimensional Change Compared to Nylon 6,6

Figure 58 compares the dimensional change due to moisture absorption of AMODEL AS-1133 HS resin with that of 33% glass reinforced nylon 6,6 at 100% RH. To ensure a valid comparison, both resins were molded under conditions that promote maximum crystallinity. In the case of the AMODEL resin, a mold temperature of 275°F (135°C) was used. For the nylon 6,6, the mold temperature was 200°F (93°C). Plaques 0.125 in. (3.6 mm) thick were exposed to 100% RH at room temperature.

AMODEL resin absorbs moisture much more slowly than nylon 6,6, because the diffusion coefficient at room temperature of water in nylon 6,6 is approximately five times larger than that of AMODEL resins. Therefore, for 4 inch x 4 inch x 0.125 inch (102 mm x 102 mm x 3.6 mm) thick plaques, nylon 6,6 reaches equilibrium in approximately four months while AMODEL AS-1133 HS resin requires over two years.

For this reason, accelerated conditioning was often used to achieve the higher moisture contents required by some tests. Accelerated conditioning does have some “side effects” as explained on page 7.

Figure 58. Comparison of the Dimensional Change Due to Moisture Absorption GR AMODEL and Nylon 6,6 Resins

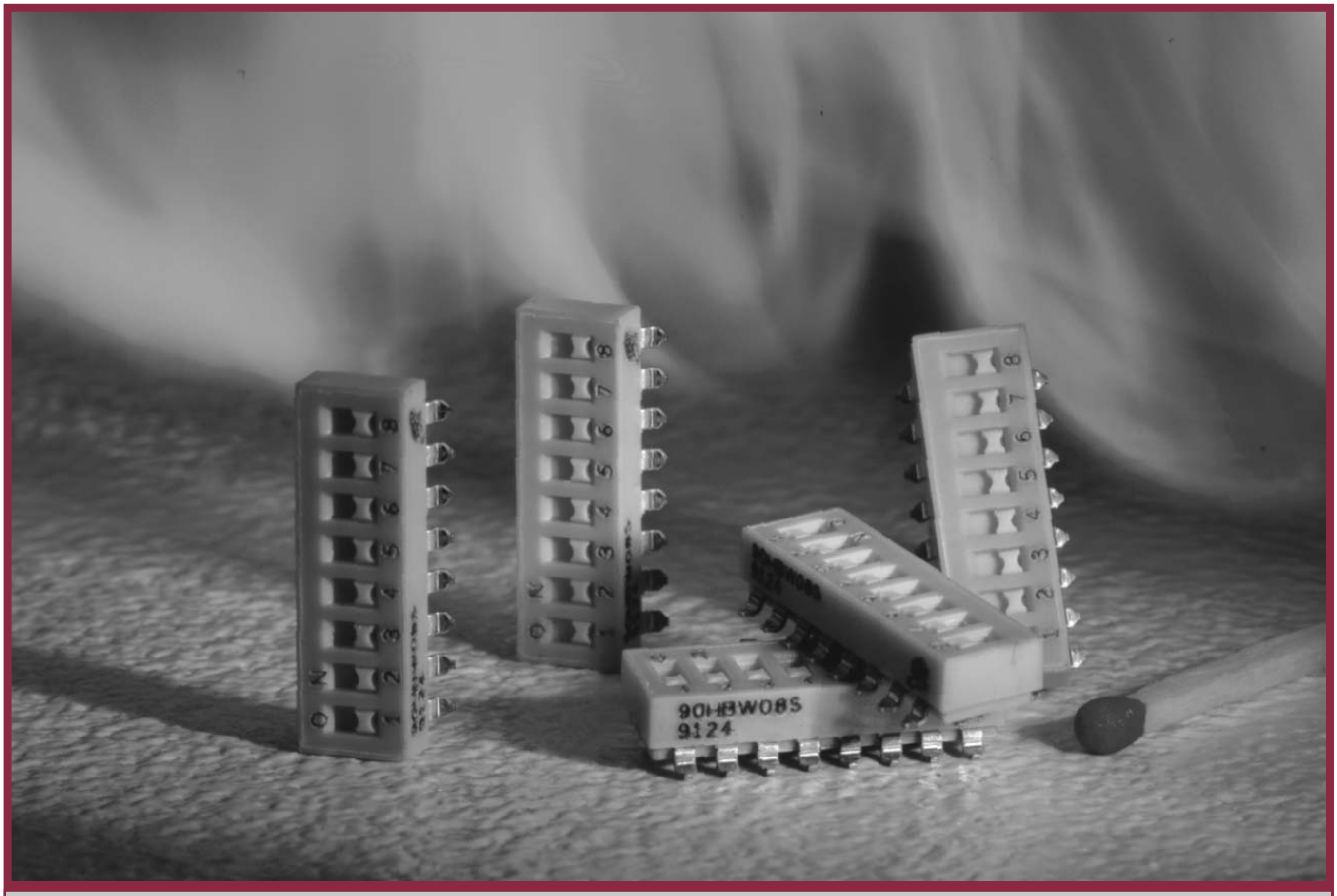


Thermal Properties

Thermal properties refer to the way a material responds to changing temperatures. Thermal properties include the effects of temperature on:

1. Strength and stiffness,
2. Dimensions,
3. Chemical changes in the polymer itself due to thermal or oxidative degradation,
4. Softening, melting, or distortion, and
5. Morphology.

The properties of the material in the molten state are discussed in the section on processing. The behavior of the material while burning is discussed in the section on combustion properties.



SURFACE MOUNT DIP SWITCHES WITHSTAND 500°F (260°C)

A line of surface mount DIP switches, which will withstand IR reflow as well as VPS assembly operations, has been introduced by Grayhill Inc. Believed to be the first truly process compatible DIP switches, their components will withstand 500°F (260°C). Housing and top seals will also withstand high pressure aqueous cleaning.

Grayhill engineers selected AMODEL AF-1133 V0 resin with a UL 94 V-0 rating for the molded switch cases. Other thermoplastics were considered and rejected. LCPs were not cost-effective. Nylon 4,6 was tried unsuccessfully, as were PCT and PPS. AMODEL resin molds in existing tooling and provides the required performance, because of its lower moisture absorption, chemical resistance, and high temperature capability.

Deflection Temperature Under Load

The test most commonly used by the plastics industry to measure thermal capability is ASTM D 648, *Standard Test Method for Deflection Temperature of Plastics Under Flexural Load*, as illustrated in Figure 59. This test is similar to an obsolete test called “Heat Distortion Temperature” and the acronym HDT is still commonly used.

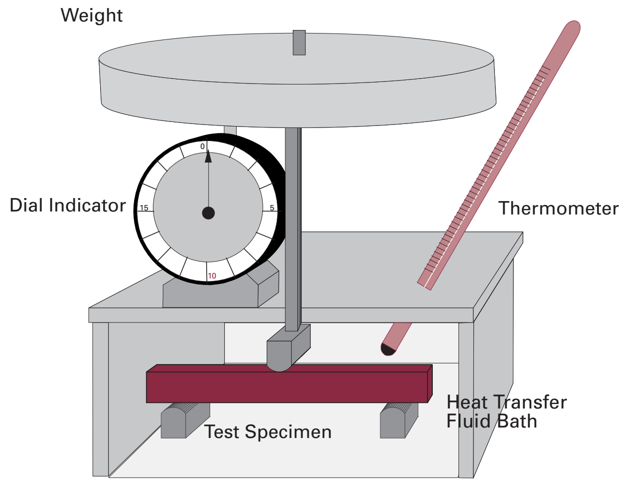
In this test, the deflection of a test specimen supported at two points and loaded in the center to an outer fiber stress of either 66 psi (0.45 MPa) or 264 psi (1.82 MPa) is monitored while the temperature is increased 3.6°F(2°C) per minute. When the deflection reaches 0.010 in. (0.25 mm), the temperature is noted and reported as the “Deflection Temperature” at the specified stress. The test specimens for this test are injection molded rectangular cross section bars 5 x 0.5 x either 0.125 or 0.250 inch (127 x 13 x either 3.2 or 6.4 mm).

Certain test parameters can have a significant influence upon the results obtained in this test. The designer should be certain that data from multiple sources are comparable. The test parameters that should be considered are specimen thickness and thermal history. The test may be performed as molded or after heat treating or “annealing” for several hours at a temperature of about 320°F (160°C) for AMODEL PPA.

In general, annealing reduces the variability in deflection temperature measurements, while raising the value somewhat. Figure 60 shows the effects of mold temperature and annealing on deflection temperature at 264 psi (1.8 MPa) for AMODEL AS-1133 HS resin. As can be seen, mold temperature and/or annealing effects can cause the deflection temperature to vary by as much as 30°F (17°C). Most deflection temperature data in this manual were generated on specimens annealed at 320°F (160°C) for 2 hours.

Deflection temperature data should be used as a general reference for thermal performance only, since semi-crystalline plastic resins can be used in applications that experience temperatures higher than their deflection temperature value.

Figure 59. Deflection Temperature Apparatus

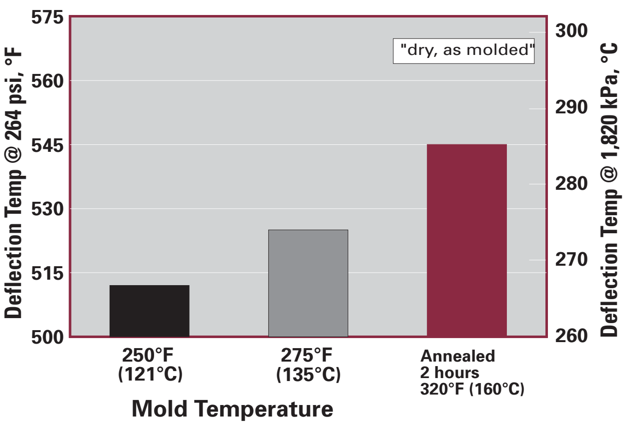


Deflection Temperature is a modulus at temperature measurement.

Classical stress/strain analysis indicates that this test actually measures the temperature at which the flexural modulus is 35,000 psi (240 MPa) when the applied stress is 66 psi (0.45 MPa), or 140,000 psi (965 MPa) when the applied stress is 264 psi (1.8 MPa). Because the test method directs that the indicator be re-zeroed after five minutes, any creep strain that occurs in the first five minutes is effectively subtracted from the endpoint strain lowering the actual modulus at the end point of the test. The initial modulus can be related to the creep strain.

In summary, deflection temperature does not measure thermal capability, it simply provides one point on the modulus versus temperature curve.

Figure 60. Effect of Mold Temperature and Annealing on Deflection Temperature of AMODEL AS-1133 HS Resin



Deflection Temperature Values for AMODEL Resins

Deflection temperature values range from 248°F (120°C) at 264 psi for AMODEL ET-1000 HS resin to 574°F (301°C) at 66 psi for AMODEL AS-1145 HS resin. It was previously shown in Figure 22 on page 26 that the glass fiber loading in AMODEL resin had an effect on the modulus.

Figure 61 shows the effect of glass fiber loading on the deflection temperature at 264 psi for several glass reinforced grades of AMODEL polyphthalamide.

Figure 62 shows the deflection temperature values for various mineral and glass fiber/mineral AMODEL PPA products.

Figure 63 compares the deflection temperature at 264 psi of AMODEL AS-1133 HS resin with a 33% glass fiber reinforced nylon 6,6 and a 30% glass fiber reinforced polyphenylene sulfide. AMODEL AS-1133 HS resin offers a 75°F (42°C) higher deflection temperature than nylon 6,6 and about 45°F (25°C) higher than PPS.

Figure 61. Deflection Temperature Glass Reinforced AMODEL Resins

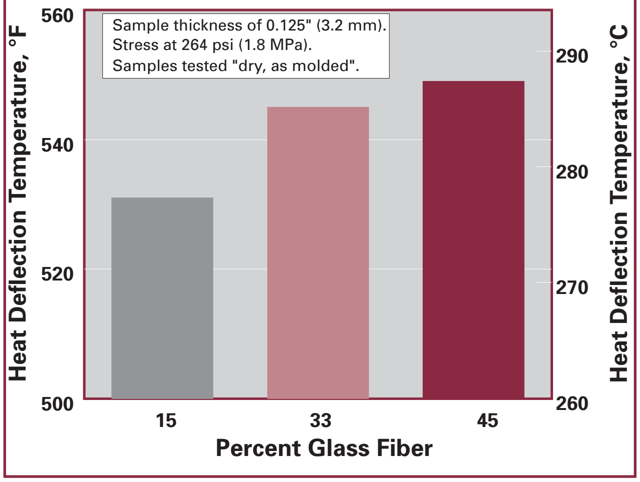


Figure 62. Deflection Temperature Mineral and Mineral/Glass Filled AMODEL Resins

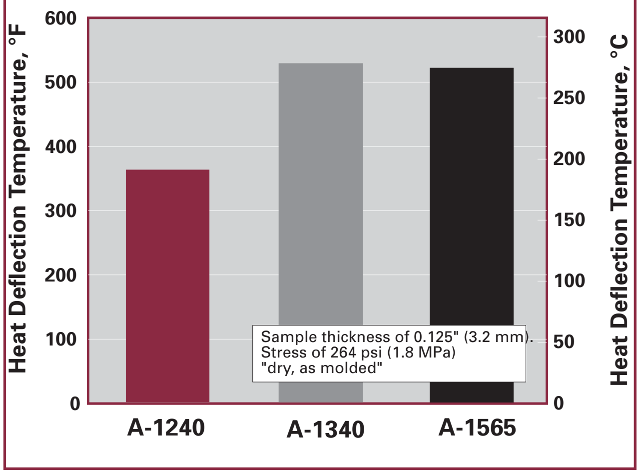
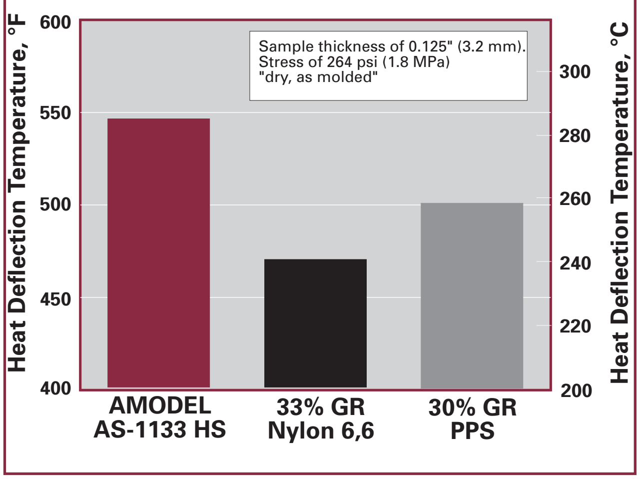


Figure 63. Deflection Temperature Glass Reinforced Resins



Thermal Expansion Coefficient

The dimensions of most materials increase with increasing temperature. The coefficient of linear thermal expansion (α) is the ratio of the change in length to the change in temperature.

The coefficient of linear thermal expansion (α), as measured by ASTM E 831, of several AMODEL grades and some common metals is given in Table 14. This method provides an average value for the expansion coefficient over a temperature range.

The thermal expansion behavior of metals is uniform over the temperature range of concern. As shown in Table 14, the thermal expansion coefficients of the polymer materials are a function of the temperature range used for the measurement. In general, the polymer materials expand more above their glass transition temperature than they do below it. Also, the addition of glass fiber reinforcement results in the thermal expansion becoming directional. Since glass fibers tend to become oriented in the flow direction, and since glass has a lower thermal expansion coefficient than the polymers, the coefficient of expansion are generally lower in the flow direction than the transverse direction

The data shown in Table 14 compares the coefficients of linear thermal expansion for AMODEL AS-1133 HS resin and AS-1145 HS resin with 33% glass reinforced nylon 6,6 between 32°and 482°F (0° and 250°C) in both transverse and flow directions. In the flow direction, the thermal expansion is primarily controlled by the low coefficient of linear thermal expansion of the glass fiber and is similar for all three materials. In the transverse direction, however, the expansion is dominated by the resin and the AMODEL grades show much less expansion than the polyamide.

These differences can become particularly important when a plastic part is constrained, such as, when it is fastened with bolts and the bolts must stay tight despite thermal cycling.

Thermal Expansion Calculation

If the coefficient α is known, the change in length of an uniform straight bar raised to a temperature T_f can be calculated from:

$$\Delta L = \alpha L (T_F - T_0)$$

where:

ΔL = change in length

L = original length

α = coefficient of linear thermal expansion

T_F = final temperature

T_0 = original temperature

The values shown in Table 14 should allow the design engineer to estimate the magnitude of the thermal stresses in parts molded from AMODEL resins due to thermal expansion.

Variation of Thermal Expansion Coefficient with Temperature

Thermal Mechanical Analysis allows the measurement of the expansion coefficient over a narrow temperature range. Figure 64 shows a plot of the coefficient of linear thermal expansion versus temperature for selected AMODEL resins. These values are especially useful near the glass transition temperature, where the other methods often fail to provide very reproducible data.

Figure 64. Thermal Expansion Coefficient vs. Temperature

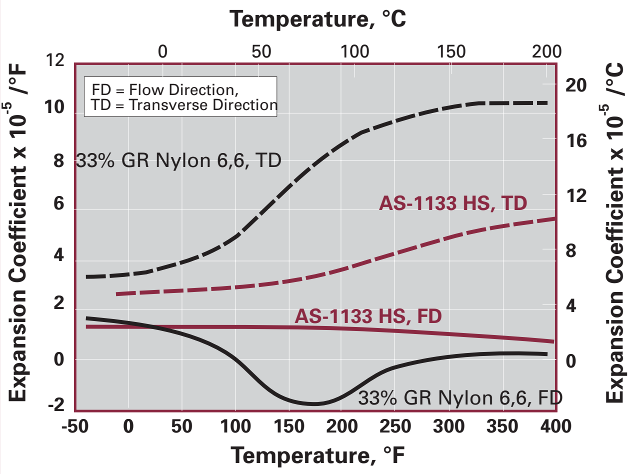


Table 14.
Coefficient of Linear Thermal Expansion (CLTE), x 10^{-5}

		Temperature Range			
		32 to 212°F	0 to 100°C	320 to 480°F	160 to 250°C
Material	**Direction**	**°F**	**°C**	**°F**	**°C**
AMODEL A-1115 HS	FD [1]	1.9	3.5	0.7	1.2
	TD [2]	3.3	5.9	5.3	9.5
AMODEL AS-1133 HS	FD	1.3	2.4	0.8	1.5
	TD	3.3	6.0	5.6	10.0
AMODEL AS-1145 HS	FD	0.8	1.5	0.6	1.0
	TD	2.8	5.0	5.6	10.0
AMODEL A-1230 L	FD	2.3	4.1	4.9	8.9
	TD	2.7	4.9	6.2	11.2
AMODEL A-1240 L	FD	1.9	3.4	4.4	7.9
	TD	2.2	4.0	5.3	9.5
AMODEL A-1340 HS	FD	1.6	2.9	1.1	1.9
	TD	2.6	4.6	5.1	9.2
33% Glass Reinforced nylon 6,6	FD	1.3	2.4	0.8	1.5
	TD	7.2	13.0	9.5	17
40% Glass Reinforced PPS	FD	1.2	2.2		
	TD				
Zinc die-casting alloy		1.5	2.7	1.5	2.7
Aluminum die-casting alloy		1.4	2.5	1.4	2.5
Stainless steel		1.0	1.8	1.0	1.8
Carbon steel		0.8	1.4	0.8	1.4

Thermal Conductivity

Thermal conductivity is the rate at which heat energy will flow through a material. This property is important in applications where the polymeric material is used as a thermal insulator, or where heat dissipation is of concern.

The measurement of thermal conductivity was performed in accordance with ASTM F 433, *Standard Practice for Evaluating Thermal Conductivity of Gasket Materials*. The test is conducted by placing a sample between plates controlled at different temperatures and monitoring the heat flow through the sample. The thermal conductivity was determined at three average temperatures, 104°F (40°C), 212°F (100°C), and 302°F (150°C), by setting the hot plate about 12°F (7°C) above the average and setting the cold plate about 12°F (7°C) below the average temperature.

The thermal conductivity of various grades of AMODEL resin was measured at each of the stated temperatures and the results are presented in Table 15. Higher thermal conductivity values indicate greater heat flow, while lower values indicate better thermal insulating characteristics.

Figures 65 and 66 show that the thermal conductivities of several commercial grades of AMODEL PPA resin increase with increasing temperature.

Figure 65. Thermal Conductivity of Glass Reinforced AMODEL Resins

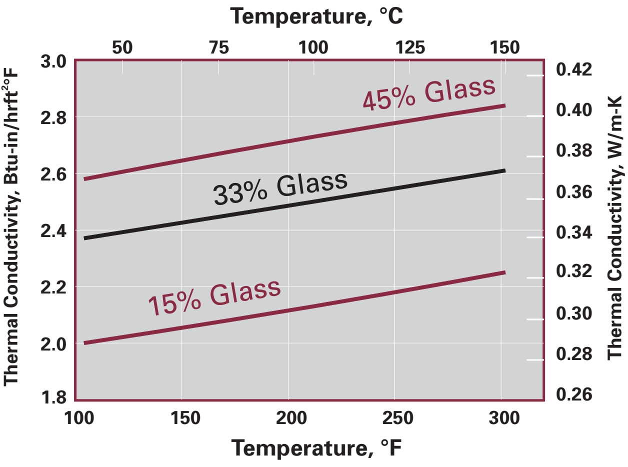


Figure 66. Thermal Conductivity of Mineral Filled AMODEL A-1240 L Resin

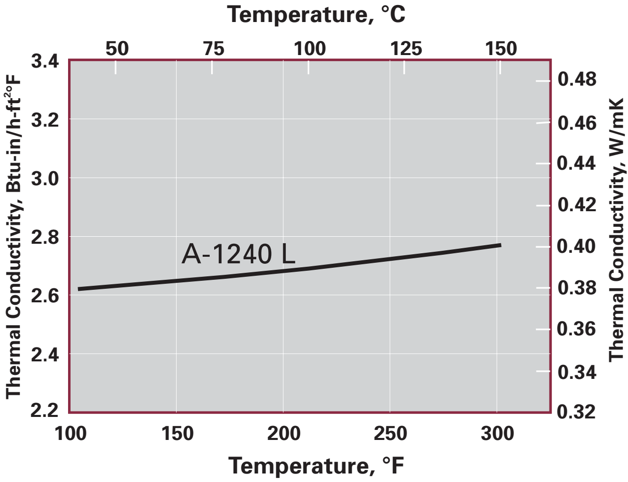


Table 15.
Thermal Conductivity of AMODEL PPA Resins

AMODEL Grade	Additive	Amount, %	Average Temperature, °F (°C) 104 (40) Btu in / hr ft² °F	104 (40) W / m K	212 (100) Btu in / hr ft² °F	212 (100) W / m K	302 (150) Btu in / hr ft² °F	302 (150) W / m K
A-1115 HS	glass	15	2.00	0.289	2.13	0.307	2.25	0.324
AS-1133 HS	glass	33	2.37	0.341	2.50	0.360	2.61	0.376
AS-1145 HS	glass	45	2.58	0.372	2.73	0.393	2.84	0.409
A-1240 L	mineral	40	2.62	0.377	2.69	0.388	2.77	0.399
A-1340 HS	mineral/glass	25/15	2.93	0.422	2.98	0.430	3.02	0.436
A-1440 HS	mineral	40	3.20	0.461	3.20	0.462	3.22	0.464

Specific Heat

Specific heat is defined as the amount of heat required to change the temperature of a unit mass one degree. Figure 67 shows that the specific heat of AMODEL A-1000 resin, the base resin common to all commercial AMODEL grades, is a function of temperature. Notice that the specific heat changes significantly at the melting point. This type of behavior is typical for semi-crystalline thermoplastics.

The relationship between specific heat and temperature is also shown for AMODEL AS-1133 HS resin in Figure 68.

This information is important to process engineers because it is used in the calculation of the heat input needed to process AMODEL resins on equipment such as extruders or injection molding machines.

Figure 67. Specific Heat vs. Temperature AMODEL A-1000 Polyphthalamide

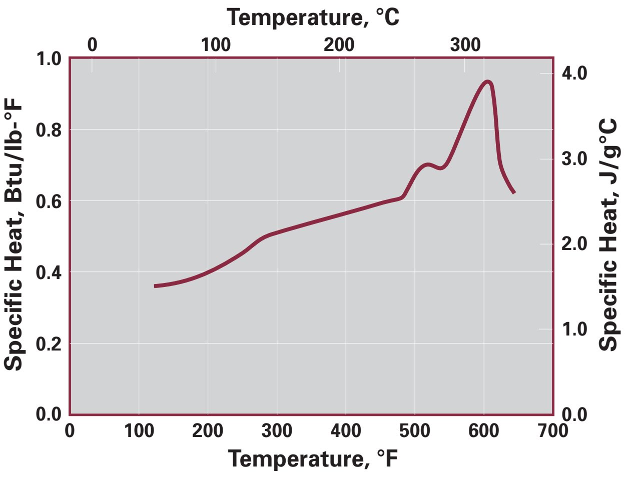
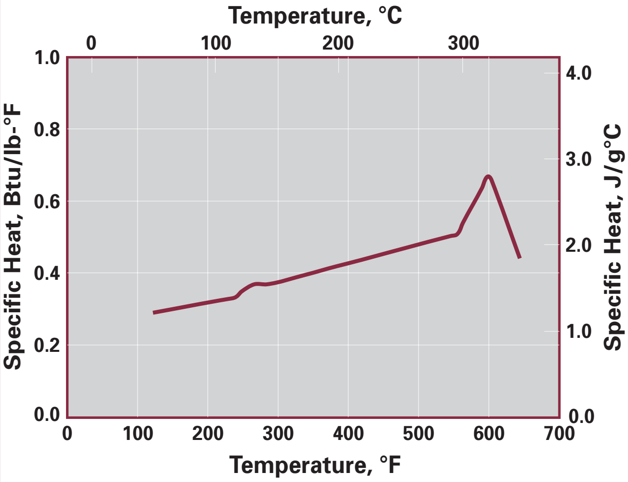


Figure 68. Specific Heat vs. Temperature AMODEL AS-1133 HS



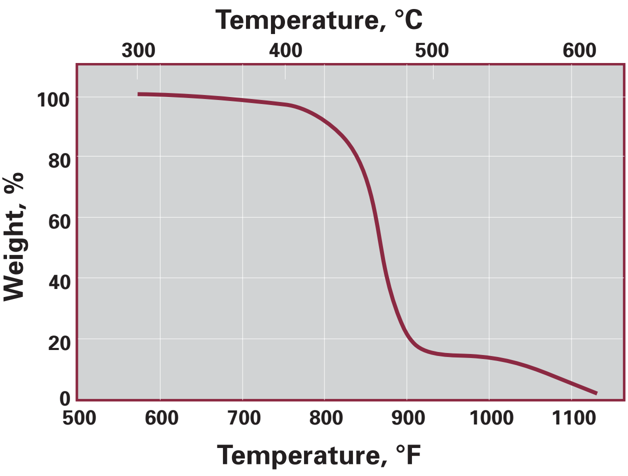
Thermal Stability

The general term, thermal stability, is used to describe the ability of a material to resist loss of properties due to heat. Various methods are used to evaluate this tendency. In the next section, we will discuss several of these methods, including thermogravimetric analysis, and long-term heat aging.

Thermogravimetric Analysis

Thermogravimetric analysis is performed by increasing the temperature of a small sample of the test material at a constant rate while monitoring its weight. The atmosphere is controlled and the test can be performed using air or an inert atmosphere, such as nitrogen. Figure 69 shows the weight loss of AMODEL A-1000 resin as a function of temperature in air at a heating rate of 18°F/min (10°C/min). Figure 69 shows that AMODEL PPA resins are thermally stable beyond the recommended upper processing temperature limit of 660°F (349°C).

Figure 69. Thermogravimetric Analysis
AMODEL A-1000 Resin



Thermal Aging

Most polymeric materials exhibit some loss of performance properties after long-term exposure to elevated ambient temperatures. While some polymers are more stable than others, the property loss is typically a function of both exposure time and temperature. Because the property losses result from both oxidative attack and thermal degradation, the term thermal oxidative stability is frequently used.

Thermal oxidative stability limits the acceptable long-term use temperature of some polymers. To evaluate these long-term effects on the properties of AMODEL polyphthalamide, molded test specimens of glass fiber reinforced AMODEL and nylon 6,6 resins were placed in circulating air ovens at several elevated temperatures. Specimens were removed from the oven at regular intervals, then tested at room temperature for tensile strength and impact resistance.

Typically, these aging tests are run until the property being monitored has been reduced to one-half its starting value. The aging tests are conducted at several aging temperatures and an “Arrhenius Plot” is prepared. An “Arrhenius plot” plots the heat aging time required to reduce a property to one-half of its starting value, sometimes referred to as its half-life, against the reciprocal of the aging temperature in degrees Kelvin. The advantage of analyzing the data in this manner is that the plot is usually a straight line and, therefore, easily extrapolated.

Figure 70 shows the plot of tensile strength half lives of AMODEL AS-1133 HS resin and GR nylon 6,6 versus the aging temperature. Amodel PPA maintains its tensile strength longer than nylon 6,6 does.

Figure 71 shows the thermal aging curves for notched Izod half lives of AMODEL AS-1133 HS resin and GR nylon 6,6 versus aging temperature. AMODEL also requires longer aging times before loss of impact resistance occurs vis a vis the nylon 6.6 resin.

Thermal aging tests like this are used to compare plastic materials and to estimate their service life. The service life of a material at a particular end use temperature will be largely dependent upon the requirements of the application and should be judged on the basis of its heat aging data and actual or simulated end use testing.

Figure 70. Thermal Aging Comparison
Glass Reinforced Resins
Tensile Strength

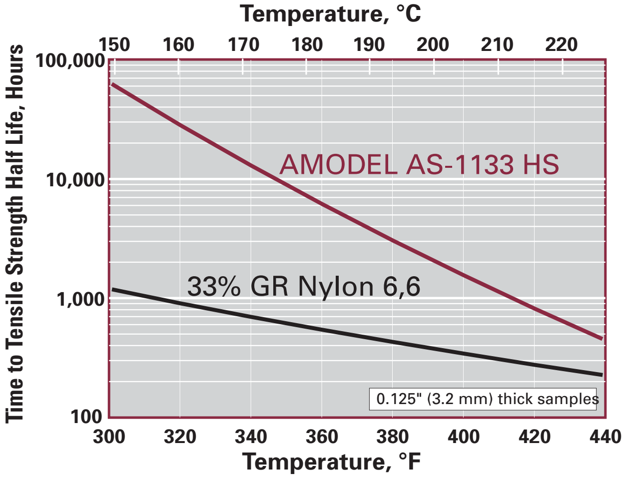
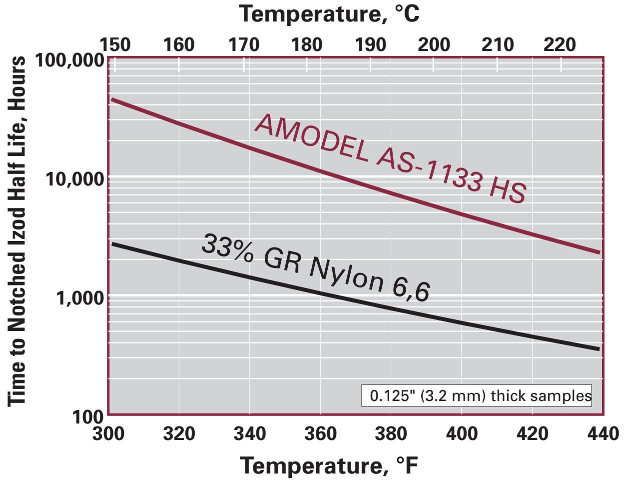


Figure 71. Thermal Aging Comparison
Glass Reinforced Resins
Izod Impact Strength



Relative Thermal Index (UL)

A primary function of Underwriters Laboratories Inc is to assist in the assessment of the risk of fire associated with electrical devices. Because insulating materials may deteriorate over time some method of evaluating this tendency and providing guidance to designers and users of electrical devices was required. Underwriters Laboratories (UL) has developed a method and rating system for this purpose. This method is UL Standard 746B, *Polymeric Materials, Long-Term Property Evaluation*. A similar method is ASTM D 3045, *Standard Practice for Heat Aging of Plastics Without Load*.

Based on the results of aging tests as described in the previous section, Underwriters Laboratories assigns a rating called the “Relative Thermal Index” to insulating materials. Because all material properties do not decay at the same rate, a material may have different Relative Thermal Indices for electrical properties, mechanical properties without impact, and mechanical properties with impact.

The Relative Thermal Index or RTI is determined by a statistical analysis of thermal aging data for the properties being evaluated. The RTI predicts the aging temperature that a material can endure for 100,000 hours and still retain at least fifty percent of the initial property or properties being measured.

Because the rate of decay is greater for thinner specimens, UL gives RTI ratings for each thickness tested.

To obtain a UL RTI rating, a long-term heat aging program is performed. Sets of test specimens molded from the material to be tested are put into ovens at preset temperatures. Periodically specimens are removed and tested. The results for each aging temperature are plotted on a time versus property graph, until the property being measured has declined to 50 percent or less of its initial value. This combination of time and aging temperature can be referred to as the “half-life” for that property, material, and thickness.

The half-lives (time to 50% or less) for a particular property, which were experimentally determined at four aging temperatures, are plotted against the reciprocal of the absolute aging temperature. The points should establish a straight line which can be extrapolated to predict the half-life of the material for the particular property at other temperatures. This is called an “Arrhenius plot”.

To estimate the RTI for the material, the best fit straight line is drawn through the four half-life points for tensile strength and extended to 100,000 hours. The temperature at which this line crosses the 100,000 hours line is an estimate of the RTI for the material. If only three half-life points are available, such as when the data for the fourth temperature is still under test, then a provisional RTI can be granted. The RTI assigned by UL may be somewhat lower as statistical methods are used to compensate for experimental variability.

Testing of AMODEL resins for the establishment of UL Relative Thermal Indices is a continuing long-term activity. The UL ratings of some AMODEL resins when this manual was printed is shown in Table 16.

Table 16.
UL Relative Thermal Indices of AMODEL Resins

AMODEL Grade	Thickness		Relative Thermal Index Mechanical With Impact		Mechanical Without Impact	
	in.	mm	°F	°C	°F	°C
AF-1133 V0	0.06	1.5	256	130	256	130
AF-1145 V0	0.06	1.5	239	115	248	120
AF-1550 V0	0.06	1.5	302	150	302	150
AF-4133 V0	0.06	1.5	256	130	256	130
AFA-4133 V0(Z)	0.06	1.5	256	130	256	130
AFA-6133 V0(Z)	0.06	1.5	256	130	256	130
AFA-6145 V0(Z)	0.06	1.5			256	130
	0.12	3.0	284	140	284	140

Combustion Properties

This section describes the resistance of AMODEL resins to burning and ignition, and the smoke density characteristics of the material once it has been ignited. Described below are glow wire test results, classifications according to UL 94 and ASTM smoke density test results.

Glow Wire Testing

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

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

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

The test can be applied at one or more recommended temperatures and at any wall thickness needed. Recommended temperatures are 1022°F (550°C), 1202°F (650°C), 1382°F (750°C), 1562°F (850°C), and 1760°F (960°C). Thickness is usually mandated by the design or the requirements of the device. It is most difficult to resist ignition at the high glow wire temperature and thinner wall sections.

AMODEL resins have passed glow wire testing as shown in Table 17.

Smoke Density Test (NBS)

The results in this section are data from small scale laboratory testing and are not intended to reflect hazards of these or any other materials under actual fire conditions.

When a material burns, smoke is generated. The quantity and density of the generated smoke is important in many applications. ASTM E 662, *Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials,* 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. The data in Table 18 was generated in both flaming and non-flaming modes. A six tube burner is used to apply a row of flamelets across the lower edge of the specimen. A photometric system aimed vertically is used to measure light transmittance as the smoke accumulates. The specific optical density (D_s) is calculated from the light transmittance. The maximum optical density is called D_m.

Table 17.
Glow Wire Test Results

Conditions Passed

AMODEL Grade	Thickness		Temperature	
	in.	mm	°F	°C
AS-1133 HS NT	0.1	2.5	1,760	960
AS-1145 HS NT	0.1	2.5	1,760	960
AS-1133 HS BK 324	0.1	2.5	1,760	960
AS-1145 HS NT	0.1	2.5	1,760	960
AF-1133 V0 NT	0.06	1.6	1,760	960
	0.1	2.5	1,760	960
AF-1145 V0 NT	0.06	1.6	1,760	960
	0.1	2.5	1,760	960

Table 18.
Smoke Density

AMODEL Grade	D_s @ 4 minutes	D_m	D_m Corr.
Flaming Mode			
AS-1133 HS	565	510	469
AF-1133 V0	711	773	756
Non-Flaming Mode			
AS-1133 HS	3	162	162
AF-1133 V0	12	386	382

Vertical Flammability per UL 94

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 using the material. 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 inch (125 mm) length, 0.5 inch (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 premarked 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 premarked 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.

AMODEL AS-1133 HS resin has obtained a 94HB rating in the *Horizontal Burning Test*, at thicknesses down to 0.8 mm in a black color.

20 MM Vertical Burn Test

Materials can be classified 94V-0, 94V-1, or 94V-2 on the basis of 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 done 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 19 lists the criteria by which a material is classified in this test.

In the *20 MM Vertical Burning Test*, AMODEL resins AF-1115 V0, AF-1133 V0, and AF-1145 V0 have been recognized by UL with a 94V-0 rating at specimen thicknesses down to 0.032 inch (0.8 mm) in black and natural colors.

Table 19.
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 ($t1 + t_2$ 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

500 MW Vertical Burning Test

A material which passes the flammability requirements established by the *500 MW Vertical Burning Test* earns either a 94-5VA or 94-5VB rating. This particular test is the most severe of the three described. The dimensions of the molded bars used in this test are identical to those used for the 20 MM Vertical Burning Test. Additionally, plaques are required that measure 5.9 inches (150 mm) by 5.9 inches (150 mm) by the minimum and maximum thicknesses required for the application. The bars are clamped in a vertical position with a 125 mm high flame applied five times for five seconds each time with a five second interval between each application. The plaques are clamped in a horizontal, flat position with a 125 mm high flame applied to the bottom surface at a 20 degree angle using the same burn times described for the bars. Table 20 lists the criteria that must be met to obtain a 94-5VA or 94-5VB rating.

When this manual was published there were no AMODEL products formally recognized by Underwriters Laboratories with a 94-5V rating. However, when tested in our laboratory in accordance with the *500 MW Vertical Burning Test*, the flame retardant AMODEL products have exhibited UL 94-5VA performance.

Table 20.
UL Criteria for
Classifying Materials 5VA or 5VB

Criteria Conditions	**94-5VA**	**94-5VB**
Afterflame time plus afterglow time after fifth flame application for each individual bar specimen	≤ 60s	≤ 60s
Cotton indicator ignited by flaming particles or drops from any bar specimen	No	No
Burn-through (hole) of any plaque specimen	No	Yes

HIGH-DENSITY, STACKING PRINTED CIRCUIT BOARD CONNECTORS

Subminiature, low-insertion force, high-density, stacking printed circuit board connectors from Hypertronics Corporation are available in AMODEL PPA. They are used for through-board mounting for high density packages, with components on both sides of the circuit board. Uses include military and computer applications, as well as burn-in sockets, medical devices, commercial aircraft, and ground transportation equipment.

Originally a user of thermosets, Hypertronics decided to look at thermoplastics for cost, performance and economics. Polyphenylene sulfone (PPS), like diallyl phthalate, is a very low ductility material which restricts connector design options. Various nylons, thermoplastic polyesters (TPE), polybutylene terephthalate (PBT), as well as sulfone polymer blends, were considered. Hypertronics found that AMODEL PPA molds in existing tooling designed for glass-filled nylons, and that it provides the required performance because of its lower moisture absorption, chemical resistance, and temperature capability.

Hypertronics uses AMODEL AF-1115 VO resin with a UL 94V-0 rating. It provides excellent contact retention by deforming as the contact shoulder passes. Its elastic recovery locks the contact in place.

Electrical Properties

Many applications for thermoplastic resins depend upon their ability to function as electrical insulators. A wide variety of tests have been developed to measure specific aspects of material performance in electrical applications. A brief description of some of the more common tests follows:

Dielectric Breakdown Voltage and Strength - UL 746A §18 - ASTM D 149

Dielectric strength is a measure of the ability of a material to resist high voltage without dielectric breakdown. It is measured by placing a specimen between two electrodes and increasing the applied voltage until dielectric breakdown occurs. The dielectric strength is reported at the highest voltage prior to failure. Of the various methods included in ASTM D 149, UL 746A specifies the short-time test using a uniform rate of voltage increase of 500 volts per second.

Although the results are reported in units of volts/mil (kV/mm), the dielectric strength is a function of thickness, moisture content, and temperature. Therefore, data on different materials are comparable only for equivalent sample thickness, moisture content, and test temperature.

Volume Resistivity - UL 746A §19 - ASTM D 257

The volume resistivity of a material is defined as the electrical resistance of a unit cube of material. The material is subjected to 500 volts DC for 1 minute, and the current through the material is measured. Materials with higher volume resistivity are more effective at electrically isolating components.

UL 746A specifies that the test be run on two sets of specimens: one set conditioned for 48 hours at 73°F (23°C) and 50% relative humidity; and the other conditioned for 96 hours at 95°F (35°C) and 90% relative humidity.

Volume resistivity is particularly sensitive to temperature changes as well as changes in humidity. Data on different materials are comparable only for equivalent moisture content and temperatures. Materials with resistivities above 10^8 ohm-cm are considered insulators, while those with values of 10^3 to 10^8 ohm-cm are partial conductors.

Surface Resistivity - UL 746A §19.4 - ASTM D 257

The surface resistivity of a material is the electrical resistance between two electrodes on the surface of the specimen. The material is subjected to 500 volts DC for 1 minute, and the current along the surface of the material is measured. Surface resistivity is an approximate measure because some finite thickness of material is carrying the current. Surface resistivity is affected by surface contamination and is not considered a basic material property.

UL specifies the same specimen conditioning used for volume resistivity.

Data from this test are best used when materials are being evaluated and selected for testing in applications in which surface leakage may be a problem.

Dielectric Constant - ASTM D 150

The dielectric constant is defined as the ratio of the capacitance of a condenser using the test material as the dielectric to the capacitance of the same condenser with a vacuum replacing the dielectric. Insulating materials are used in two very distinct ways. First, to support and insulate components from each other and the ground, and second, to function as a capacitor dielectric. In the first case, it is desirable to have a low dielectric constant. In the second case, a high dielectric constant allows the capacitor to be physically smaller. Dielectric constants have been found to change rapidly with increasing temperature or moisture contents, hence data on different materials are comparable only at equivalent moisture content and temperature.

Dissipation Factor - ASTM D 150

Dissipation Factor is a measure of the dielectric loss, or energy dissipated, when alternating current loses energy to an insulator. In general, low dissipation factors are desirable because they correspond to a better dielectric material. Contamination, testing frequency, temperature, and humidity can affect the dissipation factor.

High-Voltage, Low-Current, Dry Arc Resistance - UL 746A §20 - ASTM D 495

This arc resistance test measures the time, in seconds, that a 12,500 volt arc can travel between two tungsten rod electrodes on the surface of a material, following a specified test sequence of increasing severity, until a conductive path or track is formed. Failure is dependent on temperature, frequency, and conditioning. A material with a high value for arc resistance would be beneficial in electrical applications that may be exposed to high voltage, and where the likelihood of arcing exists.

Comparative Tracking Index - UL 746A §21 - ASTM D 3638

The Comparative Tracking Index is defined as the voltage at which a permanently conductive path is formed with the application of 50 drops of electrolyte applied at a rate of 1 drop per second. The surface is subjected to a low-voltage alternating stress combined with a low current. High Comparative Tracking Index (CTI) values indicate high resistance to the formation of conductive tracks.

High-Voltage Arc-Tracking-Rate UL 746A §22

The High Voltage Arc Tracking Rate (HVATR) measures the susceptibility of a material to form a visible carbonized conducting path over its surface when subjected to repeated high-voltage, low-current arcing. The HVATR value is the rate, in mm/minute, at which a conducting path is produced on the surface of a material under standardized test conditions. This test simulates a malfunctioning high-voltage power supply. Lower values indicate better performance.

Hot Wire Ignition - UL 746A §29 - ASTM D 3874

The Hot Wire Ignition (HWI) test measures the relative resistance to ignition of a material by an electrically heated wire. A portion of a test specimen is wrapped with a heater wire under specified conditions and a current is passed through the wire at a linear power density of 6.5 W/in. (0.26 W/mm). The current flow is maintained until ignition occurs, and the time to ignition is recorded. Higher Hot Wire Ignition values indicated better resistance to ignition by contact with a hot wire.

High-Current Arc Ignition - UL 746A §30

This test measures the number of 240-volt 32.5-ampere arcs on the surface of a material required to cause ignition or a hole. The distance between the electrodes in increased at a rate of 10 in. (254 mm) per second. The maximum number of arcs to be used is 200.

This test measures the performance of an insulating material in close proximity to arcing.

High-Voltage Arc Resistance to Ignition UL 746A §31

The High-Voltage Arc Resistance to Ignition test measures the ability of a material to resist ignition under the influence of a high-voltage, low-current arc on its surface. The application of the high-voltage arc is continued until ignition or 5 minutes (300 seconds). If ignition occurs, the time to ignition is reported. If ignition does not occur the value >300 is reported. In this test, UL-746A, an absolute numerical index for the tested sample is established. Higher values correspond to better performance levels.

UL Relative Thermal Indices

The UL Relative Thermal Indices are the result of thermal aging tests and, therefore, appear in the Thermal Stability section on page 56.

Table 21 lists results of electrical property testing for several AMODEL resins.

AMODEL resins have excellent electrical properties. Typically, the flame retardant grades would be selected for electrical applications. These AMODEL grades earn performance level class (PLC) ratings of either 0 or 1 in the important UL746A tests.

Table 21.
Electrical Properties

Property	Test Method ASTM/ UL 746A §	Units	AMODEL PPA Grade				
			AS-1133 HS	A-1340 HS	AF-1133 V0	AF-1145 V0	AF-1550 V0
			DAM	DAM	DAM	DAM	DAM
Dielectric Strength, 1/16" (1.6 mm)	D 149 §18	V/mil (kV/mm)		680 (27.6)	610 (24.8)	660 (26.9)	635 (25.8)
Volume Resistivity[1]	D 257 §19	ohm-cm	$1\text{x}10^{16}$	$2\text{x}10^{15}$	$3\text{x}10^{15}$	$1\text{x}10^{15}$	$2\text{x}10^{16}$
Surface Resistivity[1]	D 257 §19.4	ohm	$2\text{x}10^{15}$	$2\text{x}10^{15}$	$2\text{x}10^{15}$	$2\text{x}10^{15}$	$1\text{x}10^{15}$
Dielectric Constant	D 150	at 100 Hz	3.9	4.5	4.0	3.8	4.3
		at 1 MHz	4.2	4.3	4.9	5.2	4.3
Dissipation Factor	D 150	at 100 Hz	0.012	0.005	0.009	0.010	0.005
		at 1 MHz	0.017	0.017	0.008	0.008	0.012
Comparative Tracking Index	D 3638 §21	volts [PLC][2]	550	550	550 [1]	550 [1]	500 [1]
High Voltage Arc Track Rate	§22	mm/min [PLC][2]			20 [1]	18 [1]	4 [0]
Hot Wire Ignition	§29	sec [PLC][2]			150 [0]	150 [0]	150 [0]
High-Current Arc Ignition	§30	arcs 1/16" (1.5 mm) [PLC][2]			150 [0]	150 [0]	64 [1]
		arcs 1/32" (0.8 mm) [PLC][2]			74 [1]	74 [1]	69 [1]
High Voltage Arc Resistance to Ignition	§31	sec [PLC][2]			300 [0]	300 [0]	300 [0]

1. Conditioned for 96 hours at 95°F (35°C) and 90% relative humidity.
2. PLC = Performance Level Class per UL 746A, values shown are UL listed.

Environmental Resistance

As previously mentioned, the performance of polymeric materials may be reduced by environmental factors. This section discusses the effects of environmental factors, such as chemical exposure, conditions likely to promote hydrolysis, exposure to gamma and/or ultraviolet radiation, on the performance of AMODEL resins. When appropriate, the effects of these environmental factors on the performance of competitive resins is included for comparison.

Chemical Resistance

AMODEL resins are semi-crystalline polyphthalamides, and like other members of the semi-crystalline polyamide family, they exhibit excellent chemical resistance to common organic solvents. However, the chemical structure of AMODEL resins is highly aromatic — imparting an even greater degree of chemical resistance to an even broader range of chemicals.

It is difficult to predict the exact effect of chemical exposure on a polymeric component because the reagent, the concentration of the reagent, the exposure time, the temperature of the reagent, the temperature of the polymeric component, and the stress on the component all affect the extent of attack and any change in performance. While the only reliable method for evaluating the effect of chemical attack on the performance of a polymeric component is prototype testing, screening tests are often performed to provide general guidance and compare materials.

Screening chemical resistance testing was performed by immersing ASTM D 638 Type I tensile bars in various chemicals for 30 days at the indicated test temperatures. The AMODEL resin used was the 33% fiber glass reinforced grade – AMODEL AS-1133 HS. Data on 33% glass reinforced nylon 6,6 and 30% glass reinforced polyethylene terephthalate (PET) is provided for comparison.

The material performance was rated as shown in Table 22. In addition to the performance rating, data on the percent change in tensile strength, length, and weight are reported.

The chemicals used for the screening tests were classified into three groups:

1. Organic solvents (Table 23),
2. Aqueous solutions (Table 24), and
3. Automotive fluids (Table 25).

The screening evaluation using aqueous solutions at elevated temperatures showed a loss in tensile strength for all three of the resins tested. This phenomenon is common to all glass reinforced thermoplastics. The loss of tensile strength for AMODEL AS-1133 HS resin in deionized water at 200°F (93°C) is initially rapid due to loss of interfacial adhesion between the glass fibers and the resin matrix, and then slows to a gradual rate reflecting hydrolytic attack. Aqueous solutions of antifreeze or zinc chloride produce a similar effect. Nylon 6,6 is severely attacked by the zinc chloride solution. PET is severely attacked by the antifreeze solution and even badly hydrolyzed by distilled water at elevated temperatures.

Table 22.
Key to Chemical Resistance Ratings

Symbol	Rating	% reduction in tensile strength
E	Excellent	≤ 10
A	Acceptable	≤ 50 but ≥ 10
U	Unacceptable	> 50

Table 23.
Screening Chemical Resistance Tests — Organic Chemicals

30 day immersion at 73°F (23°C)

Reagent	Resin	Rating	Tensile Strength, % Retained	Change in Length, %	Change in Weight, %
Acetone	AMODEL AS-1133 HS	E	97	0.1	0.2
	33% glass nylon 6,6	E	99	0.2	0.2
	30% glass PET	A	72	0.3	3.2
Isopropanol	AMODEL AS-1133 HS	E	99	0.0	0.2
	33% glass nylon 6,6	E	112	0.0	0.3
	30% glass PET	E	109	0.0	0.3
Methanol	AMODEL AS-1133 HS	A	83	0.1	2.9
	33% glass nylon 6,6	A	68	0.5	5.6
	30% glass PET	E	96	0.1	0.5
Methylene Chloride	AMODEL AS-1133 HS	E	94	0.0	1.1
	33% glass nylon 6,6	E	90	0.1	2.4
	30% glass PET	A	71	2.0	9.5
Methyl Ethyl Ketone	AMODEL AS-1133 HS	E	103	0.0	0.1
	33% glass nylon 6,6	A	113	0.0	0.1
	30% glass PET	A	72	0.1	3.0
Toluene	AMODEL AS-1133 HS	E	101	0.0	0.1
	33% glass nylon 6,6	E	109	0.1	0.2
	30% glass PET	E	91	0.1	1.6
1,1,1 trichloroethane	AMODEL AS-1133 HS	E	99	0.0	0.2
	33% glass nylon 6,6	E	110	0.0	0.2
	30% glass PET	E	100	0.0	2.3
Trichloroethylene	AMODEL AS-1133 HS	E	102	0.0	0.3
	33% glass nylon 6,6	E	97	0.0	0.4
Freon® 113	AMODEL AS-1133 HS	E	96	0.0	0.1
	33% glass nylon 6,6	E	99	0.0	0.2
n-Heptane	AMODEL AS-1133 HS	E	104	0.0	0.1
	33% glass nylon 6,6	E	96	0.0	0.2

Freon is a registered trademark of E. I. duPont de Nemours and Company.

Table 24.
Screening Chemical Resistance Tests — Aqueous Chemical Solutions

30 day immersion at indicated temperature

Solvent	**Conc.**	**Temperature, °F (°C)**	**Resin**	**Rating**	**Tensile Strength, % Retained**	**Change in Length, %**	**Change in Weight, %**
Ammonium Hydroxide	10%	73 (23)	AMODEL AS-1133 HS	E	96	0.1	0.8
			33% glass nylon 6,6	A	61	0.2	4.5
			30% glass PET	E	95	0.2	0.4
Deionized Water	100%	200 (93)	AMODEL AS-1133 HS	A	69	0.2	3.4
			33% glass nylon 6,6	A	62	0.2	5.0
			30% glass PET	U	19	0.0	2.4
Sodium Chloride	10%	73 (23)	AMODEL AS-1133 HS	E	97	0.1	2.1
			33% glass nylon 6,6	A	67	0.2	3.3
			30% glass PET	E	98	0.0	0.3
Zinc Chloride	50%	200 (93)	AMODEL AS-1133 HS	A	66	0.1	4.8
			33% glass nylon 6,6	U	0	*	*
			30% glass PET	A	54	-0.1	0.6
Sulfuric Acid	36%	73 (23)	AMODEL AS-1133 HS	E	92	0.0	1.8
			33% glass nylon 6,6	U	0	*	*
			30% glass PET	E	94	0.0	0.3
Sodium Hydroxide	10%	73 (23)	AMODEL AS-1133 HS	E	93	0.0	1.6
			33% glass nylon 6,6	A	62	0.0	3.1
			30% glass PET	A	70	0.0	-4.2
Sodium Hypochlorite	5%	73 (23)	AMODEL A-1133 HS	E	94	0.0	1.4
			33% glass nylon 6,6	A	57	0.0	-1.5
			30% glass PET	E	94	0.0	0.4

* = Attacked

Table 25.
Screening Chemical Resistance Tests — Transportation Fluids

30 day immersion at indicated temperature

Fluid	Temperature, °F (°C)	Resin	RATING	Tensile Strength, % Retained	Change in Length, %	Change in Weight, %
50% Antifreeze Solution	220 (104)	AMODEL AS-1133 HS	A	77	0.2	5.6
		33% glass nylon 6,6	A	54	0.3	8.3
		30% glass PET	U	0	*	*
Brake Fluid	120 (49)	AMODEL AS-1133 HS	E	99	0.0	0.4
		33% glass nylon 6,6	E	105	-0.1	0.2
		30% glass PET	E	97	0.0	1.0
Diesel Fuel	73 (23)	AMODEL AS-1133 HS	E	98	0.0	0.1
		33% glass nylon 6,6	E	100	0.0	0.3
		30% glass PET	E	100	-0.1	0.0
Gasohol (10% Ethanol)	73 (23)	AMODEL AS-1133 HS	A	86	0.0	1.4
		33% glass nylon 6,6	A	65	0.1	3.5
		30% glass PET	E	93	-0.1	0.7
Hydraulic Fluid	120 (49)	AMODEL AS-1133 HS	E	92	0.0	0.3
		33% glass nylon 6,6	E	103	0.0	0.3
		30% glass PET	E	105	-0.1	0.1
JP-4 Jet Fuel	73 (23)	AMODEL AS-1133 HS	E	95	0.0	0.4
		33% glass nylon 6,6	E	100	0.0	0.3
		30% glass PET	E	100	0.0	0.1
Motor Oil	250 (121)	AMODEL AS-1133 HS	E	100	0.0	0.1
		33% glass nylon 6,6	E	106	0.0	-0.2
		30% glass PET	E	91	-0.1	-0.6
Power Steering Fluid	120 (49)	AMODEL AS-1133 HS	E	97	0.0	0.1
		33% glass nylon 6,6	E	106	0.0	0.2
		30% glass PET	E	108	0.0	0.0
Transmission Fluid	250 (121)	AMODEL AS-1133 HS	E	97	0.0	0.1
		33% glass nylon 6,6	E	105	-0.1	-0.2
		30% glass PET	A	64	0.1	-0.5

Chemical Compatibility

Table 26 can be used as a general guide to the chemical resistance of AMODEL resins. However, this data should be used for screening only. As mentioned earlier, the performance of AMODEL resins under actual chemical exposure conditions will vary with differences in mechanical stress, concentration, time and/or temperature. It is recommended that tests be conducted under conditions close to those anticipated in the actual application to get reliable performance information.

Table 26.
General Chemical Compatibility Guidelines for AMODEL PPA Resins

Reagent	**Rating**
Aliphatic Hydrocarbons	E
Aromatic Hydrocarbons	E
Oils	E
Greases	E
Chlorinated Hydrocarbons	E
Methylene Chloride	A
Chloro-Fluoro Carbons	E
Ketones	E
Esters	E
Higher Alcohols	E
Methanol	A
Phenols	U
Strong Acids	A
Alkalis	E

Resistance to Automotive Antifreeze

AMODEL resins have excellent resistance to ethylene glycol/water solutions like those used as cooling fluids in automotive applications.

Injection molded ASTM D 638 Type I tensile bars of the candidate resins were immersed in aqueous solutions containing 50% antifreeze at the specified temperature. The antifreeze used was Prestone®[1] II. After the specified immersion time, the bars were removed, rinsed, and cooled to room temperature. After the usual conditioning, at least 24 hours at 73°F (23°C) and 50% relative humidity, the tensile properties were determined according to ASTM D 638.

Figure 72 shows the tensile strength of AMODEL AS-1133 resin, two glycol resistant grades of AMODEL polyphthalamide (AS-1933 and AS-1945), and a glycol resistant grade of nylon 6,6 after immersion in 50% antifreeze solutions at 275°F (135°C). While all of the resins are affected by the glycol solution, the standard AMODEL AS-1133 is superior to the glycol-resistant nylon 6,6 formulation, and AS-1933 and AS-1945 are superior to the AMODEL AS-1133 resin. The higher glass content version has the highest strength of all.

Figure 73 presents the tensile strength retention data for the glycol resistant grade of AMODEL polyphthalamide containing 33% glass (AS-1933) as a function of exposure temperature in a 50% antifreeze solution. The results indicate the glycol resistance is diminished with increasing temperature, suggesting the temperatures over 275°F (135°C) should be avoided.

Figure 72. Strength Retention of Glass Filled Resins Exposed to 50% Antifreeze Solution at 275°F(135°C)

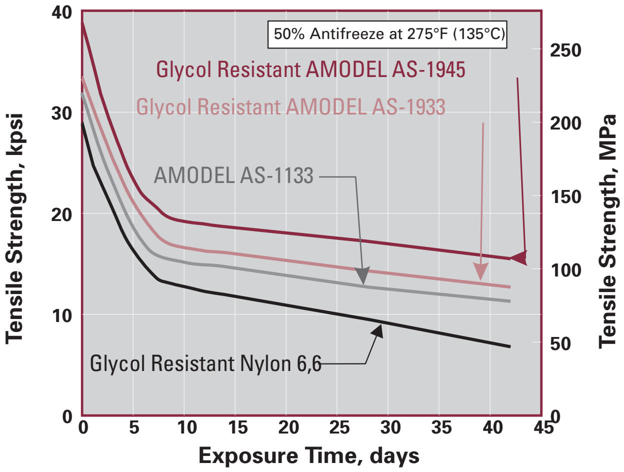
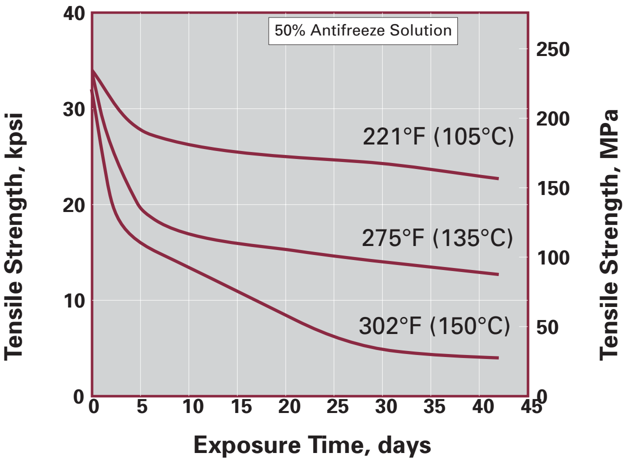


Figure 73. Strength Retention of Glycol Resistant AMODEL w/ 33% Glass (AS-1933) at Various Temperatures



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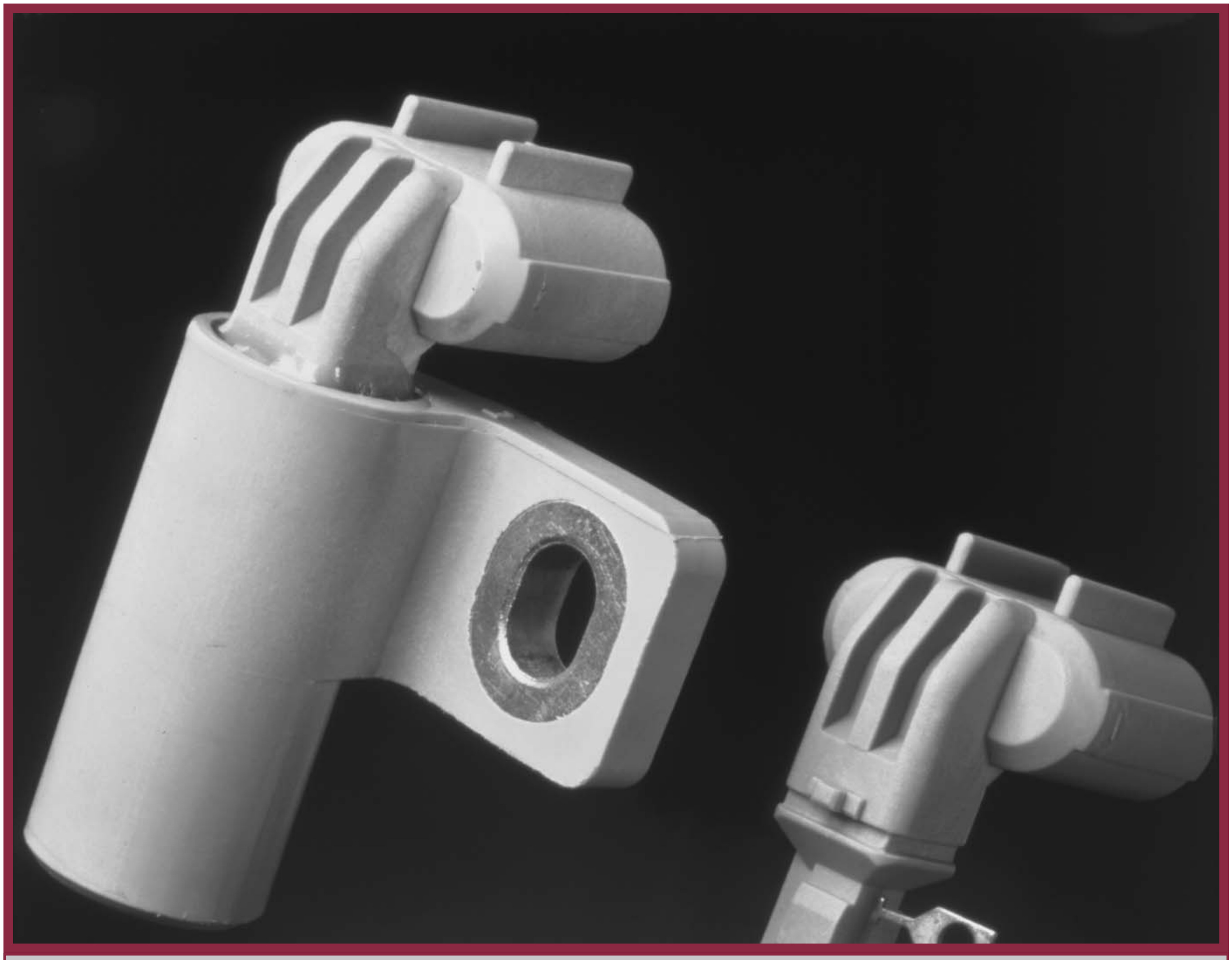
[1] Prestone is a registered trademark of First Brands Corporation



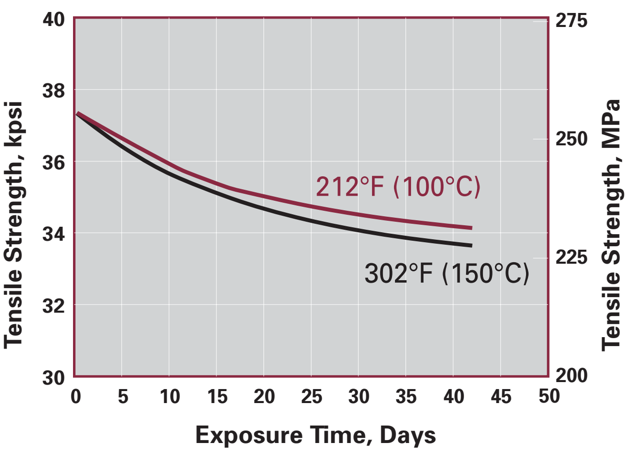
AUTOMOTIVE CAM SENSOR USES AMODEL PPA RESIN

AMODEL polyphthalamide (PPA) resin has replaced nylon as the cam shaft sensor connector material for the 1993 Chrysler family sedans — Chrysler Concord, Dodge Intrepid, Eagle Vision and Chrysler New Yorker. The magnetically operated sensor monitors the position of the rotating cam in the 3.5 liter engine.

Resistance to Automotive Power Steering Fluid

AMODEL resins have excellent resistance to automotive power steering fluid. Injection molded ASTM D 638 Type I tensile bars of AMODEL AS-1145 HS resin were exposed to power steering fluid at 212°F (100°C) and 302°F (150°C). The power steering fluid used was GM9985010. After immersion times of 7, 21, and 42 days, the tensile properties of AMODEL AS-1145 HS resin were determined in accordance with ASTM D 638. Figure 74 shows the tensile strength retention of AMODEL AS-1145 HS resin as a function of immersion time and temperature. The AMODEL resin retains about 90% of its tensile strength, even at the higher exposure temperature.

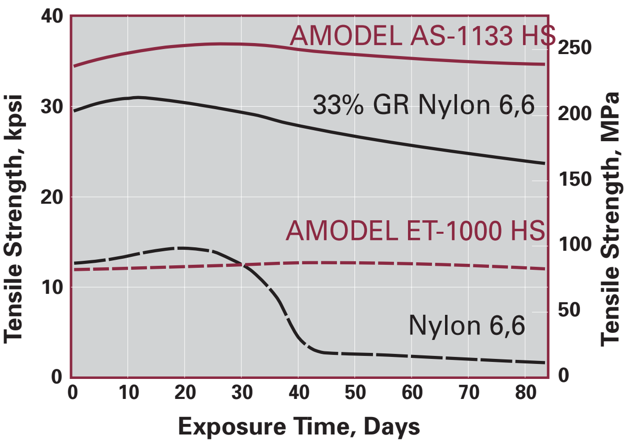
Figure 74. Tensile Strength Retention of AMODEL AS-1145 HS Resin Exposed to Power Steering Fluid



Resistance to Automatic Transmission Fluid

AMODEL resins have excellent resistance to automotive automatic transmission fluid. Injection molded ASTM D 638 Type I tensile bars of AMODEL AS-1133 HS resin, AMODEL ET-1000 HS resin, a 33% GF nylon 6,6, and an unreinforced nylon 6,6 were immersed in automatic transmission fluid (Dexron® IIE)at 275°F (135°C) for 7, 14, 28, and 42 days. After immersion, the tensile properties of these materials were determined in accordance with ASTM D 638. Figure 75 shows a comparison of the tensile strength retention of these engineering resins as a function of immersion time. It clearly demonstrates that both reinforced and unreinforced AMODEL resins are highly resistant to automatic transmission fluid at 275°F (135°C), while the strength of the reinforced nylon 6,6 declines steadily and the strength of the unreinforced nylon 6,6 deteriorates severely after about 30 days.

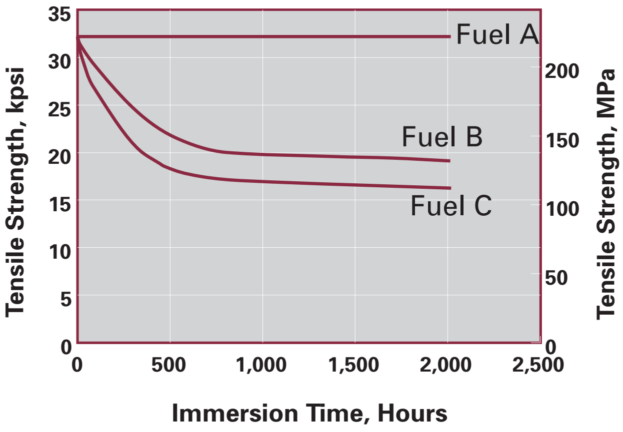
Figure 75. Strength Retention of Resins Exposed to Automatic Transmission Fluid



Resistance to Automotive Flex Fuels

AMODEL resins maintain good resistance to automotive fuels. Injection molded ASTM D 638 Type I tensile bars of AMODEL AS-1133 HS resin were immersed in three different flex fuels whose temperatures were maintained at 140°F (60°C). Fuel A consisted of a blend of 50% toluene and 50% iso-octane with sodium chloride and formic acid included as additives. Fuel B consisted of a blend of 35% toluene, 35% iso-octane, and 30% methanol with water, sodium chloride, and formic acid included as additives. Finally, fuel C consisted of a blend of 7.5% toluene, 7.5% iso-octane, and 85% methanol with water, sodium chloride, and formic acid included as additives. Figure 76 shows the effect of the fuels on the tensile strength of AMODEL AS-1133 HS resin as a function of immersion time. Fuel A has the least effect on the AMODEL resin.

Figure 76. Strength Retention of AMODEL AS-1133 HS Exposed to Flex Fuels at 140°F (60°C)



Chrysler PCV Valves Use AMODEL PPA Resin

A new PCV valve design for the 1993 Chrysler LH car series (Dodge Intrepid, Eagle Vision and Chrysler Concorde) is made of AMODEL A-1145 HS PPA resin. The production-level part screws directly into the engine intake manifold, eliminating the need for a manifold nipple and a second interconnecting hose.

AMODEL A-1145 HS resin had the highest torque among all the materials evaluated (500 in-lb), and had the required thermal and creep stability to prevent torque loss, according to Chrysler Engineering. It performs at underhood temperatures up to 300°F (149°C) and is chemically resistant to oil splashes.

Compared with conventional nylons, AMODEL PPA resins offer five times lower permeability, higher strength- and stiffness-to-weight ratios and improved dimensional stability for such associated applications as fuel rails and quick connects.

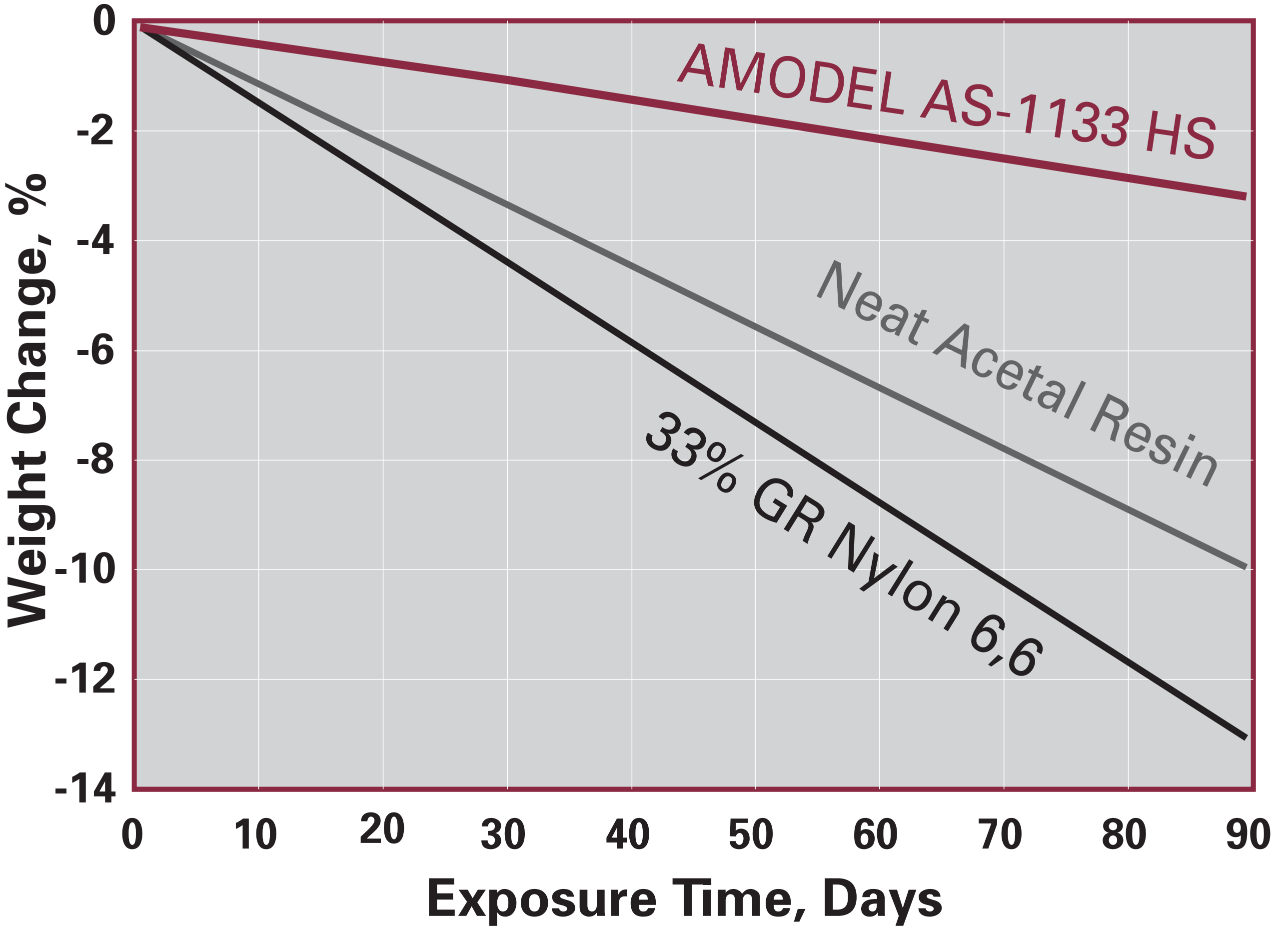
Resistance to Chlorinated Water

Plastic materials are frequently used in applications that come in contact with chlorinated water. Examples include plumbing fixtures and fittings. It is important that these materials be able to withstand exposure to chlorinated water found in municipal water supplies. Accelerated testing was done at elevated temperatures to assess the usefulness of AMODEL resins in these applications.

ASTM D 638 Type I tensile bars were injection molded from AMODEL AS-1133 HS resin, an unreinforced acetal resin, and a 33% glass reinforced nylon 6,6 and subsequently exposed to water containing 30 parts per million (0.003 %) of chlorine at 180°F (82°C). Weight change was monitored as a function of time. The attack by the aqueous chlorine is seen as weight loss originating at the exposed surfaces.

The results, shown in Figure 77, indicate that AMODEL resin is more resistant to degradation by water containing chlorine than polyacetal or nylon 6,6.

Figure 77. Resistance to Chlorinated Water at 180°F (82°C) , Comparison of AMODEL PPA to Acetal and Nylon



Steam Sterilization Resistance

Steam autoclaves are widely used to sterilize medical devices. As a result, resistance to steam sterilization is important. To evaluate this property in a manner consistent with actual practice, 50 ppm morpholine was added to the steam to simulate typical boiler additives. Injection molded test bars of AMODEL ET-1000 HS and AS-1133 HS resins were exposed to 30 minute cycles from room temperature to steam at 270°F (132°C) in an autoclave. These parts were tested for tensile strength, elongation, modulus, and notched Izod after 50 and 100 cycles of exposure. The results are given in Table 27.

Figure 78 compares the tensile strength retention of AMODEL AS-1133 HS resin and 33% glass reinforced nylon 6,6 due to steam sterilization. These curves are shown as a function of the number of cycles of exposure to steam in an autoclave.

Figure 78. Steam Sterilization Resistance Comparison

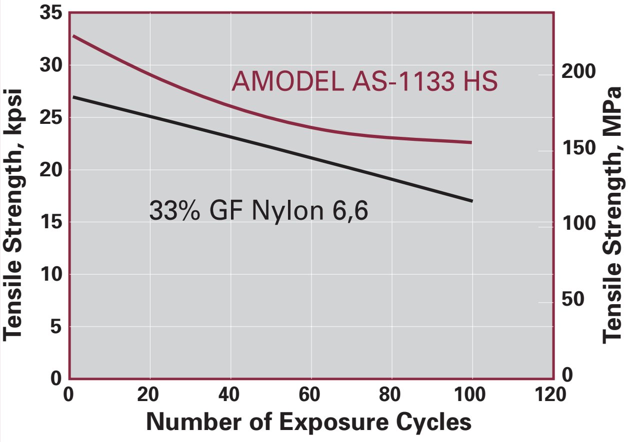


Table 27.
Retention of Mechanical Properties after Steam Exposure
% Retention of Unexposed Value

Material	Property	Cycles - Steam Exposure	
		50 cycles	100 cycles
AMODEL ET-1000 HS	Tensile Strength	113	98
	Tensile Elongation	108	105
	Tensile Modulus	110	114
	Notched Izod	100	100
AMODEL AS-1133 HS	Tensile Strength	76	70
	Tensile Elongation	65	65
	Tensile Modulus	88	88
	Notched Izod	74	66

Gamma Radiation

AMODEL AS-1133 HS resin has excellent resistance to gamma radiation. Tests on injection molded tensile bars exposed to 5.0 megarads of gamma radiation indicate essentially no significant affect on the mechanical properties of AMODEL AS-1133 HS resin. Results are given in Table 28.

Table 28.
Effect of Gamma Radiation on
AMODEL AS-1133 HS

% Retention of	**5 mrad Exposure**
Tensile Strength, psi	90
Tensile Elongation, %	100

Ultraviolet Light Stability

Virtually all plastic components will receive some ultraviolet (UV) radiation exposure, because it is found in natural sunlight and some fluorescent lighting. In general, ultraviolet radiation tends to degrade plastics, and polyamides are not particularly resistant to ultraviolet radiation; when intended for outdoor exposure, they are usually formulated with carbon black.

To evaluate the effect of ultraviolet radiation on the performance of AMODEL resins, testing was performed using an accelerated weathering machine, the Sunshine Carbon Arc Model X-W Weather-Ometer®[1] made by Atlas Devices. This machine generates UV radiation using three carbon arcs (six rods) situated in its center. Surrounding the rods are special glass panels which filter out the portion of the ultraviolet radiation having wavelengths below 255 nm, which are not found in direct sunlight. A cylindrical framework or rack, with clips to hold test specimens, revolves around the panels.

The Weather-Ometer continuously exposes specimens to alternate wet/dry cycles. During the wet cycle, the lights are turned off and the specimens are sprayed with water for 18 minutes. Two water sprayers with nozzles located between the panels and the racks, allow room temperature water to be sprayed onto the specimens. During the dry cycle, the water is turned off and the specimens are exposed to the carbon arc radiation for 102 minutes. The temperature inside the Weather-Ometer is monitored by a sensor mounted on the rack but not in the direct path of the radiation. The black panel temperature, as it is called, is maintained at 145°F (63°C).

Both glass reinforced and toughened grades of AMODEL and nylon 6,6 resin were tested. In addition to the natural material, special versions containing carbon black were included. Prior to weathering, the tensile properties and color were measured. During the accelerated weathering test, samples were periodically removed and the tensile properties and color measured. Tensile properties were measured in accordance with ASTM D 638. The colors were measured using a Gardner “Spectrogard” spectrophotometer and reported using the CIELAB system.

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[1] Weather-Ometer is a registered trademark of Atlas Devices

The effect of accelerated weathering on the tensile strength of neat resins is shown in Figure 79. The natural unreinforced nylon 6,6 exhibited a dramatic reduction in tensile strength, much greater than can be accounted for by moisture adsorption. The addition of carbon black does seem to effectively block some of the UV radiation. The toughened AMODEL resin without carbon black shows a reduction in tensile strength that is less than that seen with the nylon 6,6. The grades containing carbon black show excellent resistance to UV radiation.

Figure 80 compares the tensile modulus retention of AMODEL and nylon 6,6 neat and/or toughened resins. With accelerated weathering, the AMODEL resins show a minor increase in modulus or stiffness. The nylon resins show a dramatic decline in the first 1,000 hours, which may be due to moisture absorption, followed by gradual stiffening. The use of carbon black has only a minor effect.

The results of accelerated weathering testing of the glass reinforced resins are shown in Figure 81. The tensile strength of the nylon 6,6 was reduced by 40%. Adding carbon black helped; the strength reduction was about 25 percent. The AMODEL resins showed less than a 10% decline; and when carbon black was added, the decline was only about 5%.

Figure 79. Effect of UV on Tensile Strength of Neat Resins

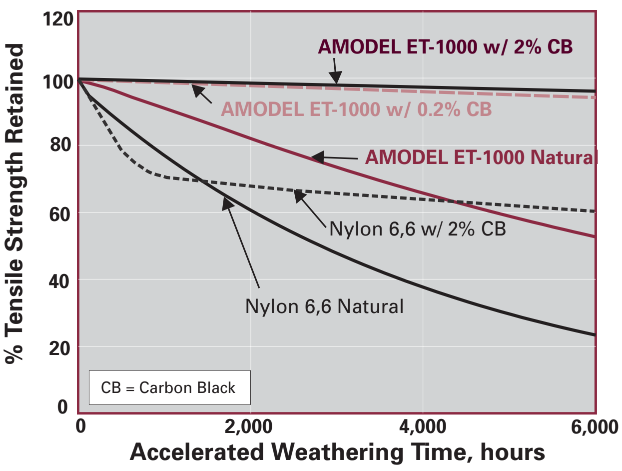


Figure 80. Effect of UV on Tensile Modulus of Neat Resins

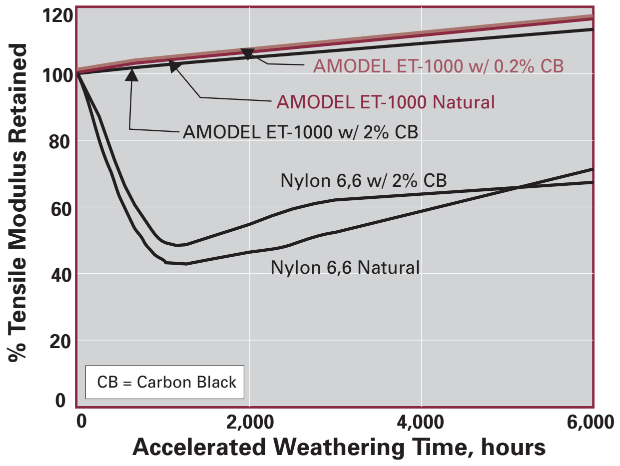


Figure 81. Effect of UV on Tensile Strength of Glass Reinforced Resins

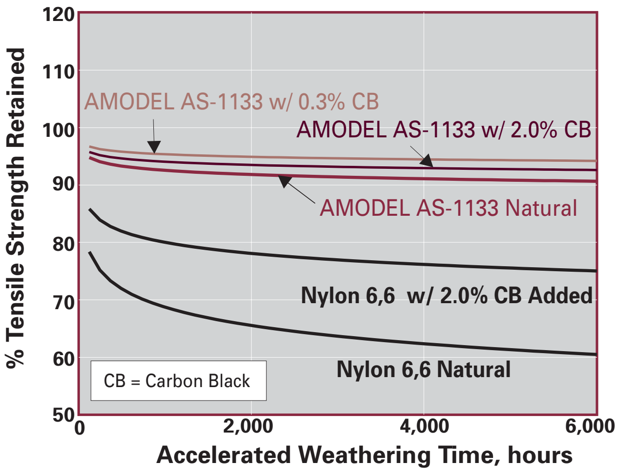


Figure 82 depicts the changes in the moduli of the glass reinforced materials upon exposure to accelerated weathering.

The modulus behavior of the nylon resins was similar to that seen with the unreinforced resins. Again the carbon black does seem to be effective in mitigating the degrading effects of the UV light.

The AMODEL resins show only slight increases in modulus, thereby, exhibiting excellent resistance to degradation by UV radiation.

The results of this work are summarized in Table 29. The only significant color change to the AMODEL resins occurred with AMODEL ET-1000 HS NT resin where the rather large delta b* value indicates a significant amount of yellowing had occurred.

The natural color nylon 6,6 resins showed high delta L* values indicating a lightening. This kind of change is often referred as chalking.

Figure 82. Effect of UV on Tensile Modulus of Glass Reinforced Resins

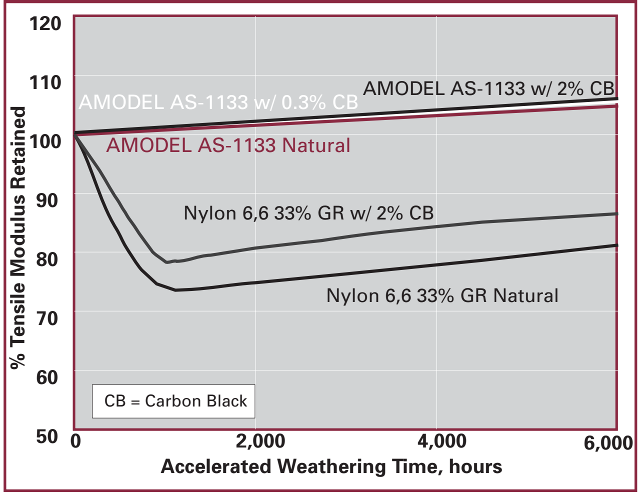


Table 29.
Effects of Ultraviolet Radiation on the Properties of AMODEL and Nylon Resins

After 6,000 Hours of Accelerated Weathering	Nylon 6,6		AMODEL ET-1000 HS			Nylon 6,6		AMODEL AS-1133		
	Unreinforced		Unreinforced			33% Glass		33% Glass		
	Natural Color	UV Resistant	Natural Color	0.2% Carbon Black	2.0% Carbon Black	Natural Color	2.0% Carbon Black	Natural Color	0.3% Carbon Black	2.0% Carbon Black
Retention of Tensile Strength, %	22	61	49	96	97	58	78	91	95	94
Retention of Elongation at Break, %	27	27	8	37	50	97	135	97	104	100
Retention of Tensile Modulus, %	71	67	112	112	115	81	87	106	107	104
Color Change CIELAB System										
Delta L*1	23.6	-10.6	-5.4	-10.3	-15.1	31.3	-9.6	2.2	-2.8	-9.4
Delta a*2	-3.1	0.0	-1.1	-0.4	0.0	2.8	0.0	1.1	0.1	0.0
Delta b*3	-7.6	0.6	13.7	2.2	0.6	-5.7	0.1	2.0	1.1	0.6
Delta E	24.9	10.6	14.8	10.5	15.1	31.9	9.6	3.1	3.0	9.4

[1] change in luminosity (positive change indicates lightening)

[2] a* is red to green (positive indicates closer to green)

[3] b* is blue to yellow (positive indicates closer to yellow)

DESIGN INFORMATION

In this section, basic design principles and general recommendations are presented to assist the design engineer in designing plastic components that meet the cost/performance requirements of their applications. Guidelines are given on the effects of stresses caused by assembly, temperature changes, environmental factors, and time as it relates to creep.

Of the various materials available to a design engineer, thermoplastics offer the greatest variety, versatility and freedom of design. Plastics can be translucent or opaque, rigid or flexible, hard or soft. Plastic materials are available that provide a wide range of chemical resistance, from chemically inert to selective solubility in certain environments. Broad versatility is also available for other properties like strength, stiffness and impact resistance, lubricity and thermal capability. Blends and alloys are possible that further increase the material choices for a particular application.

At times, designing with plastics may appear more complicated than with metals. But the diversity of products, conversion processes, and secondary operations (welding, inserts, printing, painting, metallizing) available with plastics gives the designer unprecedented freedom as shown in Table 30.

A designer may be tempted to make a plastic part that merely duplicates the dimensions of a metal part without taking advantage of the versatility of the plastic material or the design freedom offered. This approach can lead to inefficient designs or parts that are difficult to produce, or whose performance is less than optimal.

The following sections discuss those areas of mechanical design and stress analysis that relate to designing with plastics, comparing metal to plastics and discussing factors that are specific to plastics alone.

Table 30.
Design Benefits of AMODEL Resin over Metals

AMODEL Resin Characteristics	**Benefit in Design**
AMODEL resins are fabricated by the injection molding process, which allows substantial design freedom.	° Ribs, bosses, or cored sections can be readily incorporated. ° Snap fits can be molded in, simplifying assembly. ° Eliminate many secondary operations such as drilling, tapping, boring, deburring, and grinding. ° Metal inserts can be easily used where necessary to optimize part strength. ° Features from several metal parts of an assembly may be combined into a single part, simplifying assembly and reducing cost.
AMODEL resins are thermoplastic.	° Parts may be joined with ultrasonic or vibration welding rather than fasteners. ° Color may be molded-in rather than added afterward as paint.
AMODEL resins resist chemicals.	° Parts will not rust, and resist corrosion.
AMODEL resins have low coefficients of friction.	° Self-lubricating bearing surfaces can often be molded into the part, eliminating a separate bearing.
AMODEL resins have lower densities than metals.	° The weight of parts and assemblies will usually be reduced.

Mechanical Design

The use of classical stress and deflection equations provide starting points for part design. Mechanical design calculations for AMODEL resins will be similar to those used with any engineering material. As with all plastics, however, the analysis used must reflect the viscoelastic nature of the material. In addition, the material properties can vary with strain rate, temperature, and chemical environment or with fiber orientation for fiber reinforced plastics. Therefore, the analysis must be appropriate for all anticipated service conditions.

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

The initial step in any part design analysis is the determination of the loads the part will be subjected to, and calculation of the resultant stress and deformation or strain. The loads may be externally applied or result from stresses due to temperature changes or assembly.

An example of an externally applied load is the weight of medical instruments on a sterilizer tray. Examples of assembly loads are the loads on a housing flange when it is bolted to an engine or the load on the hub of a pulley when a bearing is pressed into it. Thermally induced stresses can arise when the temperature of the assembly increases and the dimensions of the plastic part change more or less than the metal part to which it is attached.

Using Classical Stress/Strain Equations

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

1. the part can be analyzed as one or more simple structures;
2. the material can be considered linearly elastic and isotropic;
3. the load is a single concentrated or distributed static load gradually applied for a short time; and
4. the part has low residual or molded-in stresses.

While all of these assumptions may not be strictly valid for a particular situation, the classical equations can provide a starting point for analysis. The design engineer can then modify the analysis to take into consideration the effects of the simplifying assumptions.

A variety of parts can be analyzed using a beam bending model. Table 31 lists the equations for maximum stress and deflection for some selected beams.

The maximum stress () occurs at the surface of the beam furthest from the neutral surface, and is given by:

$$\sigma = \frac{M\,c}{I} = \frac{M}{Z}$$

where:

$M = \textit{bending moment},\ \text{in lbs}\,(\text{N}\cdot\text{m})$

$c = \textit{distance from neutral axis},\ \text{in}\,(\text{m})$

$I = \textit{moment of inertia},\ \text{in}^4\,(\text{m}^4)$

$Z = \frac{I}{c} = \textit{section modulus},\ \text{in.}^3\,(\text{m}^3)$

Table 32 gives the cross sectional area (A), the moment of inertia (I), the distance from the neutral axis (c), and the section modulus (Z) for some common cross sections.

For other crosssections and/or geometries, the design engineer can consult stress analysis handbooks or employ finite element analysis.

Deflection Calculations

To determine the deflection of a proposed part design using classical equations, a modulus of elasticity value is required. It is important that the appropriate value be used. The value must represent the modulus of the material at or near the temperature and humidity expected in the application. Room temperature values can be found in the property tables on pages 9 to 14. Elevated temperature values can be found in the graphs on page . If the load is sustained, then the apparent or creep modulus should be used. Values are given in the isochronous stress/strain curves, Figures 42 through 45 on page 38.

Stress calculations

After the designer has calculated the maximum stress, those values are then compared to the appropriate material property, i.e., tensile, compressive, or shear strength. The comparison should be appropriate in terms of temperature and humidity to the requirements of the application.

Reinforcing Fiber Orientation Considerations

When designing with plastics, especially filled plastics, the designer must be cognizant of the effects of the fillers and reinforcing fibers on the mechanical properties of the plastic. The processing of filled plastics tends to cause orientation of fibers or high-aspect-ratio fillers parallel to the direction of flow. Throughout this manual, properties have been given both with and across flow direction whenever practical.

Since the design of the part and the processing are interrelated, the designer should consider what portions of the part are likely to to be oriented and how the properties will be affected. Shrinkage, strength, stiffness and coefficient of thermal expansion will differ depending on the aspect ratio of the fiber (the ratio of its length to its diameter) and the degree of fiber orientation. Perpendicular to the fiber orientation, the fibers act more as fillers than as reinforcing agents.

When molding polymers, there are instances where melt fronts meet (commonly known as weld lines) as when the plastic melt flows around a core pin. However, the reinforcement in the plastic, if present, does not cross the weld line. Thus the weld line does not have the strength of the reinforced polymer and at times can even be less than the matrix polymer itself. These factors must be taken into account when designing parts with reinforced plastics.

Limitations of Design Calculations

The designs given by the application of the classical mechanical design equations are useful as starting points, but some critical factors are simply not adequately considered by these analyses. The viscoelastic behavior of polymeric materials limits application of some of the design equations to, for example, low deflection cases. Often the calculation of maximum stress contains a number of simplifying assumptions which can diminish the credibility of the results, or the expected failure mode is buckling or shear, where the appropriate property data is lacking.

Also, the impact resistance of a design is directly related to its ability to absorb impact energy without fracture. It is difficult to predict the ability of a design to absorb energy. In addition, even armed with the energy absorption requirements, practical toughness constants for engineering resins don’t exist. The results of laboratory testing vary with the type and speed of the impact test, even for fixed geometries. Therefore, the ability of the design to withstand impact must be checked by impact testing of prototype parts.

Similarly, fatigue test results will vary depending on the cyclic rate chosen for the test, the dynamics of the test, and the test specimen used. Therefore, they should only be used as a rough indication of a material’s ability to perform in a fatigue application.

Designing for Equivalent Part Stiffness

Sometimes, a design engineer wants to replace a metal part with one made of plastic, but still wants to retain the rigidity of the metal part. There are two fairly simple ways to maintain the stiffness of a part when substituting one material with another material — even though the materials have different moduli of elasticity.

In the first method, the cross sectional thickness is increased to provide the stiffness. In the second, ribs are added to achieve greater stiffness. An example of each approach follows.

Changing Section Thickness

In reviewing the deflection equations in Table 31, the deflection is always proportional to the load and length and inversely proportional to the modulus of elasticity and moment of inertia.

Selecting one case, for example, both ends fixed with a uniformly distributed load, the deflection is determined by:

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

Therefore, to equate the stiffness using two different materials, the deflections are equated as follows:

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

Since the load and length are to remain the same, the FL^3 becomes a constant on both sides of the equation and what remains is:

(1)

$$\{EI\}_{metal} = \{EI\}_{plastic}$$

This, then, is the governing equation for equating part stiffness.

If the metal part were magnesium having a modulus of elasticity E of 6.5 million psi and the thermoplastic chosen to replace it was AMODEL AS-1145 HS resin having a modulus of elasticity of 2.0 million psi, we need to increase the moment of inertia I of the plastic version by increasing the part thickness or adding ribs.

Substituting the E values in equation (1):

$$\left(6.5\times10^6\right)I_{metal} = \left(2.0\times10^6\right)I_{AMODEL}$$

$$3.25\, I_{metal} = I_{AMODEL}$$

From Table 32, the moment of inertia for rectangular sections is:

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

where b is the width and d is the thickness of the section, substituting into our equation to determine the required thickness yields:

$$3.25\, d^3_{metal} = d^3_{AMODEL}$$

If d for the metal part is 0.1000 in. then the thickness is AMODEL resin is:

$$d_{AMODEL} = \sqrt[3]{3.25(0.1)^3} = 0.148\, in.$$

or 48 percent thicker than the magnesium part. However, ribs can be used to effectively increase the moment of inertia as discussed in the next section.

Adding Ribs to Maintain Stiffness

In the last section, it was determined that if a metal part were to be replaced with a part molded of AMODEL AS-1145 HS resin, a part thickness of 0.148 inch would be required to equal the stiffness of a 0.100 inch thick magnesium part.

By incorporating ribs into the AMODEL design, the wall thickness and weight can be reduced very efficiently and yet be as stiff as the magnesium part.

To demonstrate this, the moment of inertia (*I*) of the new rib design can be equated with that of the 0.148 inch thick plate design. Selecting the same material, AMODEL AS-1145 HS, the modulus of elasticity remains 2.0 million psi in both cases; therefore, if the moment of inertia of the ribbed design is equal to the plate design, the parts will have equivalent deflection and/or stiffness.

From Table 32, the *I* for a ribbed section is selected. By assuming that the section width "*b*" is the same for both, the I_{rib} has to be equal or greater than the I_{plate}. Assigning a section width "*b*" = 1.0 inch, the moment of inertia of a ribbed construction that will satisfy that condition can be calculated.

The moment of inertia for the plate design is:

$$I_{plate} = \frac{bh^3}{12} = \frac{1 \times (0.148)^3}{12} = 2.7015 \times 10^{-4}$$

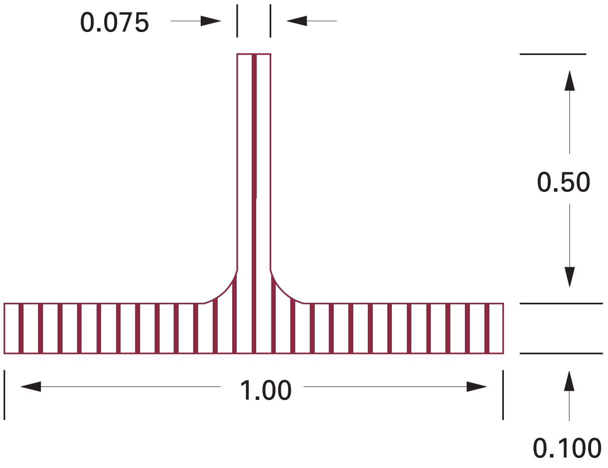
By choosing the arbitrary rib design shown in Figure 83, and working through the calculations, the moment of inertia is found to be:

$$I_{rib} = 33.19 \times 10^{-4}$$

Therefore, the ribbed design will be 9.5 times stiffer than the AMODEL plate design or the original magnesium part that was 0.100 inch thick.

The same rib having half the height would still produce a part twice as stiff as the magnesium part. The ribbed design shown requires placing a rib every one inch of section width.

Figure 83. Adding Ribs to Increase Stiffness Sample Calculation



Designing for Sustained Load

Up to this point, the stress strain calculations and examples have dealt with immediate stress/strain response and therefore short-term properties. If the part in question must sustain loads for long periods of time or at elevated temperatures, apparent (creep) modulus values must be used to account for the additional strain and part deflection that may occur. An example showing how the calculations are modified for sustained load follows.

Calculating Deflection

If a cantilever beam with a rectangular cross-section, as shown in Figure 84, is loaded with a 10 pound force at the free end, what is the deflection after 4,000 hours ?

From Table 31 on page 88, the deflection of a cantilever beam is given by:

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

where *I*, the moment of inertia, as shown in Table 32. is:

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

and *E* is the flexural modulus of the material.

Calculating the moment of inertia for this example gives:

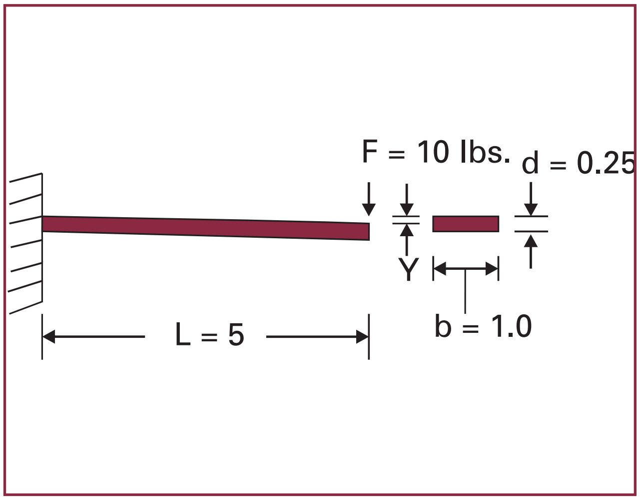
$$I = \frac{(1)(0.25)^3}{12} = 0.0013$$

The data sheet for AMODEL AS-1133 HS resin gives 1,650,000 psi for the flexural modulus. Using this value and the equation previously cited, the short-term room temperature deflection can be calculated by:

$$Y = \frac{(10)(5)^3}{3(1{,}650{,}000)(0.0013)}$$

$$Y = 0.194\ inches$$

Figure 84. Cantilever Beam Bending Load Example



If the application requires that the load be sustained for a long time, we would expect the deflection to be greater than this because of creep. To calculate the deflection considering the creep, we would use the apparent modulus instead of the short-term flexural modulus. The value of apparent modulus shown for AMODEL AS-1133 HS resin at 1000 hours in Figure 47 is 1,100,000 psi. Therefore the calculated deflection is:

$$Y = \frac{(10)(5)^3}{3(1{,}100{,}000)(0.0013)}$$

$$Y = 0.290\ inches$$

The deflection is about fifty percent greater when a sustained load is considered.

Calculating Allowable Stress - Creep Rupture

If a load is sustained for a long time and if the load and/or temperature are high enough, rupture of the part will eventually occur due to creep,

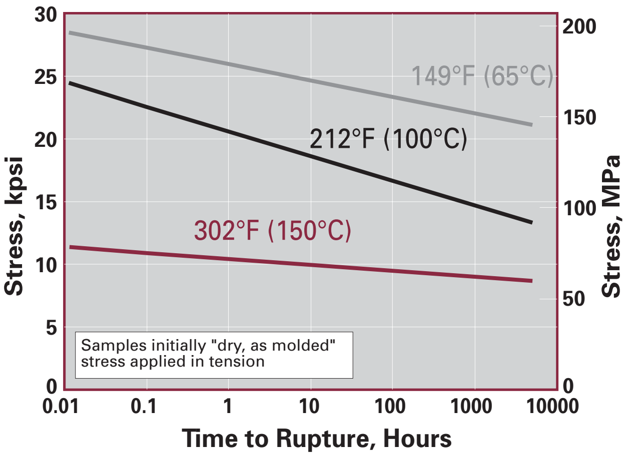
To estimate the combinations of time, temperature, and load that will cause this type of failure, creep rupture tests are conducted at various temperatures as shown in Figure 85. This figure illustrates the actual time to failure for different levels of stress so that a creep rupture envelope can be obtained. From this envelope, the safety factor in time or stress can be determined for that particular temperature.

For instance, if the application life is 1,000 hours at 149°F (65°C) for a part molded from AMODEL AS-1133 HS resin, the curve indicates that rupture will occur within that time frame if the part is exposed to a stress level of approximately 23 kpsi (158 MPa).

If the part can be redesigned to reduce the stress to 18 kpsi (124 MPa), the predicted time to rupture is now well beyond 10,000 hours. This automatically builds a safety factor into the design. Actual part testing is still recommended to confirm these results.

For operating temperatures that are different from the tested temperatures, information is usually extrapolated from known creep rupture envelopes to approximate the envelope for the temperature of interest.

Figure 85. Tensile Creep Rupture AMODEL AS-1133 HS Resin



Considering Stress Concentrations

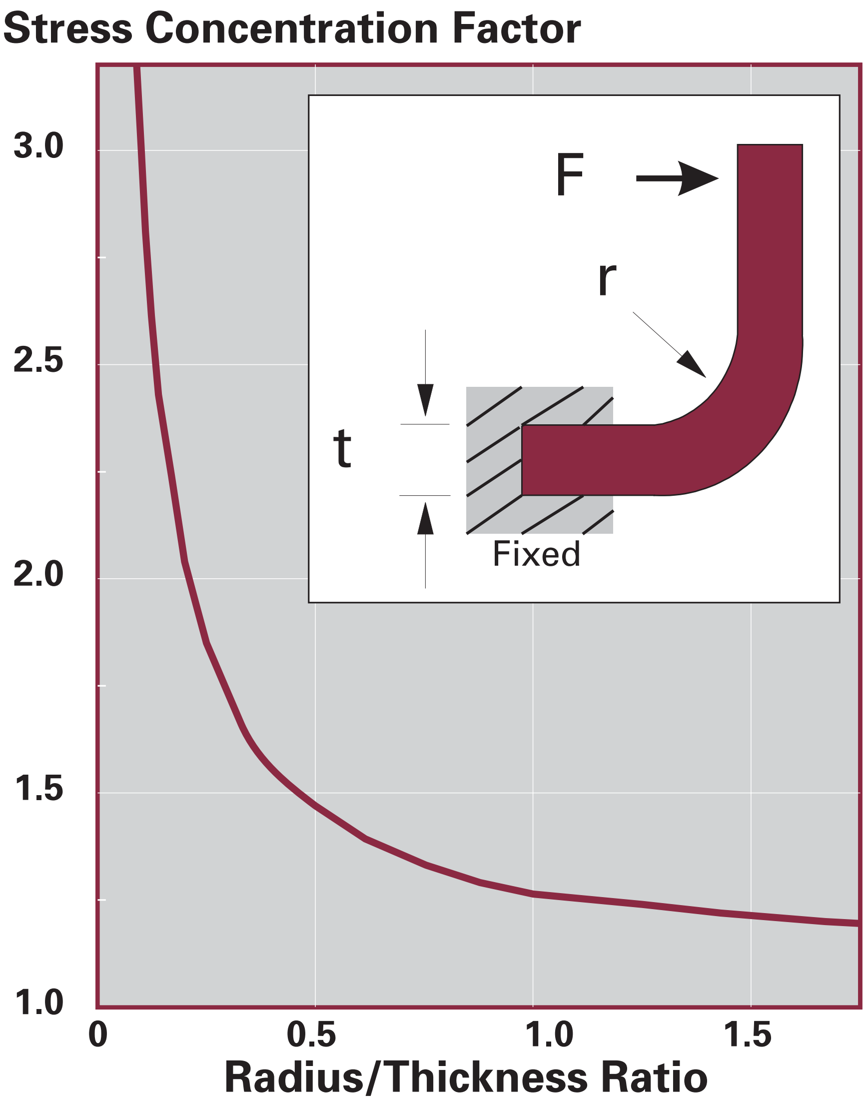
Classical mechanical design may result in a component design which fails prematurely or at a much lower stress than predicted. This could arise due to stress concentration. Stress concentrations may occur at sharp corners, around holes, or other part features. Impact and fatigue situations are especially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

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

Figure 86 shows the effect of inside corner radius on the stress concentration factor. For example, if the nominal wall thickness is 0.080 in. (2 mm) and an inside corner radius is 0.020 in. (0.5 mm), then the radius to thickness ratio is 0.25 and the stress concentration factor will be over two. A stress of x will have the effect of over 2x on the part.

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

Figure 86. Stress Concentration Factor at Inside Corners



Considering Thermal Stresses

When a plastic part attached to metal undergoes temperature changes, stresses may be induced that should be considered by the designer in the development of the part design.

Figure 87 illustrates a typical plastic flange fastened by a steel bolt to a steel frame. Because the thermal expansion of the plastic is significantly greater than that of the steel, an increase in temperature will produce an increase in compressive stresses in the plastic and tension in the bolt. It is the increase in compressive stress under the washer that must be considered if creep and loss of torque load on the bolt is of concern.

For example, the change in length of a material when exposed to a change in temperature is given by:

$$\Delta L = L(T_F - T_0)\alpha$$

where:

ΔL = change in length, in.

L = original length, in.

α = coefficient of thermal expansion, $\frac{\text{in.}}{\text{in.}\,°\text{F}}$

T_F = final temperature, °F

T_0 = original temperature, °F

Since the plastic is constrained, the unit elongation, combining both thermal expansion and strain, of both the steel bolt and the plastic, will be as follows:

$$\alpha_s\left(T_F - T_0\right) + \frac{F}{A_s E_s} = \alpha_p\left(T_F - T_0\right) - \frac{F}{A_p E_p}$$

where:

A_s = cross sectional area of the bolt

A_p = cross sectional area of the washer

E_s = modulus of steel

E_p = modulus of plastic

α_s = coefficient of thermal expansion of steel

α_p = coefficient of thermal expansion of plastic

F = increase in the tensile force of the bolt

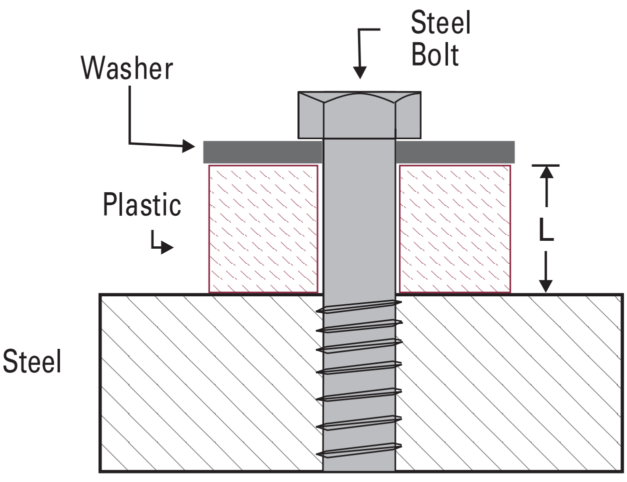
Solving for *F*

$$F = \frac{\left(\alpha_p - \alpha_s\right)\left(T_F - T_0\right)A_s E_s}{1 + \dfrac{A_s E_s}{A_p E_p}}$$

and the increase in compressive stress on the plastic will be:

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

Figure 87. Thermal Stress Example



Loss of Bolt Tightness Due to Creep

When threaded metal fasteners are used to retain or secure plastic parts to an assembly, and the assembly is subjected to changes in temperature, the difference between the thermal expansion coefficients of the metal and the plastic can cause problems. When a threaded fastener is tightened, the fastener is elongated slightly and a compressive stress is generated on the substrate. This compressive stress maintains the tightness of the bolt.

When the assembly is heated, both the plastic part and the metal fastener will expand. The plastic part, however, is constrained by the metal fastener, and cannot expand. This results in increased compressive stresses in the plastic, and a corresponding increased tendency for compressive creep or stress relaxation to occur. The relaxation of the compressive stress will result in reduced torque retention in the bolts.

To evaluate this tendency, 0.250 inch (6.4 mm) thick plaques of AMODEL AS-1133 HS resin, 33% glass reinforced nylon 6,6 and 35% glass reinforced nylon 4,6 were bolted to a metal surface with steel machine bolts tightened to 60 in-lbs (6.8 N×m) of torque with a torque wrench compressing the plastic plaque under the bolt face. The temperature of the bolted assemblies was then raised to the indicated temperatures shown in Figure 88, held for one hour, and then cooled to room temperature. The torque required to loosen the bolts was then measured.

Figure 88 compares the amount of torque retained versus temperature. The coefficient of linear thermal expansion of AMODEL resin is lower than those of the other materials tested, and therefore closer to that of the steel.

The smaller difference in thermal expansion results in lower induced stress due to the compressive strain caused by the thermal excursion in the constrained part. This translates to lower creep and therefore better torque retention for such bolted assemblies.

Figure 88. Bolt Torque Retention

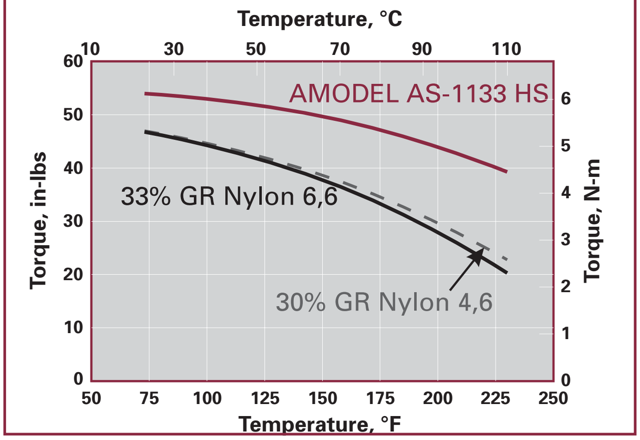
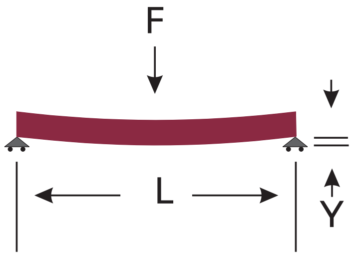


Table 31.
Maximum Stress and Deflection Equations

Simply Supported Beam
Concentrated Load at Center



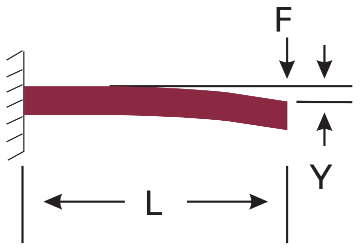
$$\sigma = \frac{FL}{4Z}$$

(at load)

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

(at load)

Cantilevered Beam (One End Fixed)
Concentrated Load at Free End



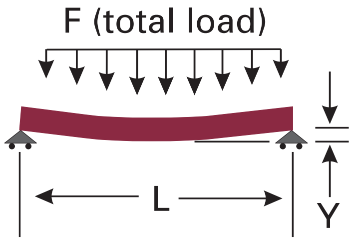
$$\sigma = \frac{FL}{Z}$$

(at support)

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

(at load)

Simply Supported Beam
Uniformly Distributed Load



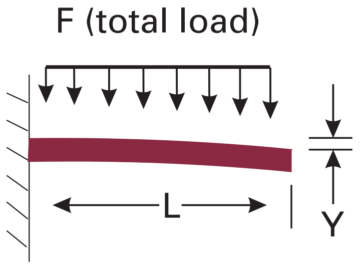
$$\sigma = \frac{FL}{8Z}$$

(at center)

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

(at center)

Cantilevered Beam (One End Fixed)
Uniformly Distributed Load



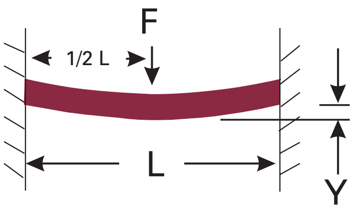
$$\sigma = \frac{FL}{2Z}$$

(at support)

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

(at support)

Both Ends Fixed
Concentrated Load at Center



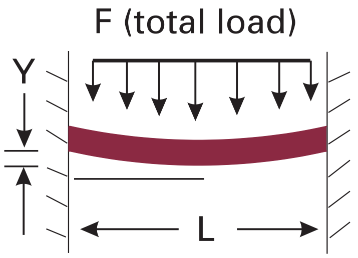
$$\sigma = \frac{FL}{8Z}$$

(at supports)

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

(at load)

Both Ends Fixed
Uniformly Distributed Load



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

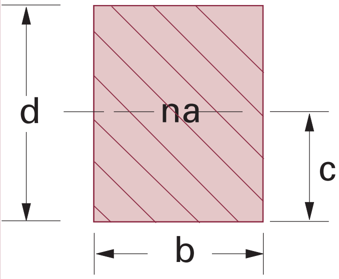
(at supports)

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

(at center)

Table 32.
Area, Moment Equations for Selected Cross Sections

Rectangular



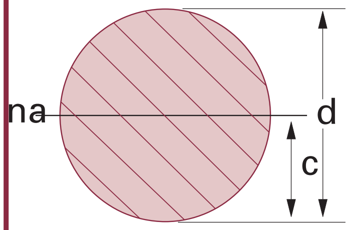
$$A = bd$$

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

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

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

Circular



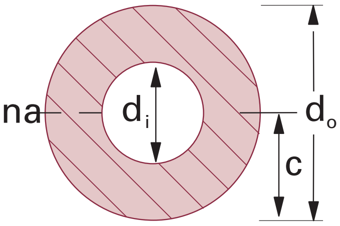
$$A = \frac{\pi d^2}{4}$$

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

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

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

Tube



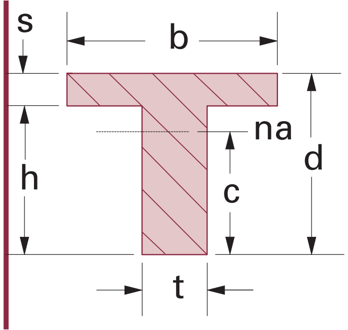
$$A = \frac{\pi (d_o^2 - d_i^2)}{4}$$

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

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

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

T-beam or Rib



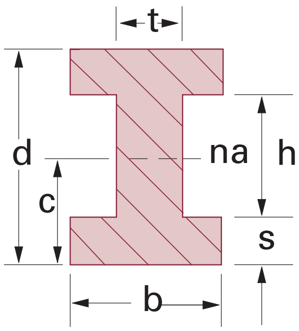
$$A = bs + ht$$

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

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

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

I-beam



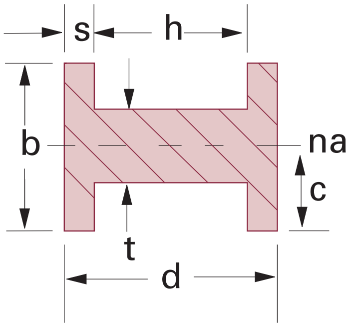
$$A = bd - h\,(b - t)$$

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

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

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

H-beam



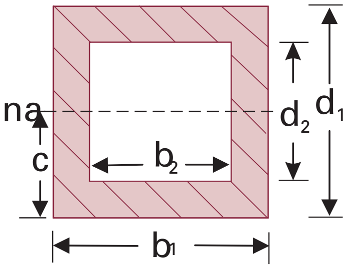
$$A = bd - h\,(b - t)$$

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

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

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

Hollow Rectangular



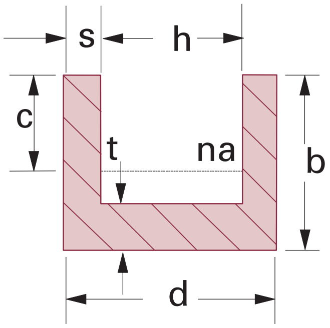
$$A = b_1 d_1 - b_2 d_2$$

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

$$I = \frac{b_1 d_1^3 - b_2 d_2^3}{12}$$

$$Z = \frac{b_1 d_1^3 - b_2 d_2^3}{6d_1}$$

U-beam



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

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

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

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

Designing for Assembly

Interference or Press Fits

One of the most economical methods that can be used to assemble two parts is a press fit. The joint is achieved by pressing or forcing the shaft into a hole whose diameter is smaller than the diameter of the shaft. The difference in diameter between the hole and shaft is referred to as the diametrical interference. The force maintaining the joint is primarily a compressive stress on the shaft resulting from the hoop stress in the hub created by the insertion of the shaft. Depending upon the relative moduli of the shaft and hub materials, the compressive stress in the shaft can also contribute to maintaining the joint. The stress holding an interference fit will exhibit relaxation over time in a manner that is analogous to creep, because the apparent modulus of the polymeric material decreases over time.

Calculating the Allowable Interference

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

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

and the geometry factor is given by:

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

where:

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

If the shaft and hub are made from the same grade of AMODEL resin, then:

$$E_h = E_s = E$$

and the interference is:

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

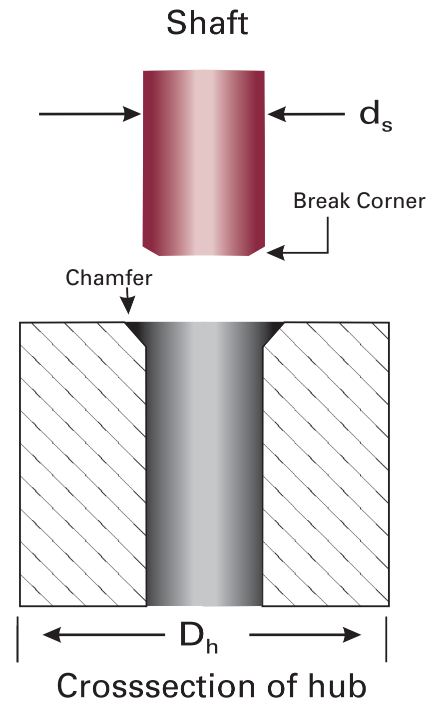
If the hub is made from AMODEL resin and the shaft is made from metal, then the interference is:

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

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

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

Figure 89 Press Fit Example



Mechanical Fasteners

Mechanical fasteners provide an economical method of joining dissimilar materials together. Fasteners frequently used with injection molded plastic parts include screws, bolts, nuts, lock washers and lock nuts. When using metal mechanical fasteners, good design practice should be used to prevent the plastic parts being assembled from becoming overstressed.

The most obvious procedure for preventing a highly stressed assembly is to control the tightening of the mechanical fasteners with torque limiting drivers. When torque cannot be controlled, as might be the case with field assembly, shoulder screws will limit compression on the plastic part. Other alternatives may be to use flange-head screws, large washers or shoulder washers. Figure 90 presents some preferred designs when using mechanical fasteners.

Repeated assembling and disassembling should be avoided when using self-tapping screws. If repeated assembly is required, thread-forming screws are recommended.

Self-tapping Screws

A common type of mechanical fastener used with plastics is a self-tapping screw. A self-tapping screw cuts or forms threads as it is inserted into the plastic and eliminates the need for molding internal threads or the secondary operation of tapping the thread form by machining. The major types are thread-forming and thread-cutting.

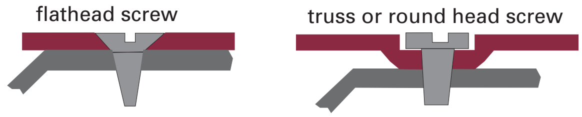
The modulus of elasticity of the plastic material plays an important role in deciding what type of self-tapping screw is most suitable for the application. For plastic materials with a modulus less than 440 kpsi (3.0 GPa), such as most unreinforced resins, thread-forming screws are best since the plastic is "ductile" enough to be deformed without cracking or shearing. For glass and mineral filled grades, thread-cutting screws are preferred.

For optimum strip-out torque, the hole diameter of the boss should be equal to the pitch diameter of the screw. The outer diameter of the boss should be equal to two or three times the hole diameter and the boss height should be more than twice the thickness of the boss.

Figure 90. Designing for Mechanical Fasteners

High bending stress when bolt is tightened.

Added bosses w/ small gap, stress becomes compressive when bosses touch.



High stress from wedging action of screw head.

Recessed design avoids wedging stresses.

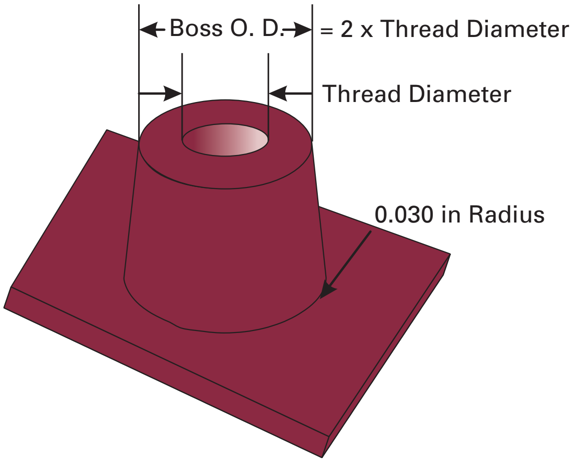
Standard screw can create high stress when tightened.

Shouldered screw limits stress when tightened.

Figure 91 illustrates the basic boss design for use with self-tapping screws.

To avoid stripping or high stress assemblies, torque controlled drivers should be used on assembly lines.

Figure 91. Boss Design for Self-Tapping Screws



Pull out force calculation:

The pull out force can be estimated by using the following equation:

$$F = \pi SDL$$

where

F = Pull out force, pounds
S = Shear strength, psi
D = pitch diameter, in.
L = thread engagement length, in.

When repeated assembly and disassembly are required or expected, threaded metal inserts should be used instead of self-tapping screws.

Threaded Inserts

Threaded metal inserts can be used to provide permanent metal threads in a plastic part; a wide variety of sizes and types are available. Inserts are usually installed in molded bosses whose internal diameter is designed for the insert. The most commonly used metal inserts are either molded-in or ultrasonically placed in the part as a secondary operation. In the case of the molded-in insert, the insert is placed in the mold and the plastic is injected around it. Stress will develop when the plastic cools around the insert. To reduce this stress, heat the inserts to the temperature of the mold.

The ultrasonic insert is pressed into the plastic by melting the plastic with high frequency vibrations, generated by an ultrasonic welding machine. The ultrasonic welding melts material around the metal insert as it is being installed, forming a bond between the insert and the plastic that is usually strong and relatively free of stress.

Figure 92 depicts the recommended insert and boss designs for use with AMODEL PPA resin.

Molded-in Threads

One of the benefits of using plastic materials instead of metals is the ability to mold thread forms directly into the part. This eliminates the secondary machining operations needed with metal parts to form the threads. molded-in threads can be either external or internal. In the case of internal threads, some type of unscrewing or collapsible core is required as shown in Figure 93. External threads can be formed more easily if the parting line of the mold can be located as shown in Figure 94. Molding very fine threads which exceed 28 pitch is usually not practical.

Figure 92. Boss Design for Ultrasonic Inserts

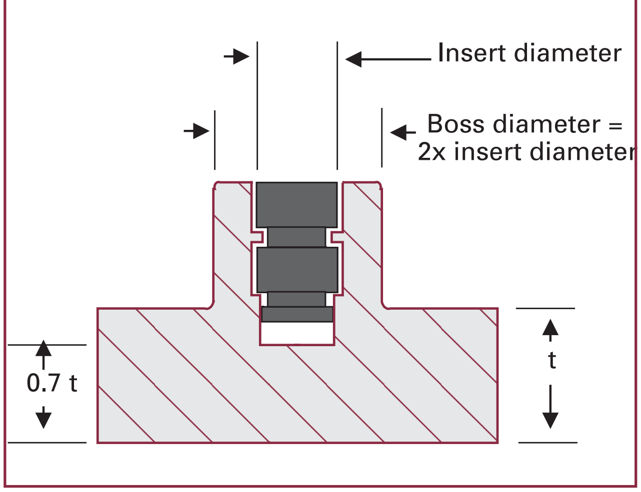


Figure 93. Internal Threads

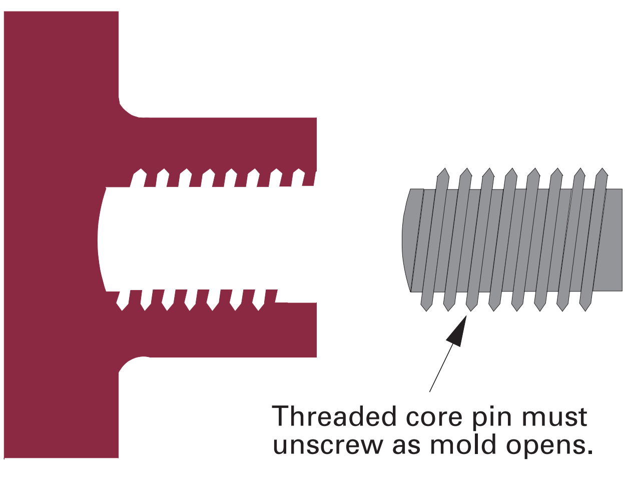
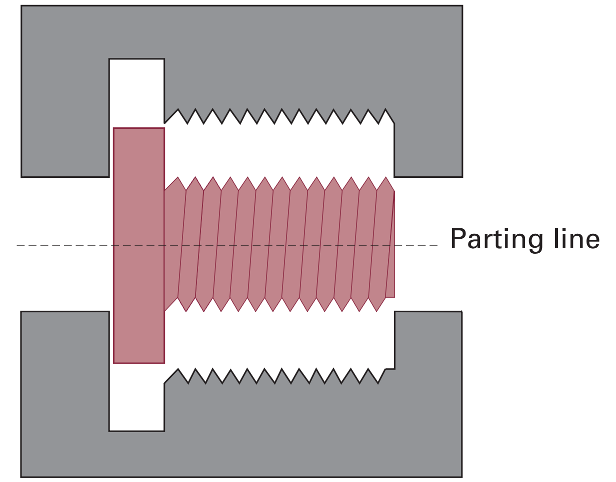

Threaded core pin must unscrew as mold opens.

Figure 94. External Threads



Designing with Snap Fits

The use of snap fits in plastics is very prevalent. All snap fit designs require the plastic to flex like a cantilever spring as it moves past an interference that is designed on the mating part. Once the flexible arm moves past the interference, it returns to its normal unflexed, unstressed position. Usually a step or protrusion has been designed on the cantilever that engages and locks into the mating part, creating a simple assembly method without additional parts. This is shown in Figure 95.

As shown in Figure 95, each cantilever arm must deflect a distance "Y" in order to be inserted. The key to proper snap design is to not exceed the strain/stress limits of the material being used. A snap fit design that has been used for a ductile, low modulus plastic will probably not be suitable for a highly reinforced, very rigid plastic.

For rigid materials, the length of the cantilever may be increased or the interference deflection "Y" reduced. Adding a "stop" can prevent over deflection of the cantilever during assembly.

Straight Cantilever Beam Equation

The relationship between maximum deflection and strain for a straight cantilevered beam was calculated as follows: From Table 31, the cantilever beam was chosen and the drawing is repeated as Figure 96. The maximum stress, is given by the following:

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

Since this beam has a rectangular cross section,

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

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

Therefore:

$$\sigma = \frac{FLd}{2I}$$

The deflection of the beam, Y, is given by:

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

Figure 95. Cantilever Type Snap Fit

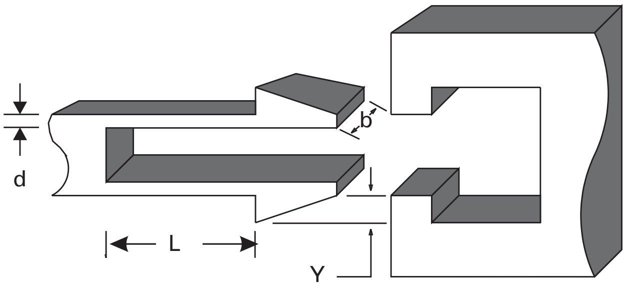
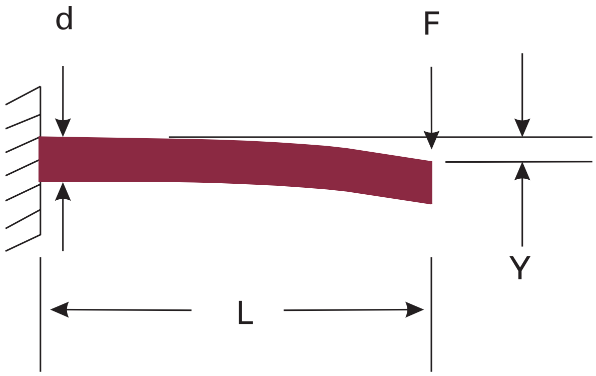


Figure 96. Cantilever Beam
Concentrated Load at Free End



Solving the deflection equation for F, the force needed to deflect the beam can be calculated as follows:

$$(1) \qquad F = \frac{3YEI}{L^3}$$

The modulus of elasticity, E, is defined as:

$$E = \frac{\sigma}{\varepsilon} \text{ and therefore } \varepsilon = \frac{\sigma}{E}$$

substituting that in the cantilever stress equation:

$$(2) \qquad \varepsilon = \frac{FLd}{2EI}$$

Using the relationship of equation (1) and substituting for *F* in equation (2) the relationship between strain and deflection is derived:

$$(3) \qquad \varepsilon = \frac{3Yd}{2L^2}$$

This equation allows the designer to calculate the strain required from the maximum deflection of a design. Table 33 summarizes maximum strain recommendations for several grades of AMODEL resins.

Once a suitable grade of AMODEL resin has been selected, the basic equations can be used to find the load, F, needed to deflect the cantilever the required amount.

In a cantilever snap fit, the stress and strain are maximum at the base of the cantilever and become proportionately lower toward the tip where the load is applied. In fact the stress and strain at any point can be calculated by substituting a different L, the distance from the load toward the fixed end. Therefore, if the cantilever thickness was gradually reduced from fixed end to tip, the beam will be able to deflect more than in the fixed thickness cantilever without incurring higher maximum stresses. In this way, the capability of the material can be maximized.

Tapered Cantilever Beam Equation

For the tapered design shown in Figure 97, h_L is the thickness at the free end. The value of the proportionality constant, , for a tapered beam design can be found in Figure 98. The maximum strain can be calculated from equation (4).

$$\varepsilon = \frac{3Yh_0}{2L^2K} \tag{4}$$

For example, if the beam thickness has been gradually reduced to half its fixed end thickness; the ratio of h_L to h_0 would be 0.5 and K (from Figure 98) would be 1.6. Therefore, the maximum strain and the corresponding stress would be multiplied the reciprocal of K, 0.625. The strain will be reduced by about 40% of the strain of a constant thickness cantilever beam design with equal deflection.

Figure 97. Snap Fit Design Using Tapered Beam

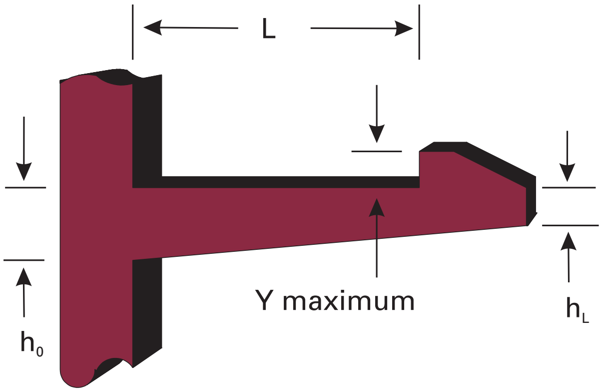


Figure 98. Proportionality Constant (K) for Tapered Beam

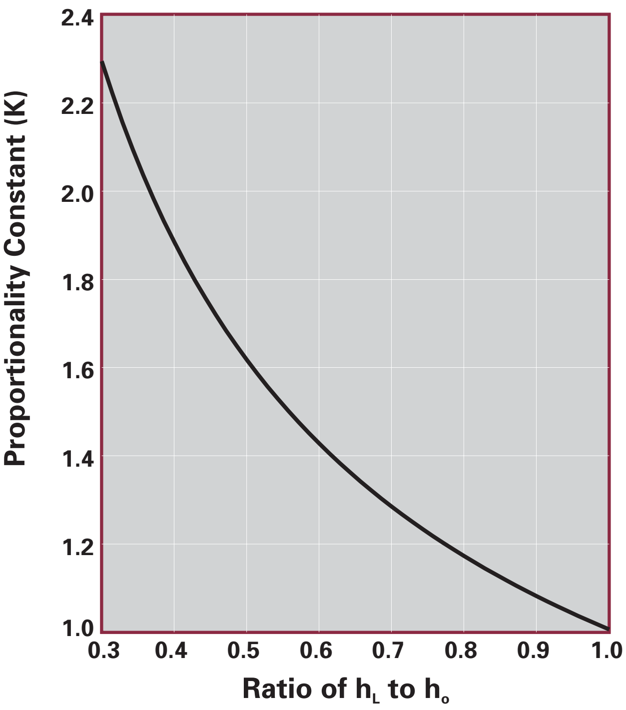


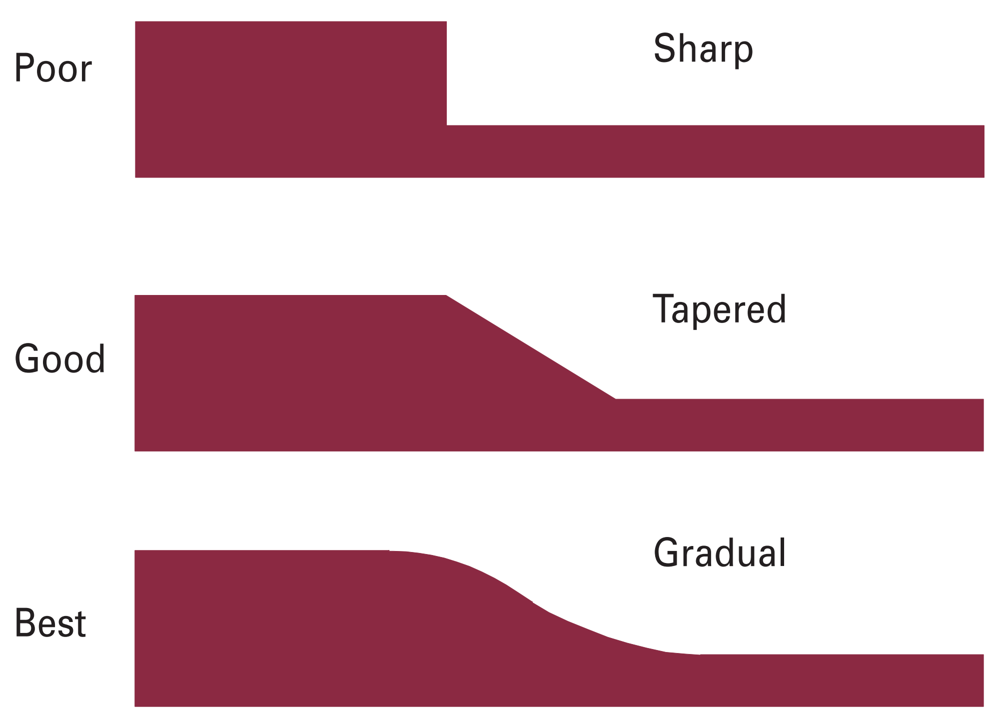
Table 33.
Strain Recommendations for Cantilever Snap-Fits

AMODEL PPA Grade	Maximum Strain, %
ET-1000 HS	1.0
A-1230 L	0.5
AS-1133 HS	1.0

Designing for Injection Molding

Many of the applications for AMODEL PPA resins will be manufactured using the injection molding process. An engineer who has designed a part to meet the performance requirements of the application must also take into account the fact that there are elements in the part design that can influence moldability. These factors include wall thickness and wall thickness transitions, draft, ribs, bosses, and coring. The effect of these factors on moldability should be considered by the design engineer before a mold is built to make the part.

Figure 99. Wall Thickness Transition



Wall Thickness

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

Where possible, wall thicknesses should be uniform or follow the guidelines presented in the next section “Wall Thickness Variation”.

Wall Thickness Variation

Part designs that contain uniform wall thicknesses are ideally suited for the injection molding process. They minimize molded-in stress, reduce the potential for sink marks on the surface of the part, and eliminate the potential for voids in a molded part. However, structural, appearance, and draft considerations may require varying wall thicknesses. When changes in wall section thickness are necessary, the designer should consider a gradual transition, such as the tapered or gradual designs shown in Figure 99.

Sharp transitions may create problems in appearance and dimensional stability, because they may result in differential cooling and turbulent flow. A sharp transition may also result in a stress concentration, which may adversely affect part performance under loading or impact.

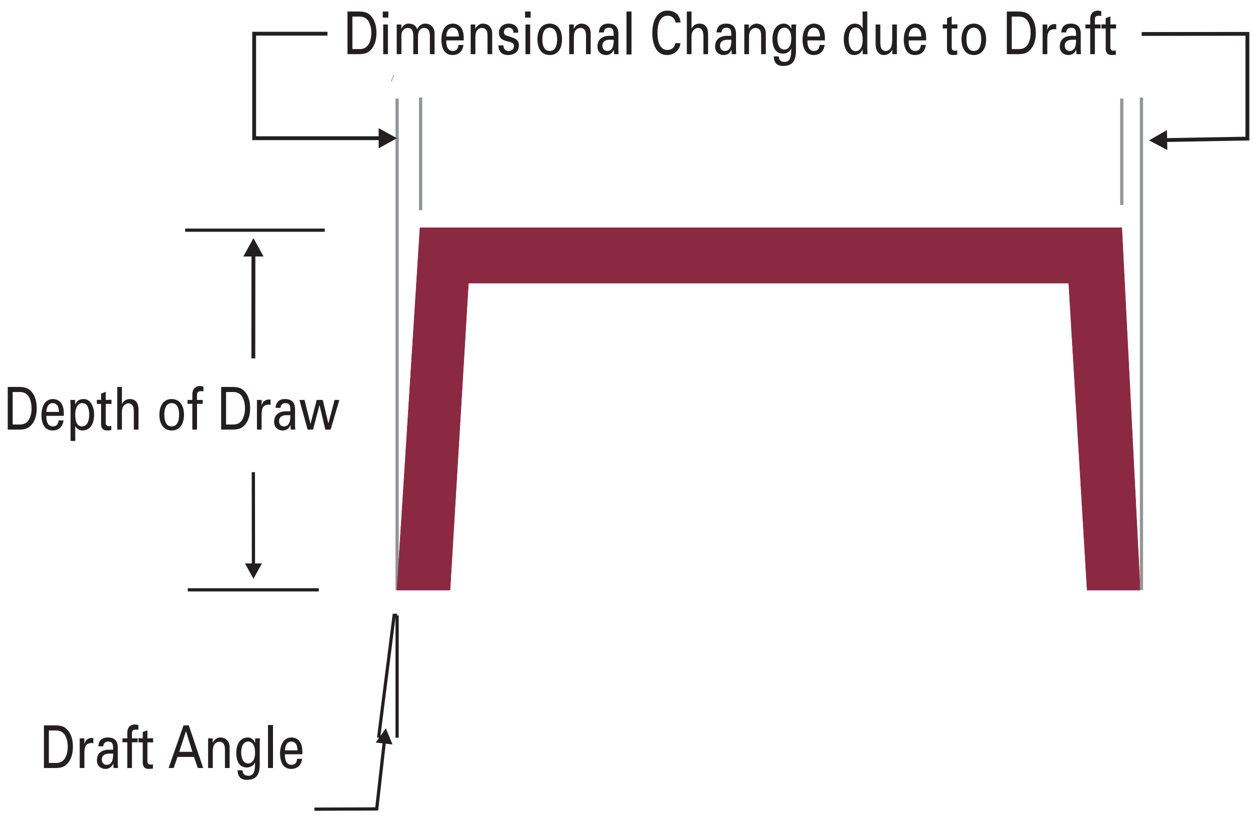
Draft Angle

To aid in the release of the part from the mold, parts are usually designed with a taper. The taper creates a clearance as soon as the mold begins to move, allowing the part to break free from its mold cavity. The taper is commonly referred to as draft, and the amount of taper as draft angle, as shown in Figure 100.

Adequate draft angle should be provided to allow easy part removal from the mold. Generally, the designer should allow a draft angle of 0.5° to 1° per side for both inside and outside walls for AMODEL resins. However, in some special cases, smaller draft angles, as low as 1/8° to 1/4°, have been used with draw polish on the mold surface.

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

Figure 100. Draft - Designing for Mold Release



Ribs

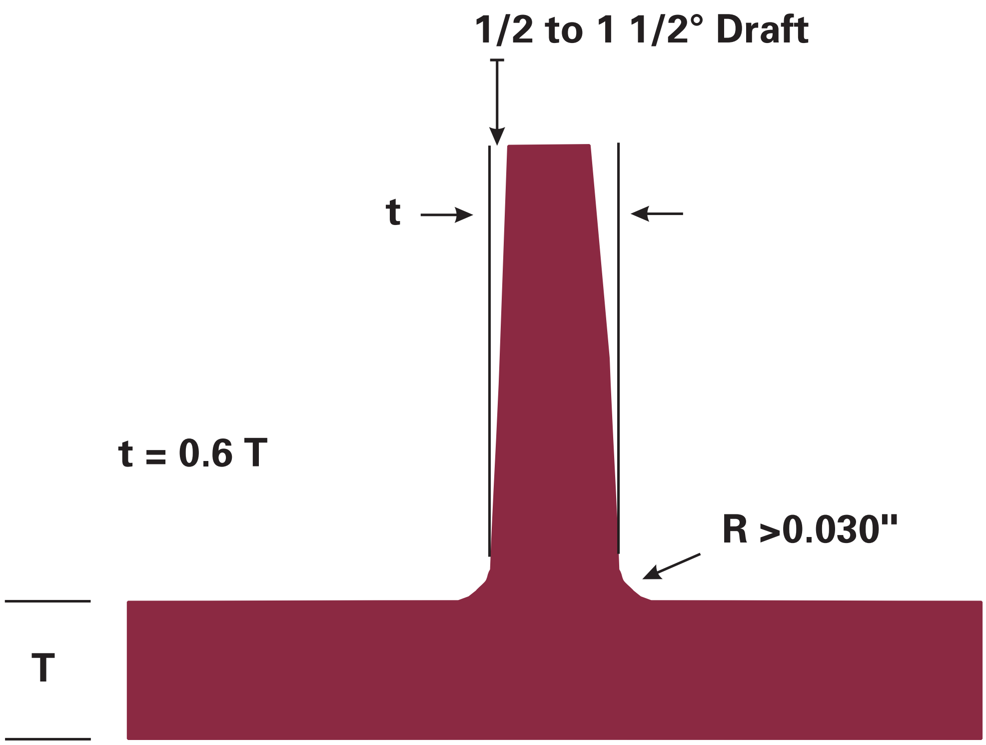
The stiffness of a part design can be increased with properly designed and located ribs, without creating thick walls as illustrated in the Design Information Section entitled “Using Ribs in Design” on page 82. Proper rib design will allow for decreased wall thickness. This will save material and weight, and shorten molding cycles. It will also eliminate thick walls, which can cause molding problems like sink marks on the surface of parts or voids on the inside of parts. Ribs that are correctly positioned may also function as internal runners, assisting plastic melt flow during molding.

Figure 101 shows recommended rib size relationships.

General Guidelines for Using Ribs

In general, the following guidelines should be used when designing with ribs. The thickness at the rib base should be no greater than 60% of the adjacent wall thickness. When ribs are opposite appearance areas, the width should be kept as thin as possible. If there are areas in the molded part where structure is more important than appearance, then ribs are often 75%, or even 100%, of the outside wall thickness. Whenever possible, ribs should be smoothly connected to other structural features such as side walls, bosses, and mounting pads. If there are several ribs in a part, they need not be constant in height or width, and are often matched to the stress distribution in the part. All ribs should have a minimum of 1/2° of draft per side and should have a minimum radius of 0.030 inch at the base to reduce stress concentrations and sink marks.

Figure 101. Recommended Rib Design



Coring

Proper design practice should include uniform wall thickness throughout a part. Heavy sections in a part can extend cycle time, cause sink marks on the part surface, cause voids within the part and increase molded-in stresses.

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

Cores which extend into the cavity will be subject to high pressure. For blind cores (cores that are unsupported) that have diameters greater than 0.060 inch (1.5 mm) the core lengths should not exceed three times the diameter, while blind cores with diameters less than 0.060 inch (1.5 mm) should not exceed twice their diameter in length. These recommendations may be doubled for through cores (cores that telescope into or shut off with the opposite side of the mold). Draft should be added to all cores as defined in the section entitled “Draft Angle”, and all tooling polished for best ejection.

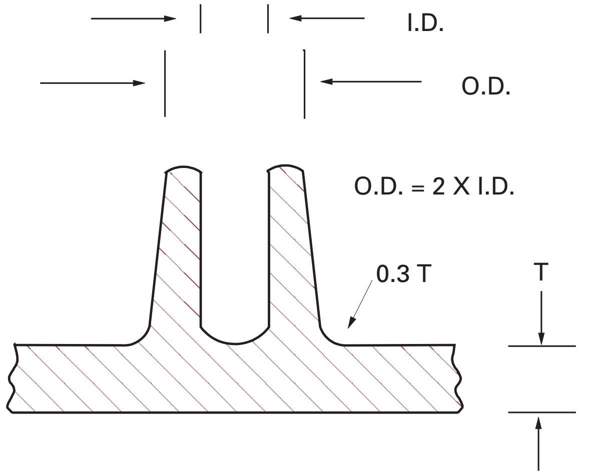
Bosses

Bosses are projections from the nominal wall of a part that will eventually be used as mounting or fastening points. The design of bosses is largely dependent upon their role in a given part. Cored bosses can be used for press fits, self-tapping screws, and ultrasonic inserts. Each of these will exert stress on the wall of the boss.

As a general guideline, the outside diameter of a boss should be twice the inside diameter of the hole, and the wall thickness at the base of the boss should not exceed 60% of the part wall thickness unless structural concerns override appearance requirements. Figure 102 illustrates these guidelines.

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

Figure 102. Boss Design
General Guidelines



SECONDARY OPERATIONS

Welding

Components produced from AMODEL resins can be readily joined using hot-plate, vibration, spin, or ultrasonic welding.

In this section, each welding method is described, and the apparatus and the conditions that produced acceptable welds with AMODEL AS-1133 HS resin are discussed. These conditions are the suggested starting points for determining welding conditions for actual applications. In some instances, additional information will be provided, such as sensitivity to welding conditions, sample geometry, or moisture content.

Because AMODEL resins absorb moisture, tests were performed on specimens conditioned to three different moisture levels; 0%, 1.8% and 3.8% moisture. These moisture contents were selected to represent the moisture levels for parts molded from AMODEL AS-1133 HS resin that had reached equilibrium in air with relative humidities of 0, 50, and 100% respectively. To simplify the discussion of results, the term “dry” will be used for the “dry, as molded” specimens, “normal” for those containing 1.8 percent moisture, and “saturated” for those containing 3.8 percent moisture.

In summary, acceptable welds can be achieved using all of the welding techniques evaluated and described in this section. Ultrasonic welding does require near-field energy application for strong welds. In general, absorbed moisture does not interfere with welding, but best results are obtained using samples that contain “normal” amounts of moisture (1.8%) or less.

Hot Plate Welding

In hot plate welding, the thermoplastic samples are pressed against a heated element to cause melting, the element is removed and the samples are forced together.

The hot plate welding machine used was a Bielomatic HV 4806 welding machine manufactured in 1986 by Leuze GMBH. The specimens used were bars 4 inches (102 mm) long, 1 inch (25 mm) wide, and 0.250 inch (6 mm) thick. The welding machine was set up to provide a nominal lap shear weld of 0.5 by 1 inch (13 by 25 mm).

Best results were obtained using a hot plate temperature of 626°F (330°C), a clamping pressure of 30 psi (207 KPa), a welding time of 40 seconds, and a hold time of 20 seconds. The strength of the bond produced was comparable to the strength of the material itself, i.e., the majority of the specimens failed at points other than the joint.

Test plaques occasionally stuck to the hot plate unless a silicone mold release was applied and the hot plate allowed to return to thermal equilibrium. Tests showed that the use of mold release did not reduce weld strength. Absorbed moisture did not significantly effect weld strength at dry (0%) and normal (1.8%) levels, but it did reduce weld strength at the saturated (3.8%) condition.

Vibrational Welding

In vibrational welding, friction is used to generate heat. One part is held stationary while the mating part vibrates 0.030 to 0.060 inches (0.8 to 1.5 mm) in a linear fashion at 100 to 400 Hz. Vibration welding is limited to flat parts.

The vibration welding machine used was a Vinton Hydroweld Vibration welding machine. This machine operates at a nominal frequency of 240 Hz. The specimens used were 4 inches (102 mm) long, by 1 inch (25 mm) wide, by one-fourth inch (6 mm) thick, and they were welded in a 1 by 0.5 inch (25 by 13 mm) lap shear configuration.

This method was very effective and welds as strong as the parent material were easily obtained. This technique proved relatively insensitive to welding conditions, giving good results at weld times as short as 0.60 seconds and pressures as low as 320 psig (2.20 MPa). Best results were obtained using specimens containing a normal (1.8%) amount of moisture.

Spin Welding

The spin welding method uses frictional heat to join two cylindrical or spherical mating parts. While one half is held stationary in a nest fixture, the mating part is spun rapidly against it. Friction at the interface raises the temperature of the material to the melt point. At that point, the spinning action is stopped, and the parts are held under pressure for cooling.

The spin welding machine used was a Mechasonic KLN Omega machine, model SPN-063. Typically the important parameters are angular speed in revolution per minute, normal force, and welding time. Because this machine is an inertia-type, the energy available for spinning the sample is limited to that stored in a flywheel. So instead of adjusting speed per se, the energy stored in the flywheel is controlled.

The specimens used for spin welding were injection molded cups. This style has an interference joint configuration. Excellent weld strength was obtained using this method.

Because welding condition settings are machine specific, they are not generally useful in setting a starting point. Rather it was observed that as forge pressure and angular velocity were increased, weld strength increased up to maximum and then decreased when an excessive amount of either pressure or velocity was applied. The explanation for this observation is that when a weld was made with too high a forge pressure, the spinning motion was stopped nearly instantaneously and not enough polymer melted and flowed. In the other extreme, a high angular velocity and a low forge pressure, the top part essentially sat on top of the bottom part and freely rotated without being forged into the interference fit. Thus, to assure a good joint, a welding condition must be found so both melting and forging occurs.

Moisture content did not significantly affect weld strength.

Ultrasonic Welding

In ultrasonic welding of thermoplastic materials, high frequency (10 to 40 KHz) mechanical vibrations are transmitted through one of the machines mating parts to the joint interface. The combination of friction and applied force causes the temperature at the joint interface to increase to the melting point of the material. Normal force is held after the vibrational energy is shut off to achieve a molecular bond or weld.

The ultrasonic welding machine used was a Branson Model 910 M, microprocessor controlled machine. With this unit it is possible to dial in the amount of energy that will be applied to the sample. The output from the booster was fed to near and far field horns. The samples used were similar to the injection molded cup used for the spin welding evaluation. Aluminum fixturing held the parts in a butt joint configuration.

Welds produced using a near field horn to joint distance [defined as 1/4 inch (6 mm) or less] were excellent. Welds made using the far field horn position were weak (one-third of the strength achieved at near field) and are probably not useful. The conditions that gave acceptable strength were weld energy of 750 J and pressure of 617 psi (4.3 MPa). The recommended interference at the shear joint should be at least 0.008 inch (0.2 mm).

Adhesive Bonding

Injection molded samples of AMODEL A-1133 HS resin were bonded with Fusor®[1] 305-1/-2 (two part epoxy) and Tyrite® 7500 A/C (two part urethane) adhesives. Both adhesives were supplied by Lord Corporation.

To prepare the test specimens, a cure cycle of 30 minutes at 250°F (120°C) followed by conditioning at room temperature for 72 hours was used when the adhesive was Fusor 305-1/-2 adhesive. When the adhesive was the Tyrite 7500 A/C adhesive, the cure cycle used was 10 minutes at 200°F (90°C) followed by conditioning at room temperature for 72 hours.

Bond strengths were tested at low temperature, room temperature, and an elevated temperature. To evaluate the effect of humid aging, specimens were conditioned for 14 days at 100°F (38°C) and 100% relative humidity. Some specimens were tested immediately after conditioning; others were tested 24 hours after conditioning.

Impact performance was determined with a side impact tester according to GM 9751P. Lap shear values were measured on an Instron testing machine at 0.5 inch/minute according to ASTM D 1002.

The results are shown in Figures 103 and 104. In general, the epoxy adhesive performed slightly better than the urethane. Acrylic adhesives are not recommended for use with AMODEL resins.

Figure 103. Lap Shear Bond Strengths
AMODEL AS-1133 HS Resin

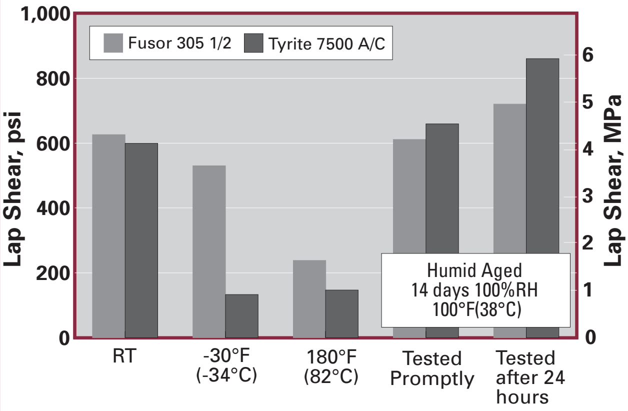
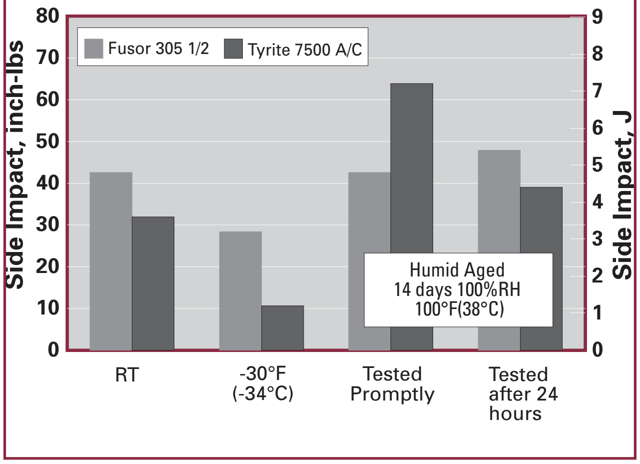


Figure 104. Side Impact Bond Strengths
AMODEL AS-1133 HS Resin



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[1] Fusor and Tyrite are registered trademarks of Lord Corporation.

Coatings and Surface Finishes

Electroless Plating

Electroless plating is a chemical process involving several steps that cleans, etches, activates and deposits a thin adherent metallic film on the plastic surface.

The etching step roughens the plastic surface on a microscopic scale to provide mechanical bonding sites for the metal. Activation is the term used to describe the adhesion of a catalytic palladium complex to the mechanical bonding sites produced in the etching step. Finally, metal plating occurs on the catalytic palladium sites produced in the activation step.

The electroless process reduces metallic ions to metal on the catalyzed surface of the plastic. This process requires no electrical current and results in a very uniform coating thickness (although very thin) across the plated surface regardless of part geometry.

Electroless coatings can be applied over the entire surface to achieve complete metallization or they can be applied selectively to metallize only required areas. For the selective process a base coat must first be applied to the specific sections of the the part that need to be be metallized. The electroless plating will then occur only on the base-coated sections of the part.

Electroless plating processes are generally used to coat plastics with metal for non-decorative, functional purposes such as EMI/RFI (electromagnetic/radio frequency interference) shielding of electrical and electronic components. The metal coating for EMI/RFI shielding is usually composed of a thin layer of copper (50-75 micro inches) that is effective at shielding followed by a layer of nickel (10-15 micro inches) for protection of the copper from corrosion as well as abrasion and wear resistance.

This process can be used with AMODEL resins that have been specifically formulated for this purpose.

Electroplating

Electroplating is a chemical process for depositing thick metal coatings on plastic substrates to achieve decorative effects and/or upgraded functionality.

The key to electroplating on plastics is preparation of the plastic surface to accept the metallic coatings that are applied by an electroless process. These coatings can then be made electrically conductive which is required to electroplate the plastic substrate. The steps used to achieve conductivity are called the “preplating” steps. The preplating treatments used for most plastics include cleaning, etching, neutralizing, catalyzing, and accelerating, followed by electroless nickel or copper deposition.

The “peel adhesion” or peel strength of the metal coating to the plastic substrate depends on the adhesion of the copper or nickel preplate to the plastic. There are two mechanisms of adhesion that interact with one another, a chemical bond and mechanical bond.

The chemical bond is the weaker of the two and is subject to loss of adhesion by chemical films and reaction with gases. They are more subject to failure due to the action of moisture, gases and corrosive environments that can dissolve the electroless deposit. They are also more susceptible to the forces of thermal expansion and contraction and mechanical stresses.

The mechanical bond is created by the etching step and is a physical interlocking of the metal into the plastic substrate. The mechanical bond is generally a more significant and stronger bond than the chemical bond.

Once the surface of the plastic part has been preplated with electroless copper or nickel it is ready for electroplating. The principle of electroplating is to electrically conduct metal atoms such as copper, nickel, and chrome off anodes placed within the plating baths through the plating solutions in those baths and onto the plastic production target. The target or production part acts as a cathode via connection to conductive plating racks. Conductivity of the plastic part is accomplished by attaching the target part to the plating rack with metal clips. This completes the electric circuit from the anode through the plating solution to the plastic part.

Grades of AMODEL resins have been developed that can be preplated using commercially available preplating chemistries developed for ABS. This allows AMODEL parts to be racked and electroplated on existing ABS plating lines without modifications to bath temperatures, concentrations and/or exposure times. These grades of AMODEL resins can be preplated using the Enthone, MacDermid and Shipley preplating chemistries that have been developed for ABS.

As with any platable plastic, the key to achieving good appearance and adhesion of a metal electroplated coating requires the proper combination of raw material consistency, molding practices, good tool design and proper handling through the plating process.

Vacuum Metalizing

Vacuum metallization is the evaporation and subsequent condensation of a metal onto a substrate in vacuum. The metal used in most industrial applications is aluminum. When the end use requirement is primarily decorative, the substrate is usually processed with two organic coatings called the basecoat and topcoat with the metal layer deposited in between. The primary function of the basecoat is to produce a smooth surface on molded plastic parts so that the metallizing layer will have maximum luster. The second major function of the basecoat is to maximize adhesion of the metal layer to the substrate. On substrates that tend to outgas in vacuum, the basecoat also provides a third function of “sealing off” a gas producing surface. The function of the topcoat is to protect the metal layer from physical, oxidative or chemical deterioration.

Basecoats that are compatible with AMODEL resin include #VB 4315 from Pearl Paints.Topcoats that are compatible with AMODEL resin include #VT 4316 from Pearl Paints.

Laser Marking

It is possible to obtain a durable high contrast mark on AMODEL resins using commercially available laser marking systems. Depending upon the wavelength and intensity of the laser system used, the appearance of the mark can range from a bleached surface to an engraved mark.

No one set of conditions can be specified for laser marking all AMODEL PPA resins. Operating parameters must be adjusted depending upon the particular application and part being marked.

The manufacturers in Table 34 have equipment which has been shown to be suitable for marking AMODEL PPA resins.

Table 34.
Sources of Lasers

Laser Vendors	Laser Type
AB LASER	Nd:YAG, CO_2
4 Craig Road	
Acton, MA 01720	
Videojet Systems International,Inc.	CO_2
1500 Mittel Blvd	
Wood Dale, IL 60191	

Inkjet Printing

Inkjet printing can be used to provide a highly visible mark on AMODEL PPA resin substrates of any color. Durability of marks made using an inkjet system depends upon the environment in which the marked part will be exposed and the type of ink used to make the mark. In many cases the durability of the mark will be satisfactory.

Equipment needs can vary depending upon the type of ink used, the speed at which the mark is made and size of the desired mark. A wide variety of equipment and inks are commercially available. Two sources are shown in Table 35.

Table 35.
Sources of Inkjet Printing Equipment

Image Ink Jet Printing Corp.
5500 Highlands Pkwy, Suite 100
Smyrna, GA 30082

Videojet Systems International,Inc.
1500 Mittel Blvd
Wood Dale, IL 60191

Painting

Several grades of AMODEL PPA resin were evaluated for their compatibility with various automotive paint systems. Representative glass-reinforced, mineral-reinforced and mineral/glass-reinforced compounds were evaluated.

As with all plastic substrates, the primer system is critical. The test specimens were cleaned with isopropyl alcohol then coated with primers and cured as per the manufacturers instructions. The plaques were tested for tape adhesion (GM9071P, method A) and cross-hatch adhesion (GM9071P, method B) and gravelometer chip resistance (GM9508P and SAEJ400) as coated and after conditioning for 96 hours with water/fog/humidity per GM4465P specification. Table 36 lists primers that meet or exceed all test requirements and represent adequate coating performance for most painted automotive applications.

Table 36.
Suitable Automotive Primers

SUPPLIER	PRIMER	DESCRIPTION
BASF	U04KD004	solvent, flexible
	U04AD041	solvent, rigid
	U36AD001	water based
PPG	RPP9870	solvent, high solids
	AHAP9470R	solvent, one coat
Red Spot	AE146	solvent, lacquer
Siebert-Oxidermo	UBP9604	solvent, high solids
	BP2024	solvent
Sherwin-Williams	E75BC2301	solvent
	E75AC6	solvent

PROCESSING INFORMATION

Proper processing of plastics is an important step in developing a cost/effective part that meets the performance requirements of the application. It is as important as selecting the proper material and engineering the proper part and mold design. The processing information contained in this manual on AMODEL resins includes information on rheology, guidelines on drying, molding machine selection, molding conditions, and tooling considerations.

Rheology of AMODEL Resins

AMODEL AS-1133 HS, A-1240 L, and AF-1133 V0 resins were characterized for their melt viscosity-temperature-shear rate behaviors. This was done to provide information for design engineers to use with flow analysis programs. The shear rate dependence of viscosity was obtained using an Kayeness Galaxy V[1] Capillary Rheometer, in the temperature range of 608° to 653°F (320° to 345°C), using a capillary die with a 0.0298 inch (0.75 mm) diameter and a length of 1.0 inch (25 mm). Resin moisture content was in the recommended range prior to testing. The apparent viscosities and apparent shear rates were obtained for a variety of temperatures and corrected.

Table 37 shows the viscosity vs. the shear rate for AMODEL AS-1133 HS, A-1240 L, and AF-1133 V0 resins at various temperatures and shear rates as required for typical flow analysis programs and part designs.

Table 37.
Shear Rate - Viscosity Data

Grade	Temperature, °F (°C)	Shear Rate, sec^{-1}	Viscosity, Poise
AS-1133 HS	616 (325)	100	9,800
		1,000	2,800
		10,000	900
	634 (333)	100	5,800
		1,000	2,100
		10,000	760
	652 (345)	100	3,400
		1,000	1,300
		10,000	500
A-1240 L	616 (325)	100	3,750
		1,000	1,600
		10,000	600
	634 (333)	100	1,550
		1,000	870
		10,000	370
	652 (345)	100	1,100
		1,000	690
		10,000	300
AF-1133 V0	600 (315)	100	29,500
		1,000	6,000
		10,000	1,200
	616 (325)	100	4,300
		1,000	1,900
		10,000	770
	634 (333)	100	1,900
		1,000	1,100
		10,000	990

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[1] The Kayeness Galaxy V Rheometer is a product of the Dynisco Corporation.

Figure 105 shows the viscosity versus the shear rate for AMODEL AS-1133 HS resin. Figure 106 shows this information for AMODEL A-1240 L resin, and Figure 107 shows it for AMODEL AF-1133 V0 resin.

Figure 105. Viscosity vs. Shear Rate
AMODEL AS-1133 HS Resin

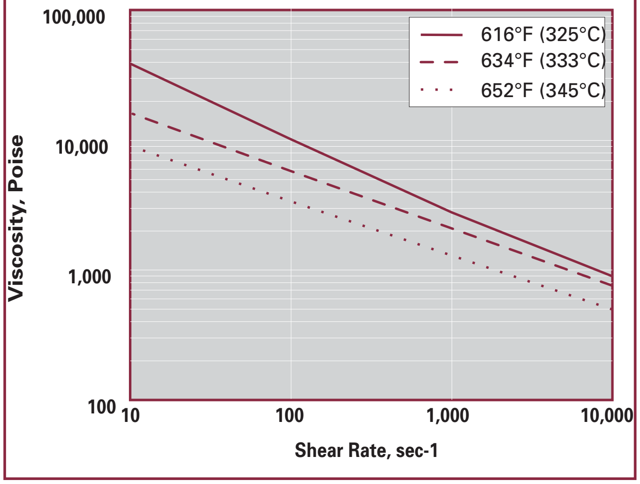


Figure 106. Viscosity vs. Shear Rate
AMODEL A-1240 L Resin

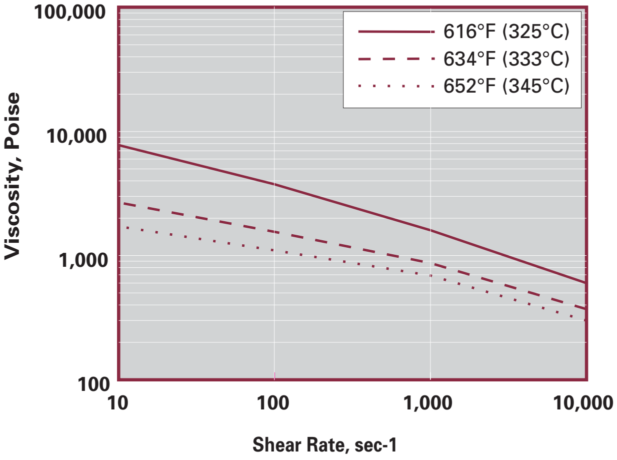
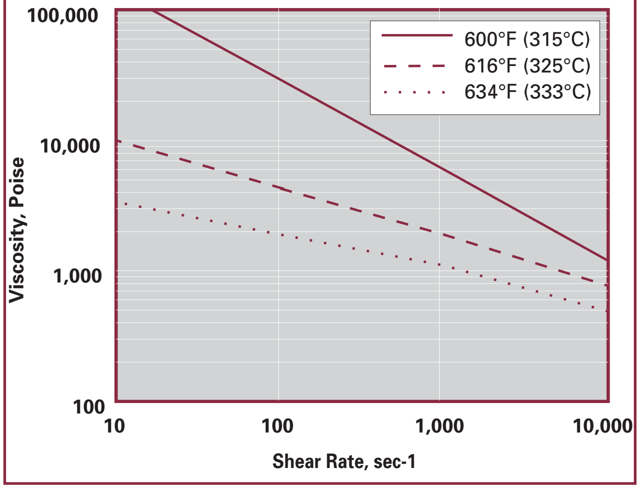


Figure 107. Viscosity vs. Shear Rate
AMODEL AF-1133 V0 Resin



Flow Analysis Constants

Table 38 gives other information that is useful for computer aided flow analysis and part design.

The specific heat data were obtained with a Perkin-Elmer Differential Scanning Calorimeter Model DSC-4 scanning from 76 to 652°F (25 to 345°C) at a scanning rate of 18°F(10°C) per minute. Melting temperature transitions were obtained by scanning from 121 to 661°F (50 to 350°C) at a scanning rate of 36°F (20°C) per minute. Freezing temperature transitions were obtained by cooling samples from 661°F (350°C), at a rate of 36°F (20°C) per minute.

The melt density was determined from samples that were compressed from 0 to 10,000 psig (68.9 MPa) at 625°F (330°C).

Thermal conductivity measurements were conducted at four temperatures in the range of 76 to 625°F (25 to 330°C).

The thermal diffusivity of the melt is computed based on the thermal conductivity, melt density (at 0 psig), and specific heat at 625°F (330°C).

Table 38.
AMODEL Resin Melt Processing Parameters

Property	**Units**	**AS-1133 HS**	**A-1240 L**	**AF-1133 V0**
Melt thermal diffusivity	cm^2/s	1.20×10^{-3}	1.16×10^{-3}	1.00×10^{-3}
Melt specific heat	cal/g/°C	0.420	0.503	0.408
Melt density at 10,000 psi	g/cm^3	1.459	1.412	1.600
No flow temperature	°C	284.0	285.2	273.2
Freezing temperature				
peak	°C	275.9	274.7	262.8
extrapolated	°C	261.3	255.8	235.7
end	°C	243.8	227.4	220.2
Heat of Crystallization	cal/g	4.91	7.27	3.49
Solid density	g/cm^3	1.473	1.451	1.650
Melt temperature				
onset	°C	280	280	291
midpoint	°C	313.3	314.9	316.3
end	°C	328.8	332.6	329.5
Latent heat	cal/g	5.55	6.72	3.79

Injection Molding

The grades of AMODEL PPA described in this Manual were developed to be processed by injection molding. Guidelines for molding machine selection, tool steel selection, and general mold design practices such as gate, runner and venting design are given. In addition, recommended drying and molding conditions for AMODEL resins are provided.

Molding Machine Selection

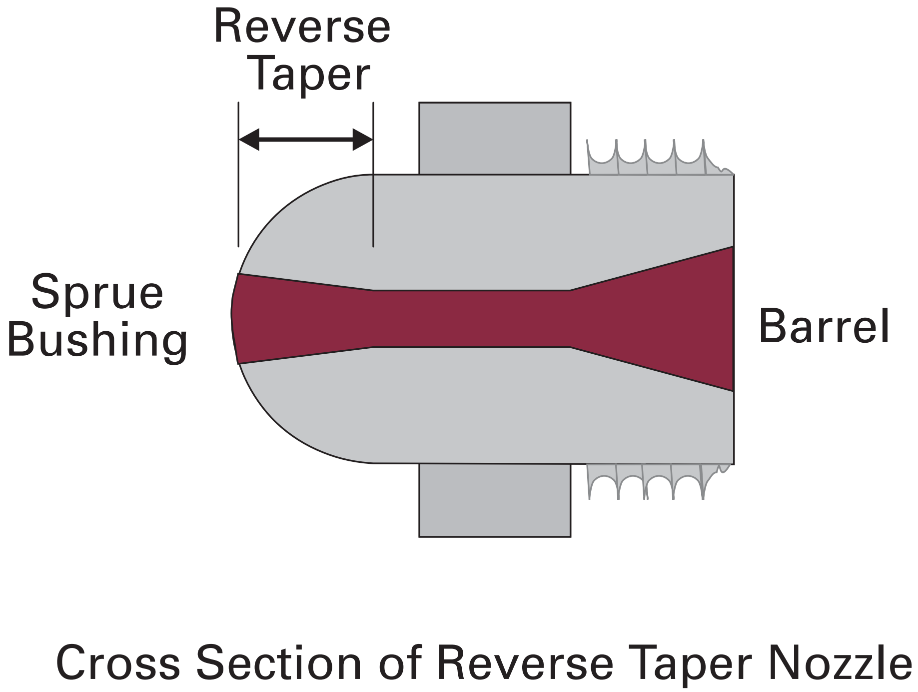
AMODEL resins can be molded on most standard injection molding machines. Most original equipment general purpose screws will also perform well for molding AMODEL resins.

Specifically, the screw should have a gradual, rather than sharp, compression or transition zone, with a Length/Diameter (L/D) ratio of at least 18:1, 20:1 preferable. A typical 20:1 L/D screw will have 10 flights in the feed zone, 4 flights in the transition zone, and 6 flights in the metering zone; with a compression ratio of 2.5-3 to 1. Screws having lower compression ratios will adequately process the material, but may require longer cycle times because lower screw speeds will be necessary to achieve melt uniformity.

Most original equipment screws will be equipped with ring check valves. While these will work, free-flow designs are preferred, because they reduce shear and provide better melt temperature control. Ball check valves are not recommended, but can be used if the flow passages are streamlined to prevent material retention in “dead spots”.

Nozzles with a reverse tapered design are recommended because they provide better control of the temperature of the sprue tip at its freeze-off point, and therefore better control of nozzle temperature.

Figure 108. Reverse Taper Nozzle



Mold Design

Mold Material Selection

The selection of the grade of tool steel to be used for a particular mold will depend on several considerations, including cavity design, cost, machinability, abrasion resistance, thermal conductivity, and corrosion resistance. In general, a steel with a surface hardness above R_C55 should be used for molds for production runs of 50,000 shots or more. Also, for those applications where there is concern about parting line damage, the bulk hardness of the cavities should be above R_C50.

If abrasion resistance is used as the sole criteria for tool steel selection, the test materials can be ranked as shown in Table 39. If corrosion resistance and resistance to parting line damage are included among tool steel requirements, then the preferred materials are 420 stainless steel, H-13, and S-7.

Table 39.
Tool Steel Selection

Abrasion Resistance Rating	Steel Type	Treatment
Best	S-7	High density chrome plated
	SS 420	Hardened
Good	H-13	Hardened
	S-7	Hardened
Inconclusive [1]	S-7	Titanium nitrided
Poor	S-7	Nickel plated
	S-7	Dichronite coated
	P-20	None

[1] Good abrasion resistance but coating flaked.

Gate Design

Most common gate designs will work with AMODEL resins. The optimum gate design will minimize the flow distance of the plastic melt in the cavity, reduce weld line problems in the part, and minimize the effects of fiber orientation and melt turbulence. The design variables are the number of gates, their size and shape, and their location.

General guidelines for gate design are:

The gate land length should be between 0.030 to 0.060 inch (0.8 to 1.6 mm).

The smallest gate dimension should be at least 50% of the part wall thickness for proper packing of the part.

The gate should be located at the thickest sections of the part to facilitate proper packing of the part.

Corners should be radiused generously to reduce shear.

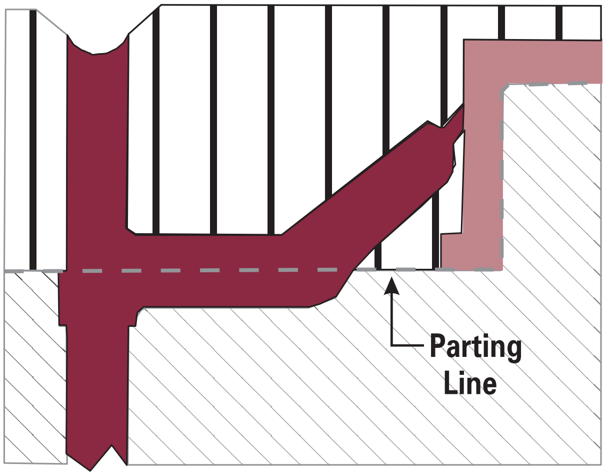
For applications where fast fill rates and part aesthetics are required, avoid gate locations and designs which result in melt turbulence.

The depth of rectangular gates should be at least 50% of the part thickness. The width of a rectangular gate should be about 1.5 to 2 times the gate depth.

Tunnel gates should be a minimum of 0.020 inch (0.5 mm) diameter with a short gate land. The angle between the part wall and adjacent side of the tunnel gate should be less than 30°. The minimum diameter of the tunnel drop should be larger than the wall thickness as shown in Figure 109.

A round gate diameter of less than 0.120 inch (3.0 mm) {0.090 inch (2.3 mm) for resins containing glass reinforcement} should be used for ease of degating with 3-plate molds. However, the gate diameter should not be less than 0.020 inch (0.5 mm) and should be approximately 50% of the part thickness or greater.

Figure 109. Tunnel Gate Configuration



Venting

Good mold design practices include adequate venting to prevent part burning and damage to the mold. Poorly vented molds can result in poor weld line strength, part burning, short shots, and tool damage (i.e., pitting). The fast mold fill rates required for good surface appearance requires deep vents. Vents should typically be 0.0015 to 0.0025 inch (0.038 to 0.064 mm) deep. Vent depth of 0.0005 to 0.0015 inch (0.013 to 0.038 mm) have been successfully used for connector molds and other parts where shot size and subsequent venting needs are very small. The vents should be as wide as practical. The vent land length should be 0.030 to 0.060 inch (0.75 to 1.5 mm) and the relief channel should be 0.030 to 0.060 inch (0.75 to 1.5 mm) deep and extend to the outside edge of the mold.

Sprue and Runner Design

Sprues and runners should be designed to provide uniform flow to all cavities with a minimum pressure loss. Full round runners are best for minimizing both heat and pressure losses. However, trapezoidal runners are a good alternative to full round runners, because they are easier to machine and therefore lower mold cost. The length and size of the runners and sprues should be kept to a minimum while still maintaining adequate flow and minimum pressure loss. Runner diameter is usually 0.250 inch (6.4 mm) or greater to provide adequate flow. Sharp corners should be generously radiused to prevent excessive shear on the plastic melt.

Although runner and sprue size should be minimized, the runner system should be sized to properly pack out the part. Where maximum part properties are required, the runner system diameter should be larger than the part wall thickness. This should allow the part to set up fully before the runner freezes off.

For large or very thick parts, large diameter sprue bushings with a 9/32 or 11/32 inch (7 to 9 mm) orifice are usually required. Thin parts with wall sections typically 0.125 inch (3.2 mm) or smaller can use sprue bushings with a 5/32 or 7/32 inch (4 to 6 mm) orifice diameter.

The runner system should be adequately vented. Without runner venting, the air in the runner will be forced into the part cavity, increasing cavity vent requirements or worsening part burning.

Runnerless Molds

Runnerless molds have been used successfully with AMODEL resins. AMODEL resins, like other semi-crystalline thermoplastics, require special attention to heat distribution in the mold when designing a runnerless tool. Typically, the temperature of each gated drop from the heated manifold will need to be separately controlled. Additional heat will also be required in areas where heat loss is great, such as manifold support points and the point at which the gate drop contacts cavity steel. Since the cost and complexity of a runnerless system can be high, tool designers should contact their Solvay Advanced Polymers' representative for suggestions on designing a runnerless system for use with AMODEL resins.

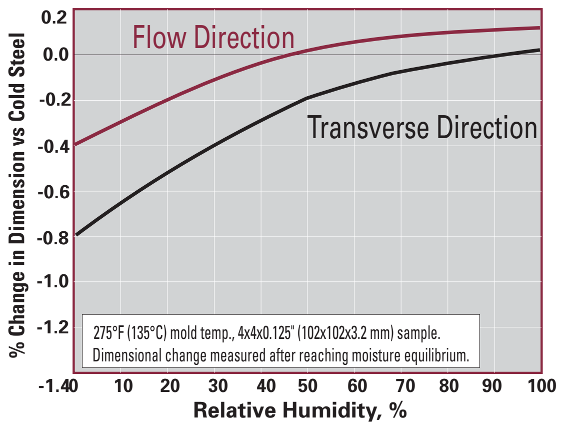
Cavity Dimensions

AMODEL PPA parts will absorb moisture and consequently undergo dimensional change. The dimensional changes depend upon the amount of moisture absorbed and will stabilize when the parts reach equilibrium with the environment. These dimensional changes must be considered when establishing dimensional tolerances for components that may be exposed to a relatively high humidity level.

To properly size mold cavities for parts to be used in humid environments, both the mold shrinkage and the moisture effects on part dimensions must be considered.

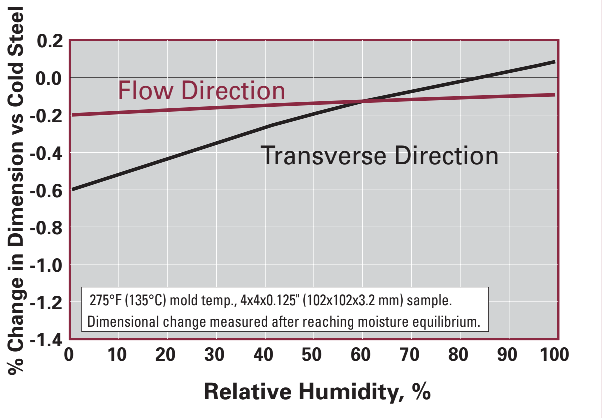
Figures 110 to 114 show the effect of moisture absorption on the dimensions of AMODEL parts. For example, as shown in Figure 110, AMODEL AS-1133 HS resin has a shrinkage of -0.4% in the flow direction under "dry, as molded" (0% Relative Humidity) conditions. However, when the part reaches equilibrium at 50% RH, the overall shrinkage from the dimensions of the mold cavity is negligible.

Figure 110. Dimensional Effects of Moisture on AMODEL AS-1133 HS Resin



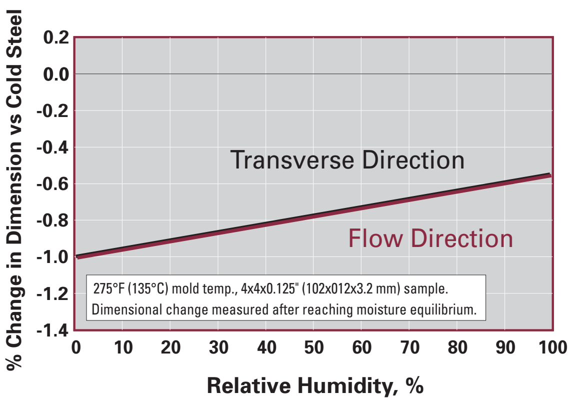
275°F (135°C) mold temp., 4x4x0.125" (102x102x3.2 mm) sample. Dimensional change measured after reaching moisture equilibrium.

Figure 111. Dimensional Effects of Moisture on AMODEL AS-1145 HS Resin



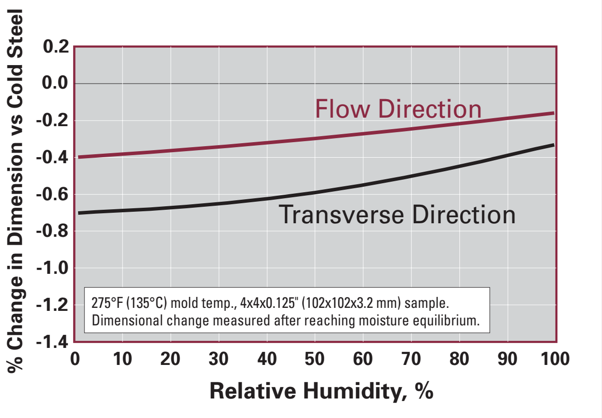
275°F (135°C) mold temp., 4x4x0.125" (102x102x3.2 mm) sample. Dimensional change measured after reaching moisture equilibrium.

Figure 112. Dimensional Effects of Moisture on AMODEL A-1240 L Resin



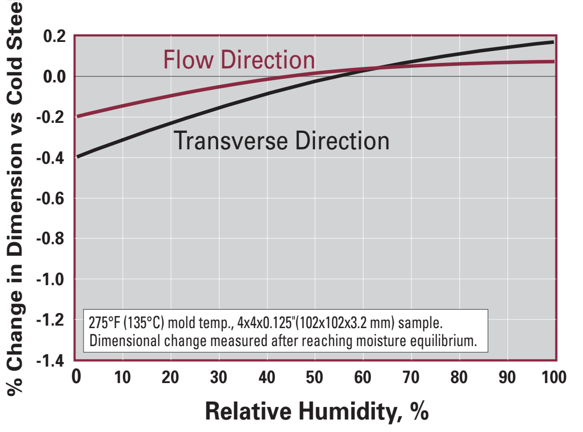
275°F (135°C) mold temp., 4x4x0.125" (102x012x3.2 mm) sample. Dimensional change measured after reaching moisture equilibrium.

Figure 113. Dimensional Effects of Moisture on AMODEL A-1340 HS Resin



275°F (135°C) mold temp., 4x4x0.125" (102x102x3.2 mm) sample. Dimensional change measured after reaching moisture equilibrium.

Figure 114. Dimensional Effects of Moisture on AMODEL AF-1133 V0 Resin



275°F (135°C) mold temp., 4x4x0.125"(102x102x3.2 mm) sample. Dimensional change measured after reaching moisture equilibrium.

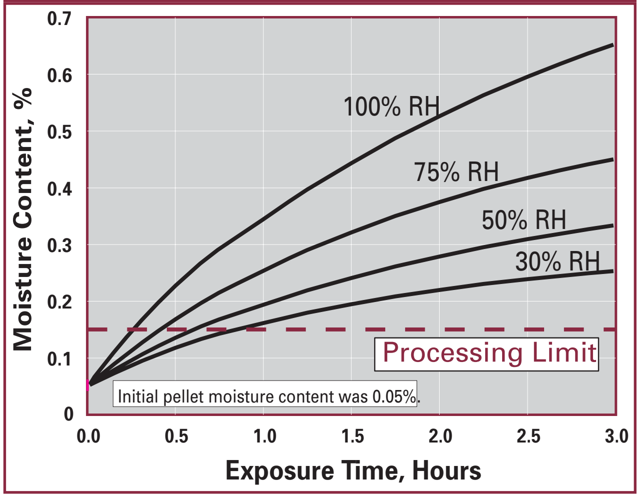
Drying

The processing characteristics and ultimate properties of AMODEL resins, like most thermoplastics, are affected by their moisture content during fabrication. If the pellet moisture content is too high when AMODEL resin is molded, several undesirable consequences may occur. The major consequences are: the molecular weight of the resin is reduced causing brittle parts, the appearance of the part will be poor, and the nozzle of the injection molding machine may drool.

The recommended pellet moisture content for processing AMODEL resins is 0.1% or less. AMODEL resins are packaged in foil-lined containers at a moisture content of less than 0.15%. A desiccant-bed hopper dryer is preferred for maintaining resin dryness once the original bag or box is opened. If one is not available, the resin should be transferred from the opened bags to a sealed hopper as rapidly as possible. Unused resin should be resealed in the bags, or transferred to another sealed container.

Once exposed to the atmosphere, AMODEL resins pick up moisture rapidly. The moisture pickup rate depends upon the Relative Humidity as shown in Figure 115. As can be seen from this graph, exposure of AMODEL resin to humid air for as little as 20 minutes can raise the pellet moisture content to above the recommended level of 0.10%.

Figure 115. Moisture Absorption of AMODEL AS-1133 HS Resin at Various Relative Humidities

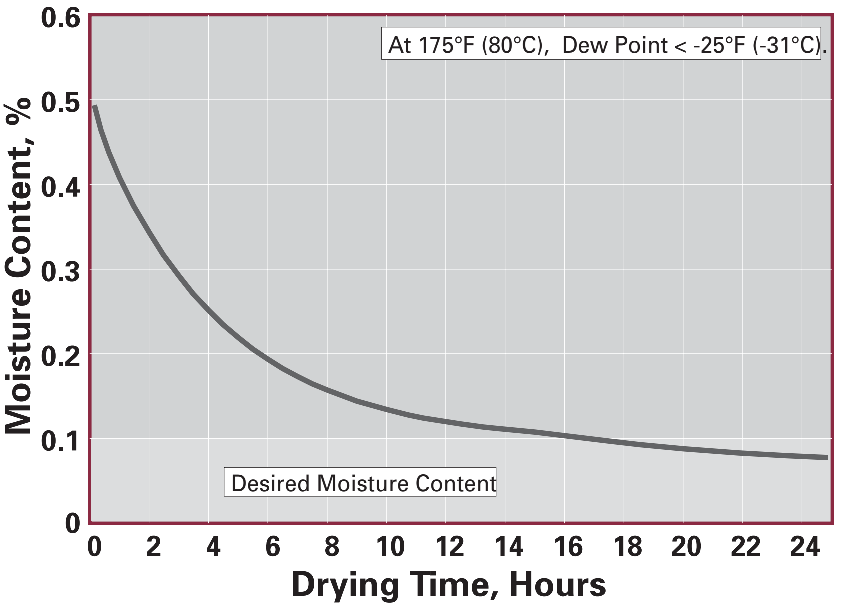


The typical drying time for AMODEL AS-1133 HS resin initially containing 0.5% moisture is shown in Figure 116.

If the resin has absorbed moisture, the recommended drying conditions are 175°F (80°C) in a desiccant-type hopper dryer, adjusted for a dew point less than -25°F (-31°C). Temperatures up to 275°F (135 °C) can be used to shorten the drying time. A slight darkening of the pellet surface may occur when dried at these higher temperatures.

The drying time for AMODEL resin which has been exposed to the atmosphere depends upon its moisture content and the time elapsed since it was exposed. The longer the elapsed time, the more moisture will have diffused to the center of the pellets, where it is most difficult to remove.

Figure 116. Typical Drying Time of AMODEL AS-1133 HS Resin



Drying curves for AMODEL AS-1133 HS and A-1240 L resins that contain 1.0 to 2.0% moisture are shown in Figures 117 and 118 as a function of drying temperature. It can be seen for extremely wet resin with moisture levels greater than 1.0 %, temperatures in excess of 175°F (80°C) are necessary to accomplish the drying in a reasonable period of time.

Although drying times can be influenced by factors such as resin type, Table 40 can be used as a rough guideline if it is not possible to analyze for moisture content.

Determining Moisture Content

The recommended procedures for determining the moisture content in AMODEL resins are ASTM D 789 or D 4019. The analyzer oven temperature should be set to 454°F (235°C) for the purpose of volatilizing moisture. Analysis time should be 30 minutes, or until the moisture evolution rate falls below 0.05 g/sec for a sample size of approximately one gram.

If the molding machine is equipped with a desiccant-type hopper dryer, drying to 0.10% moisture is sufficient, but drying to 0.03 - 0.06% moisture is preferred. If a desiccant hopper dryer is not available, then the resin should be pre-dried to 0.03 - 0.06% moisture, and the hopper should be sealed after the pre-dried resin is charged.

The following empirical relationship has been developed for determining the minimum air flow rate to effectively dry AMODEL resins:

> Air flow rate (CFM) = 0.8 times resin throughput (pounds/hour).

Figure 117. Drying Rate of AMODEL AS-1133 HS at Various Temperatures

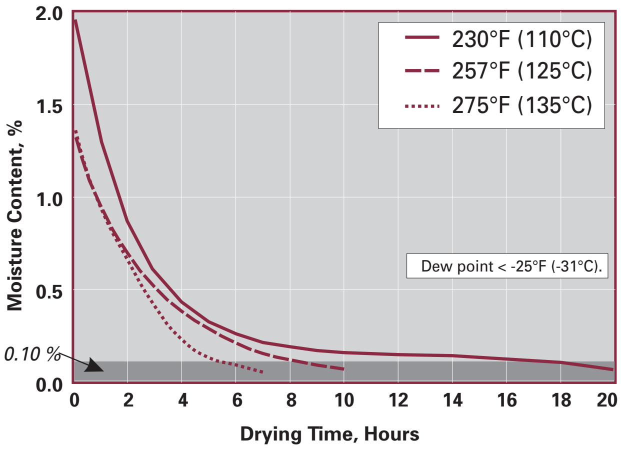


Figure 118. Drying Rate of AMODEL A-1240 L at Various Temperatures

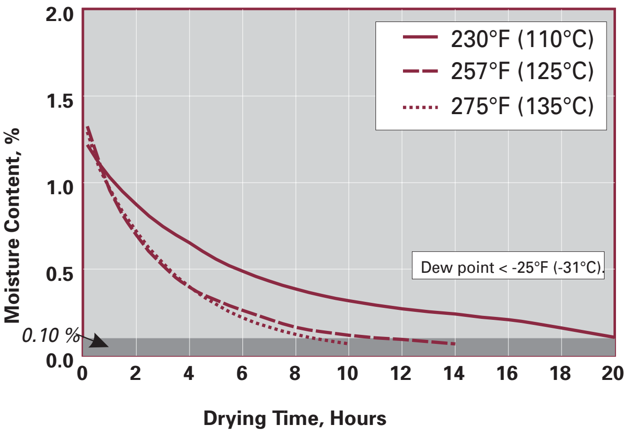


Table 40.
Drying Guidelines
for Very Wet AMODEL Resin (>1.0 % Moisture)

Dryer Inlet Air Temperature °F	Dryer Inlet Air Temperature °C	Drying Time, hours
250	121	15
230	110	22

Dew Point : -25°F (-31°C)

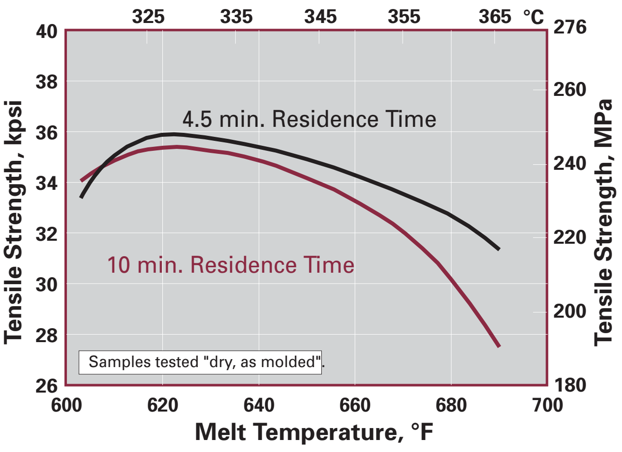
Injection Molding Conditions

Melt Temperatures And Residence Time

AMODEL resins are typically processed at melt temperatures between 610° and 660°F (321° and 349°C). These melt temperatures are usually achieved with barrel settings from 585° to 625°F (307° to 329°C). Melt temperatures above 660°F (349°C) are not recommended.

Excessive melt temperature and residence time in the barrel of the injection molding machine have a detrimental effect on the mechanical properties of the material. Under normal circumstances, tensile strength of reinforced grades is the property most affected. The effect of both melt temperature and residence time on the tensile strength of AS-1133 HS resin is shown in Figure 119.

Figure 119. Melt Temperature, Residence Time Effects on Tensile Strength of AS-1133 HS Resin



Optimum mechanical properties are obtained with melt temperatures between 620° and 630°F (327° and 332°C). At higher melt temperatures, mechanical properties begin to fall off and are more sensitive to residence time in the barrel. Residence times of 10 minutes or less are preferred for this reason, and are a direct function of barrel capacity and part weight. A conservative estimate of residence time can be calculated from the following empirical formula:

$$\text{Residence Time} = \frac{2 \text{ x Maximum Shot Size x Overall Cycle Time}}{\text{Shot Size of Part}}$$

For example, molding a one-ounce part on a four-ounce press with a 30 second overall cycle time results in a residence time of approximately four minutes.

$$\text{Residence Time} = \frac{2 \text{ x } 4 \text{ ounces x } 0.5 \text{ minute}}{1 \text{ ounce}} = 4 \text{ minutes}$$

Cycle interruptions can have a significant effect on residence time. For this reason, to insure consistent part performance, purge shots may be needed after short cycle interruptions. For longer interruptions or shutdowns, standard purge procedures using fractional melt flow polyethylene are suggested. Following good molding practice, injection pressures and rates should be adjusted to maximize packing without flashing while maintaining a good surface appearance.

Mold Temperature

Mold surface temperature affects the degree of crystallinity of all semi-crystalline polymers including AMODEL resins. As shown in Figure 120, the level of crystallinity for AMODEL resins is maximized with mold temperatures above 275°F (135°C). Mold temperatures above 275°F (135°C) also produce parts with the greatest post-mold dimensional stability, chemical resistance, and heat distortion temperatures. Lower mold temperatures can be employed, especially where these properties are not critical or where post-mold annealing can be used.

Packing

The mechanical integrity of parts molded from AMODEL resins is sensitive to packing. Adequate packing is required to compensate for the shrinkage of the melt in the mold cavity during cooling. If this precaution is not followed, voids may form in the thicker sections of the part. The occurrence of voids is common when semi-crystalline resins, such as nylon, acetals and polyesters, are molded with insufficient pack time.

These voids or porosity that form in under-packed parts can significantly reduce tensile and weld line strengths. Voids or porosity not only reduce the effective load carrying area of the part, but also act as stress risers that amplify the loss of strength.

Packing control is accomplished with the injection pressure timers. Typical injection molding presses have two-stage injection pressure controls. The first stage is called "boost", "high", "primary", or "injection pressure", and it is usually used for filling. The second stage is called "holding", "low", or "secondary", and is primarily used for properly packing the part. Packing time or hold time is the amount of time that second-stage injection (hold) pressure is applied. The term screw forward time is used for the sum of the first and second stage injection pressure times.

Figure 121 shows that the tensile strength of AMODEL AS-1133 HS resin increases as packing time is lengthened.

Figure 120. Effect of Mold Temperature on Crystallinity of AMODEL AS-1133 HS Resin

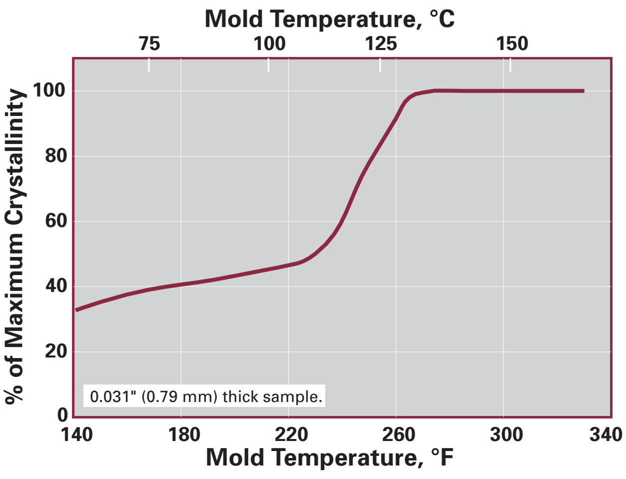


Figure 121. Effect of Packing Time On Tensile Strength of AMODEL AS-1133 HS

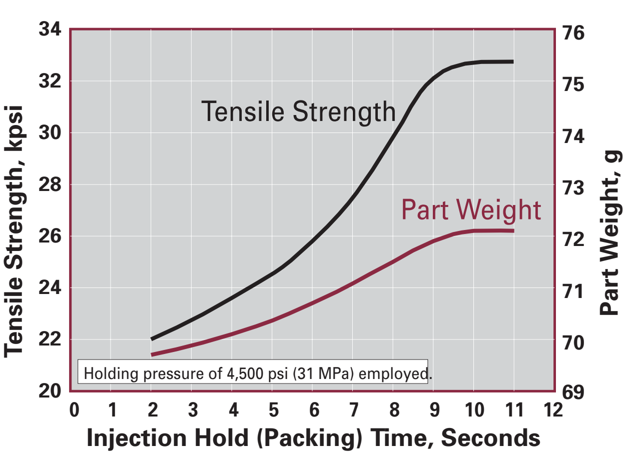


Figure 122. Effect of Packing Time on Weld Line Strength of AMODEL AS-1133 HS Resin

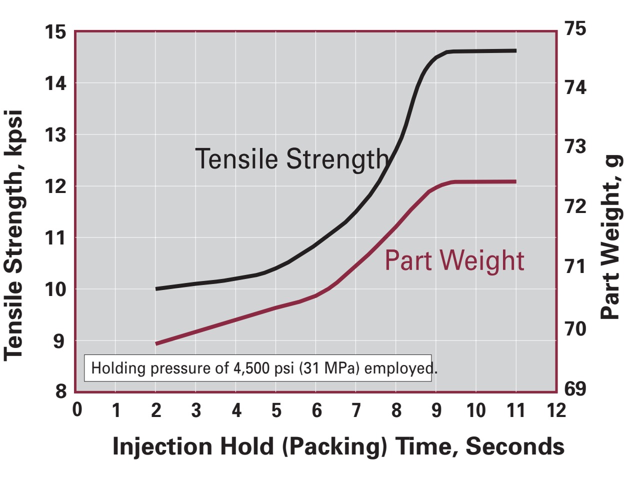


Figure 122 shows this effect for weld line strength. Increasing packing time will not be effective unless a moderate packing pressure of 4,000 to 5,000 psi (27 to 34 MPa) is employed to prevent the formation of voids and to resist the tendency of the material to back flow. Both graphs show that strength increases with increased packing time to a point, but beyond that point the material has completely filled the cavity. At this point, additional packing time is unnecessary since part properties are maximized.

Figures 121 and 122 also show that maximum tensile and weld line strengths are attained when maximum part weight is reached. The second-stage injection-pressure timer should be set to give a packing time of a least 5 seconds for each 0.060 inch (1.5 mm) of wall thickness with a packing pressure of a least 4,000 psi (27 MPa) or 400 psi (2.7 MPa) gauge pressure. Factors that can increase the packing time requirement include higher mold temperature, higher melt temperature, and increased wall thickness. Wall section thickness over 0.250 inch (6.4 mm) or very high melt or mold temperatures will require additional packing time. Measurement of part weight while varying screw forward time can be used to determine the proper packing time for any individual part.

Increasing the packing time does not necessarily result in a longer overall cycle. The cooling or mold closed time can be reduced an amount equivalent to the increase in packing time which produces an overall cycle time that is unchanged. Better packing may actually allow a cycle time reduction as shown in the following example.

Example

Here is an example of how to develop the optimum molding cycle for a particular part. For this example, consider a part with a maximum wall thickness of 0.1875 inch (4.8 mm). Using the usual guidelines to produce a molding cycle, such as part appearance and shot to shot dimensional consistency, the cycle shown as “Cycle 1" in Table 41 appears realistic. Although the parts made by Cycle 1 appear to be fully packed, they may actually contain voids and have poor strength. To determine if this condition exists, increase injection hold time and monitor part weight. If part weight increases, continue lengthening injection hold time until the maximum part weight is obtained. In this example the maximum part weight is achieved with a 15 second injection hold or pack time.

To compensate for the increase in “Overall Cycle Time” that occurs by increasing injection hold time from three seconds to fifteen seconds, other adjustments in the cycle time have to be made. For instance, since the polymer in the mold is cooling during the injection hold time, the time added to injection hold can be subtracted from the “Cooling Time”, leaving the overall cycle at 36.5 seconds. This improved cycle is shown as Cycle 2 in Table 41.

Because better packing results in better dimensional stability, the cycle may be further improved by reducing Cooling Time even more and monitoring the part dimensions from shot to shot. Using this technique, it may be possible to reduce the cooling time by another four seconds. This final adjustment will result in reduction in the “Overall Cycle Time” as shown in Cycle 3 in Table 41.

Measuring part weight can therefore be an excellent process control tool.

Table 41.
Example of Molding Cycle Development

Phase	Cycle 1	Cycle 2	Cycle 3
Injection Boost Time	1.50	1.50	1.50
Injection Hold Time	3.00	15.00	15.00
Cooling (Cure) Time	25.00	13.00	9.00
Mold Open Time	6.00	6.00	6.00
Injection Delay	1.00	1.00	1.00
Overall Cycle Time	36.50	36.50	32.50

Regrind Usage

Conventional injection molding yields one set of sprue and runners per cycle of parts. Some molders may find it desirable to re-use the resin in the sprues and runners to reduce the amount of waste that has to be discarded, as well as minimize the cost of the part. Customarily, the sprues and runners are ground and mixed with the unprocessed resin at a certain level, then dried, and processed to create new parts. Also parts which are defective, such as short-shots, or start-up, can be ground and added to the sprues and runners. The ground material intended for re-use is commonly called “regrind”.

End users usually allow the use of certain amount of reground or recycled resin in the production of their parts, if the use of regrind does not have an adverse affect on the performance of their parts. In laboratory tests in which AMODEL resins were repeatedly molded at 25 % regrind levels, no significant changes in tensile strength or notched Izod impact values were observed. The test variables that were investigated were the number of times that regrind was used (up to six generations of regrind were evaluated), the residence time (which was varied from 3 to 10 minutes), and the melt temperature (which was varied from 630° to 650°F (332° to 343°C). Figures 123 and 124 show how the tensile strength and the notched Izod impact values of AMODEL AS-1133 HS resin change as a function of regrind cycle when the percentage of regrind is 25 percent.

Figure 125 shows how the tensile strength of AMODEL AF-1145 V0 resin changes as a function of regrind cycle. Excellent retention of strength is also maintained for the flame retardant grades of AMODEL resins. The maximum recommended amount of regrind to be used with AMODEL resins is 25 percent.

Figure 123. Effect of 25% Regrind on Tensile Strength of AMODEL AS-1133 HS Resin

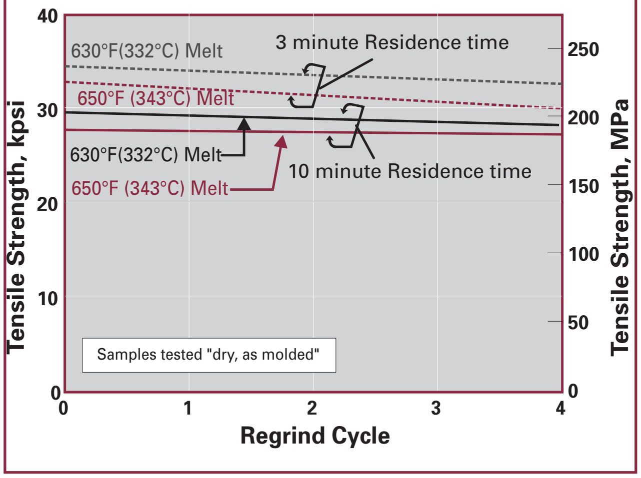


Figure 124. Effect of 25% Regrind on Izod Impact of AMODEL AS-1133 HS Resin

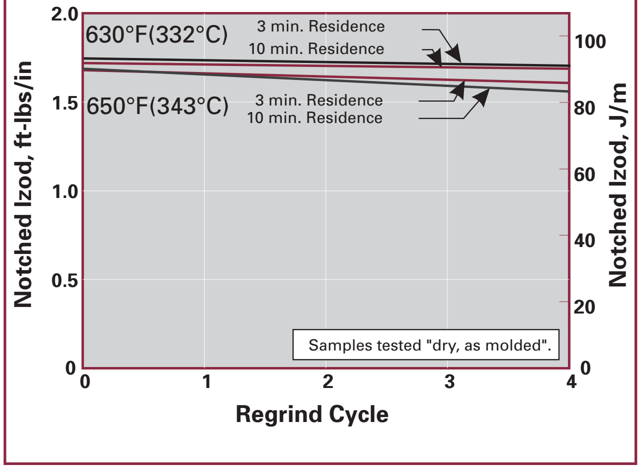
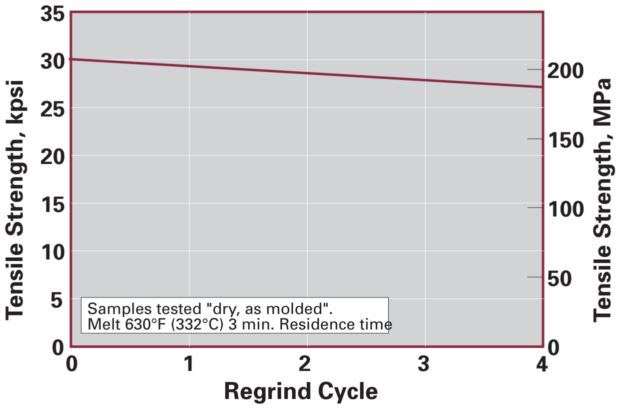


Figure 125. Effect of 25% Regrind on Tensile Strength of AMODEL AF-1145 V0 Resin



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