



design guide

version 3.3

RADEL[®] R polyphenylsulfone

RADEL[®] A polyethersulfone

ACUDEL[®] modified polyphenylsulfone

Radel[®] A polyethersulfone (PESU)
is now marketed as **Veradel[®]** PESU.

This change only affects the tradename; there are no changes to product specifications or processing. Agency listings will be updated to Veradel PESU.

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- **Mindel**® modified polysulfone
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- **Torlon**® polyamide-imide (PAI)

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

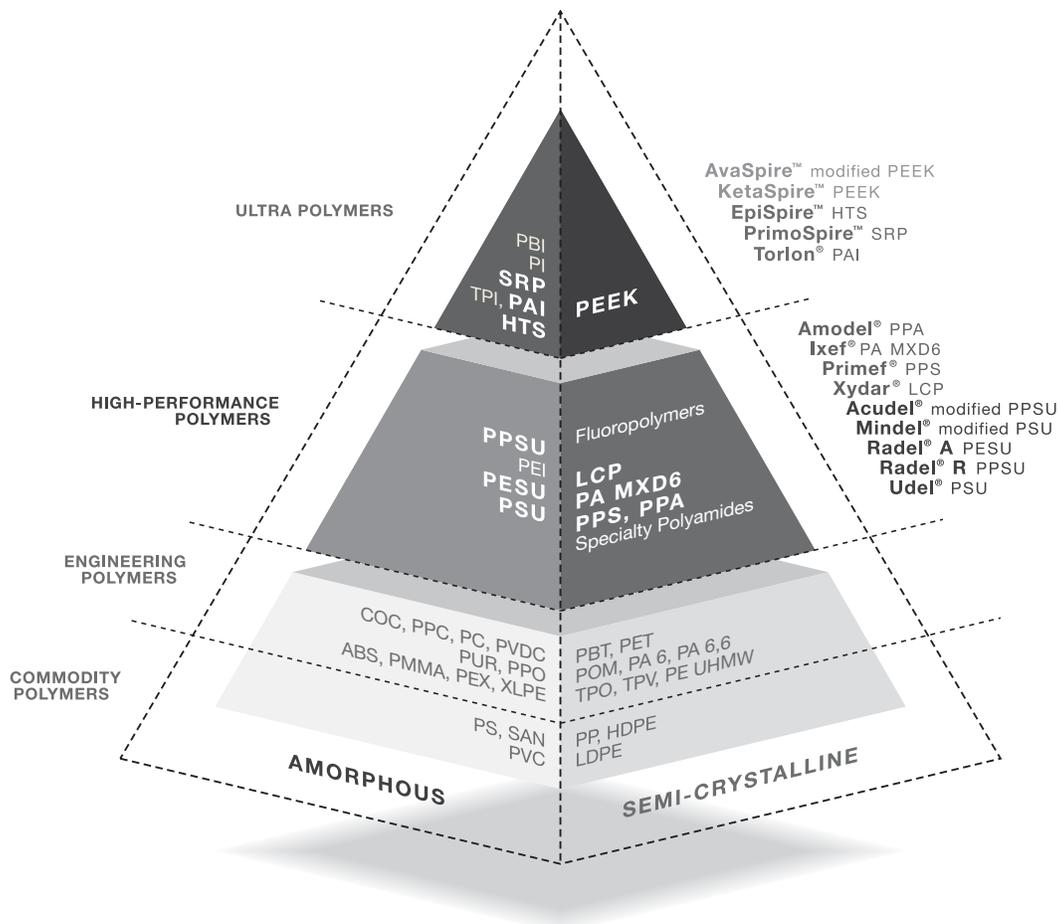


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Introduction

This design guide contains specific information about Radel A polyethersulfone, Radel R polyphenylsulfone, and Acudel modified polyphenylsulfone. The purpose of the guide is to provide the design engineer with the specific information he needs to make effective use of these materials. In addition to short-term mechanical, thermal, electrical, and physical property data, this Guide includes information about long-term properties, such as creep, fatigue, and thermal stability; resistance to chemicals and other environmental factors; and information about agency approvals. Also included are recommendations for processing these materials, for designing parts, and for secondary operations.

This document concentrates on the standard grades of Radel and Acudel products. The Radel R family also includes materials specially formulated to meet the stringent safety requirements of the commercial aircraft industry. These resins, the R-7000 series, are in compliance with the FAA regulations for heat release, smoke generation, and toxic gas emissions. These specialty grades are considered outside of the scope of this manual.

For information on the other product lines or the specialty grades of Radel R polyphenylsulfone, please consult our website at www.solvayadvancedpolymers.com or contact your sales representative.

The Radel high-temperature resin family and the Acudel modified polyphenylsulfones offer a superior combination of high-performance properties that include:

- Excellent thermal stability
- Outstanding toughness
- Good environmental stress cracking resistance
- High heat deflection temperature – over 213°C (415°F)
- Combustion resistance without additives
- Transparency
- Approved for food contact and potable water use.

In addition, Radel R polyphenylsulfone has a notched Izod of 13 ft-lbs/in. (690 J/m), virtually unlimited steam sterilizability, and excellent resistance to hot chlorinated water. Radel A polyethersulfone has a UL Relative Thermal Index of 190°C (374°F). Acudel modified polyphenylsulfones offer cost effective alternatives to Radel R polyphenylsulfone for some applications.

These properties – combined with easy processing – make the materials attractive for a wide variety of applications.

Some examples of Radel A polyethersulfone applications in electrical/electronic components include molded interconnect devices (MID's), connectors, burn-in sockets or trays, wire insulation, and housings and components of starters or contacters.

Examples of Radel R polyphenylsulfone applications include surgical trays, dental instrument holders, medical device components, and surgical instrument handles, food service equipment, and institutional feeding trays.

Radel R resin applications in transportation include aircraft interior panels, reflectors, sockets, connectors, and fuse bodies.

Radel R polyphenylsulfone and Acudel modified polyphenylsulfone have found application in pipe fittings and manifolds for plastic piping systems.

Chemistry

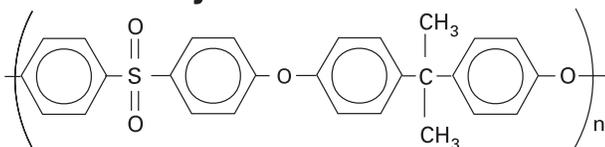
Radel A polyethersulfone and Radel R polyphenylsulfone are natural extensions of Solvay's line of high performance engineering thermoplastics. As members of the sulfone polymer family exemplified by Udel polysulfone, they offer many of the excellent properties typical of Udel polysulfone. Compared to Udel polysulfone, Radel A polyethersulfone has improved thermal capability, inherent flame resistance, better chemical resistance, and improved mechanical properties. Radel R polyphenylsulfone offers exceptional toughness and resistance to impact with even better chemical resistance than Radel A polyethersulfone.

The chemical structures of Udel polysulfone, Radel R polyphenylsulfone, and Radel A polyethersulfone are shown in Figure 1.

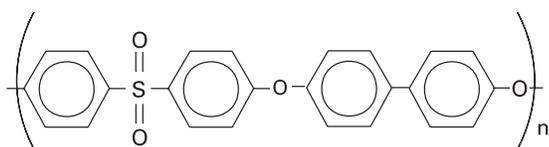
Figure 1.

Chemical Structures

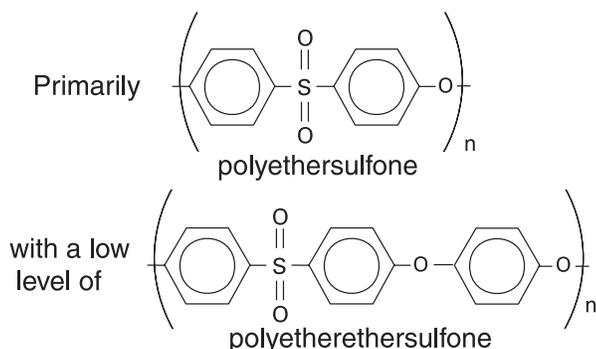
UDELE Polysulfone



RADEL R Polyphenylsulfone



RADEL A Polyethersulfone



Chemical Structure - Property Relationships

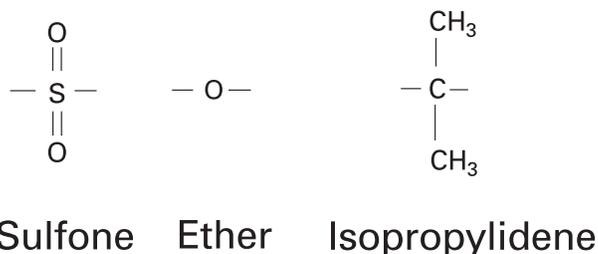
The stereo chemistry of the sulfone group disrupts any tendency for these polymers to melt crystallize, hence they are amorphous and exhibit high clarity and transparency.

These polymers are comprised of aromatic units (phenylenes) bridged with sulfone, ether, and in the case of Udel polysulfone, isopropylidene moieties.

These "bridging" moieties, shown in Figure 2, impart special performance characteristics to polysulfones; including hydrolytic stability, thermo-oxidative and melt stability, high use temperatures, and ductility. The electronegative sulfone group, in which sulfur is at its highest oxidation state, specifically affords excellent thermo-oxidative stability to the polymer, and simultaneously elevates the long-term use temperature.

Figure 2

Bridging Moieties



The phenylene ether segment contributes flexibility to the polymer backbone, which is manifested as high toughness, elongation, and ductility, as well as ease of melt fabrication. The outstanding hydrolytic stability that differentiates polysulfones from other engineering thermoplastics is a consequence of the resistance to aqueous hydrolysis of both the phenylene sulfone and ether groups. In contrast, competitive products, such as polycarbonates, polyesters, polyarylates, and polyetherimides, all contain bridging groups in their repeating units that are hydrolyzable, and therefore can exhibit molecular weight degradation resulting in severe property loss when exposed to aggressive aqueous environments, such as boiling water, steam, caustic or acidic solutions.

Polyethersulfone possesses the highest concentration of sulfone moieties in the polymer repeat unit. This polar moiety attracts water, with the result that polyethersulfone has the highest water absorption of the commercial sulfone polymers.

Radel R has a biphenylene unit that uniquely elevates the impact strength and reduces the notch sensitivity, resulting in notched Izod values greater than 13 ft-lb/in (690 J/m).

Product Data

Material Selection

The sulfone polymer family, which includes Udel polysulfone, Radel A polyethersulfone, and Radel R polyphenylsulfone are amorphous resins that combine excellent thermal stability, high strength and toughness, excellent hydrolytic stability, transparency, and good resistance to environmental stress cracking. Mindel modified polysulfones and Acudel modified polyphenylsulfones offer additional cost and performance advantages,

This section will highlight the differences between the sulfone polymers to help you decide which material will best meet your requirements. Most of these resins are transparent, but the blends are opaque.

As the lowest cost member of the family, Udel polysulfone is the most widely used. It offers the lowest color and highest clarity, and its hydrolytic stability is exceeded only by the much higher performance Radel R polyphenylsulfone. More information about Udel polysulfone can be found in the Udel Polysulfone Design Guide, which can be obtained from your Solvay representative or from our website.

Figure 3 compares the relative thermal capability of the Radel resins and their blends to Udel polysulfone and polycarbonate, and shows that the Radel resins are preferred for higher temperature environments.

Figure 4 shows a comparison of the hydrolytic stability of these resins with polycarbonate and polysulfone. Polysulfone has excellent hydrolytic stability, surpassed only by Radel R polyphenylsulfone or the modified polyphenylsulfones.

The relative performance of the Radel resins when exposed to organic solvents is shown in Figure 5. The graph shows that Radel R polyphenylsulfone has by far the greatest resistance to attack and/or stress cracking from organic solvents. Radel A polyethersulfone, Acudel modified polyphenylsulfones, and Udel polysulfone are clearly better than polycarbonate.

A key property in many applications is impact resistance. This property is difficult to quantify. Some tests measure sensitivity to notches and others measure resistance to high speed penetration. Figure 6 shows an estimate of the practical impact resistance of Radel resins which includes drop impact ratings as well as tensile impact results. The figure shows that these resins are tough, ductile materials and they all have excellent practical impact resistance.

Radel A polyethersulfone is available in both unfilled grades and glass-reinforced grades. Each type is available in a range of melt viscosities.

Figure 3

Relative Thermal Capability of Radel Resins

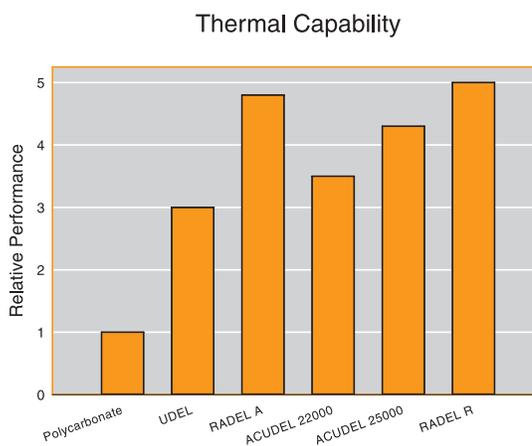


Figure 4

Hydrolytic Stability of Radel Resins

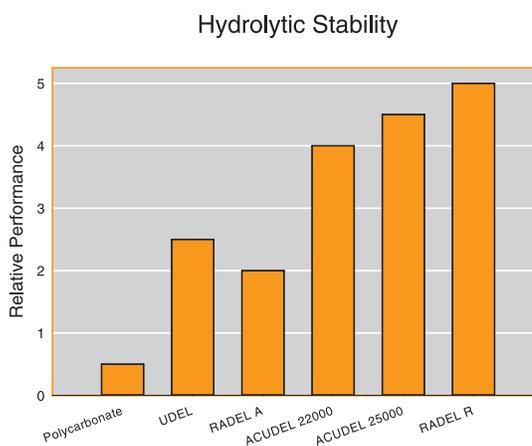


Figure 5

Resistance of Radel Resins to Organic Solvents

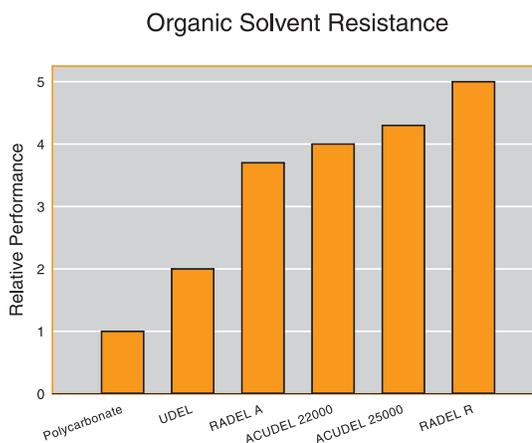
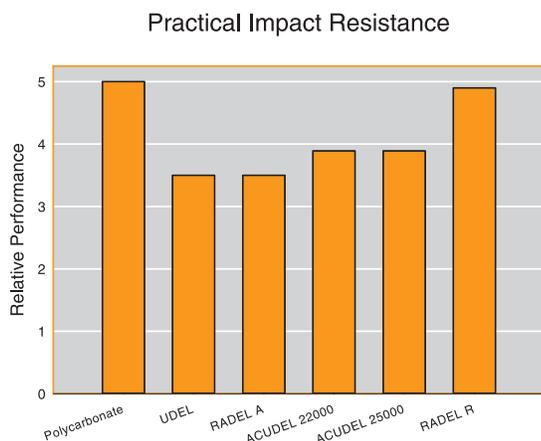


Figure 6

Impact Resistance of Radel Resins



Radel A polyethersulfone is indicated when a sulfone polymer with higher thermal capability, inherent flame resistance, better chemical resistance, and improved mechanical properties than polysulfone are required.

The glass-reinforced grades offer higher stiffness and dimensional stability, with attendant benefits in creep resistance, chemical resistance, and lower thermal expansion. Radel AG-340 and AG-360 resins are especially cost-effective, glass-reinforced blends containing 20% and 30% glass fiber respectively.

Radel R polyphenylsulfone is the material of choice for the ultimate in toughness with chemical and hydrolysis resistance superior to all commercially available transparent resins or when resistance to commercial autoclave environments is needed.

Radel R polyphenylsulfone is offered in several grades: R-5000, the general purpose transparent grade; R-5100 colors, R-5500, an extrusion grade; and R-5800, a higher flow transparent grade.

Acudel products are economical, unfilled opaque polyphenylsulfone blends designed to satisfy a broad range of challenging application design and end-use requirements.

Both Radel A polyethersulfone and Radel R polyphenylsulfone can be color matched to a wide range of colors, both transparent and opaque.

Nomenclature

The nomenclature system for Radel resins uses a letter to indicate the polymer family, “A” designates the polyethersulfone family and “R” designates the polyphenylsulfone family.

For Radel A resins, the first digit of the grade number is used to indicate the relative melt viscosity. The mechanical, physical, thermal, and chemical resistance properties of neat and glass-filled Radel A resins have been shown to be equivalent for all melt viscosities, except where noted.

Table 1 shows the grade designations of the unfilled Radel grades and the relative melt viscosities, as measured by ASTM test method D 1238 expressed as melt flow rate.

The glass-reinforced grades are indicated by adding a “G” to the basic family descriptor. Table 2 shows the composition and melt flows of the glass-reinforced Radel resins.

Table 1.

Melt Flow Rates of Neat Radel Resins

Grade Number	Typical Melt Flow Rate, g/10 min
Radel A resins	
at 380°C (716°F), 2.16 kg	
A-100*	12
A-200A**	20
A-300A	30
Acudel resins	
at 380°C (716°F), 2.16 kg	
22000	12
25000	17
35000*	10
Radel R-5000 series resins	
At 365°C (689°F), 5.0 kg	
R-5500*	15.5
R-5000/5100	17
R-5800	25

* extrusion grade ** extrusion or injection molding

Table 2

Glass-Reinforced Radel Grades

Grade Number	Composition	Melt Flow Rate at 380°C (716°F), 2.16 kg, g/10 min
AG-220	20% GR Radel A-200A	10
AG-320	20% GR Radel A-300A	14
AG-230	30% GR Radel A-200A	10
AG-330	30% GR Radel A-300A	12
AG-340	20% GR Radel A-300A Blend	18
RG-5030	30% GR Radel R	15*

*Melt flow rate measured at 365°C (689°F), 5.0 kg

Approvals

Radel resins comply with the requirements of several governmental and/or regulatory agencies, as shown below. As regulatory action is an ongoing activity, please contact your Solvay Advanced Polymers representative for information regarding a specific application requiring agency approval or recognition.

Food Contact

United States Food and Drug Administration (FDA) - Radel A polyethersulfone complies with regulation 21CFR177.1560, and is therefore suitable for direct food contact uses. Radel R polyphenylsulfone complies with the Food Contact Notification Number 000083, and is suitable to be used in repeat use food contact applications with all food types, under FDA conditions B through H.

European Commission Directive 2002/72/EEC – Commission Directive Relating to Plastic Materials and Articles Intended to Come in Contact with Foodstuffs.

Several grades of Radel A, Radel R and Acudel are recognized under each of these standards. Information on current listings for specific grades is available from your Solvay Advanced Polymers representative.

United States Pharmacopeia (U.S.P.)*

Table 3 lists the grades of sulfone resin that comply with the requirements of Class VI and are therefore suitable for use in Class II and Class III medical devices.

Table 3.

Sulfone Resins Meeting USP Class VI Requirements

Acudel modified polyphenylsulfones

25000 GY1037 25000 WH6417

Radel A polyethersulfone

A-300A NT

Radel R polyphenylsulfone

R-5000 CL301	R-5100 VT173	R-5500 GY8057
R-5000 NT	R-5100 YL1028	R-5500 GR1127
R-5100 BK935	R-5500 BK937	R-5500 WH837
R-5100 BK937	R-5500 BU1027	R-5800 NT
R-5100 BU525	R-5500 BU1200	R-5800 CL301
R-5100 GY7016	R-5500 GY1037	RG-5030 NT
R-5100 RD3031		

*Solvay Advanced Polymers does not allow or support the use of any of our products in any implant applications. If you have questions regarding our implant policy, please contact your Solvay Advanced Polymers representative.

National Sanitation Foundation

NSF International is a not-for-profit, non-governmental organization that develops standards for public health and safety. It also provides lists of materials that conform to their standards. For more complete information about NSF, please visit their website at www.nsf.org. Of their many standards, two are especially important for sulfone polymers, standard 51 “Food Equipment Materials” and standard 61 “Potable Water Materials”.

NSF Standard 51 Food Equipment Materials

Table 4.

NSF Standard 51 Certified Materials

Grade	Maximum Use Temperature, °C (°F)
Acudel modified polyphenylsulfone	
22000 BK937	100 (212)
22000 NT15	100 (212)
Radel A polyethersulfone	
A-200A	191 (375)
AG-210 NT	191 (375)
AG-220 NT	191 (375)
AG-230 NT	191 (375)
AG-310 NT	191 (375)
AG-320 NT	191 (375)
AG-330 NT	191 (375)
Radel R polyphenylsulfone	
R-5000	191 (375)
R-5100 NT15	191 (375)
R-5900 NT	191 (375)
R-5900 BK937	191 (375)

Table 4 lists the sulfone polymers certified to this standard and the maximum use temperature for the certification. The standard lists these food types: dry solids, aqueous, acidic, dairy products, oil, and alcoholic beverages. The listed materials are certified for all food types.

NSF Standard 61 Drinking Water System Components- Health Effects

Table 5 lists the sulfone polymers certified to meet NSF standard 61 at 85°C (185°F).

These tables are provided for your information only. Prior to use in an application requiring certification, you are strongly urged to go to www.NSF.org/Certified/ to get the latest listing.

Table 5.

NSF Standard 61 Certified Materials

Acudel modified polyphenylsulfone

22000 BK937	22000 WH6417	22000 WH7407
22000 NT15		

Radel A polyethersulfone

AG-330 NT

Radel R polyphenylsulfone

R-5000 NT	R-5100 NT15	R-5100 WH6417
R-5100 BK937	R-5100 BU1197	

International Water Contact Standards

Listings expire periodically and depending on market demand they may or may not be recertified. Contact your Solvay Advanced Polymers representative for the latest listing.

Water Byelaws Scheme - United Kingdom

Table 6 lists the Radel grades that have passed the tests of effect on water quality - BS 6920, and are suitable for use in contact with potable water and will be included in the Materials section, Part Two of the Water Fittings and Materials Directory:

These products are also approved for cold water and hot water use up to 85°C (185°F).

Table 6.

Radel Resins Listed as complying with BS 6920

A-100 NT	AG-320 NT	R-5100 NT
A-200A NT	AG-330 NT	R-5100 BK937
A-300A NT		R-5100 GY1037
AG-230 NT	R-5000 NT	R-5100 BU1197

German Federal Health Office

Table 7 lists the resins that have been tested and examined and found to be in accordance with the KTW recommendations of the German Federal Health Office at temperatures up to 90°C (194°F):

Table 7.

Radel Grades listed by KTW

A-100 NT	R-5100 BU1197
AG-330 NT	Acudel 22000 GY1037
R-5000 NT	Acudel 22000 BK937
R-5100 BK937	

Underwriters' Laboratories

Many commercial grades of Acudel polyphenylsulfone, Radel A polyethersulfone and Radel R polyphenylsulfone are listed in Underwriters' Laboratories Recognized Component Directory. Data relating to short-term performance are given in Table 25 on page 25. Long-term performance ratings are shown in Table 23 on page 24. For the most current listing information visit the Underwriters' Laboratories, Inc., website at www.UL.com.

Property Data

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

With polymeric materials, the mechanical properties are more time and temperature dependent than those of metals, and in some ways, they are more affected by environmental factors. To design successfully with polymeric materials, the designer must consider not only the short-term mechanical properties, but also the time, temperature, and environmental demands of each application.

Short-Term Properties

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

Typically, these property values are obtained by preparing a special test specimen, then subjecting it to an increasing load until failure, usually rupture, occurs. The test specimens are designed for obtaining reproducible results, and may give higher values than would be obtained if specimens machined from an actual part were tested. Because the tests are run quickly, the time-related effects are minimized.

Environmental factors are eliminated by running the tests in a controlled environment, thereby avoiding any reduction in properties from chemical exposure. Short-term mechanical properties usually include tensile strength and modulus, flexural strength and modulus, notched Izod impact, compressive strength, shear strength, and surface hardness.

Typical Property Tables

The typical properties of the Radel engineering resins and the Acudel modified polyphenylsulfones are shown in Tables 8 and 9.

Table 8

Typical Properties⁽¹⁾ - U.S. Customary Units

Property	Test Method	Units	Radel A				Radel R		Acudel	
			A-300A A-200A A-100	AG-320 AG-220	AG-330 AG-230	AG-340	R-5800 R-5500 R-5100 R-5000	RG-5030	22000	25000
Mechanical										
Tensile Strength	D 638	kpsi	12.0	15.2	18.3	17.3	10.1	17.4	11.2	10.1
Tensile Modulus	D 638	kpsi	385	825	1,250	980	340	1,330	390	340
Tensile Elongation	D 638	%								
at Yield			6.5	3.2	1.9		7.2		6.7	7.2
at Break			25–75	3.2	1.9	3.1	60–120	2.4	25–75	50–100
Flexural Strength	D 790	kpsi	16.1	21.0	26.0	24.5	15.2	25.1	15.7	15.3
Flexural Modulus	D 790	kpsi	420	750	1,170	860	350	1,170	400	370
Compressive Strength	D 695	kpsi	14.5	21.9	25.6		14.4			
Compressive Modulus	D 695	kpsi	388	875	1,120					
Shear Strength	D 732	kpsi	8.0	8.8	9.5		8.8		8.4	8.3
Izod Impact Strength	D 256	ft-lb/in								
notched			1.6	1.1	1.4	1.2	13.0	1.4	2.0	5.0
unnotched			NB ⁽²⁾	12	10	12	NB ⁽²⁾	12	NB ⁽²⁾	NB ⁽²⁾
Tensile Impact	D 1822	ft-lb/in ²	160	31	34		190		175	175
Rockwell Hardness	D 785		R127		R121	R124	R122			
Thermal										
Deflection Temperature ⁽³⁾	D 648	°F								
at 66 psi			417	424	428		417			
at 264 psi			399	417	420	405	405	410	387	405
Vicat Softening Point	D 1525B	°F	418	422	424					
Thermal Expansion Coefficient	E 831	μin/in°F	27	17	17	23	31	10	35	33
Thermal Conductivity	E 1530	⁽⁵⁾	1.66		2.08		2.08		1.66	1.66
Glass Transition Temperature	DSC	°F	428	428	428	428	428	428	428 ⁽⁶⁾	428 ⁽⁶⁾
Combustion⁽⁴⁾										
Oxygen Index	D 2863	%	39	40	40		38		38	38
UL 94 Rating at 0.031 in.	UL 94		94 V-0	94 V-0	94 V-0		94 V-0			
Self-ignition Temperature	D 1929	°F	936							
Electrical										
Dielectric Strength	D 149	volts/mil	380	440	440	418	360	400	470	
Volume Resistivity	D 257	ohm-cm	1.7x10 ¹⁵	>10 ¹⁶	>10 ¹⁶	1.9x10 ¹⁶	>10 ¹⁵	>9x10 ¹⁵	>9x10 ¹⁵	
Dielectric Constant	D 150									
at 60 Hz			3.51	3.84	4.11		3.44			
at 10 ³ Hz			3.50	3.84	4.13		3.45			
at 10 ⁶ Hz			3.54	3.88	4.17	3.81	3.45	3.90	3.40	
Dissipation Factor	D 150									
at 60 Hz			0.0017	0.0015	0.0019		0.0006			
at 10 ³ Hz			0.0022	0.0018	0.0018					
at 10 ⁶ Hz			0.0056	0.0081	0.0094	0.0103	0.0076	0.0090	0.0080	
Physical										
Specific Gravity	D 792		1.37	1.51	1.58	1.45	1.29	1.53	1.28	1.28
Refractive Index			1.651				1.672			
Water Absorption ⁽⁷⁾ at 24 hr	D 570	%	0.5	0.4	0.4	0.3	0.4	0.3	0.3	0.3
Water Absorption ⁽⁷⁾ at 30 days	D 570	%	1.8			0.9	1.1	0.7	0.8	0.9

(1) Typical Values - Actual properties of individual batches will vary within specification limits.

(2) NB = no break

(3) annealed 1/8" bar

(4) The data regarding combustion and combustibility are the results of small-scale laboratory tests and do not reflect the hazards of these or any other material under actual fire conditions.

(5) units are $\frac{BTU \cdot in}{hr \cdot ft^2 \cdot ^\circ F}$ (6) Value shown is value of major blend component
(7) Measured from completely dry

Table 9.

Typical Properties⁽¹⁾ - SI Units

Property	Test Method	Units	Radel A				Radel R		Acudel	
			A-300A A-200A A-100	AG-320 AG-220	AG-330 AG-230	AG-340	R-5800 R-5500 R-5100 R-5000	RG-5030	22000	25000
Mechanical										
Tensile Strength	D 638	MPa	83	105	126	119	70	120	77	70
Tensile Modulus	D 638	GPa	2.65	5.70	8.62	6.76	2.34	9.17	2.69	2.34
Tensile Elongation	D 638	%								
at Yield			6.5	3.2	1.9		7.2		6.7	7.2
at Break			25–75	3.2	1.9	3.1	60–120	2.4	25–75	50–100
Flexural Strength	D 790	MPa	111	145	179	169	105	173	108	105
Flexural Modulus	D 790	GPa	2.90	5.17	8.07	5.93	2.41	8.07	2.76	2.55
Compressive Strength	D 695	MPa	100	151	177		99			
Compressive Modulus	D 695	GPa	2.68	6.03	7.72					
Shear Strength	D 732	MPa	55	61	65		61		58	57
Izod Impact Strength	D 256	J/m								
notched			85	59	75	64	694	75	106	265
unnotched			NB ⁽²⁾	640	530	625	NB ⁽²⁾	640	NB ⁽²⁾	NB ⁽²⁾
Tensile Impact	D 1822	kJ/m ²	336	65	71		400			
Rockwell Hardness	D 785		R127		R121	R124	R122			
Thermal										
Deflection Temperature ⁽³⁾	D 648	°C								
at 0.45 MPa			214	218	220		214			
at 1.82 MPa			204	214	216	207	207	210	197	207
Vicat Softening Point	D 1525B	°C	214	217	218					
Thermal Expansion Coefficient	E 831	μm/m°C	49	31	31	41	56	18	63	59
Thermal Conductivity	E 1530	W/mK	0.24		0.30		0.30		0.24	0.24
Glass Transition Temperature	DSC	°C	220	220	220	220	220	220	220 ⁽⁵⁾	220 ⁽⁵⁾
Combustion⁽⁴⁾										
Oxygen Index	D 2863	%	39	40	40		38		38	38
UL 94 Rating at 0.8 mm	UL 94		94 V-0	94 V-0	94 V-0		94 V-0			
Self-ignition Temperature	D 1929	°C	502							
Electrical										
Dielectric Strength	D 149	kV/mm	15	17	17	16	15	16	18	
Volume Resistivity	D 257	ohm-cm	1.7x10 ¹⁵	>10 ¹⁶	>10 ¹⁶	1.9x10 ¹⁶	>10 ¹⁵	>9x10 ¹⁵	>9x10 ¹⁵	
Dielectric Constant	D 150									
at 60 Hz			3.51	3.84	4.11		3.44			
at 10 ³ Hz			3.50	3.84	4.13		3.45			
at 10 ⁶ Hz			3.54	3.88	4.17	3.81	3.45	3.90	3.40	
Dissipation Factor	D 150									
at 60 Hz			0.0017	0.0015	0.0019		0.0006			
at 10 ³ Hz			0.0022	0.0018	0.0018					
at 10 ⁶ Hz			0.0056	0.0081	0.0094	0.0103	0.0076	0.0090	0.0080	
Physical										
Specific Gravity	D 792		1.37	1.51	1.58	1.45	1.29	1.53	1.28	1.28
Refractive Index			1.651				1.672			
Water Absorption ⁽⁶⁾ at 24 hr	D 570	%	0.5	0.4	0.4	0.3	0.4	0.3	0.3	0.3
Water Absorption ⁽⁶⁾ at 30 days	D 570	%	1.8			0.9	1.1	0.7	0.8	0.9

(1) Typical Values - Actual properties of individual batches will vary within specification limits.

(2) NB = no break

(3) annealed 3.2 mm bar

(4) The data regarding combustion and combustibility are the results of small-scale laboratory tests and do not reflect the hazards of these or any other material under actual fire conditions.

(5) Value shown is value of major blend component

(6) Measured from completely dry

Tensile Properties

Tensile properties are determined by clamping a test specimen into the jaws of a testing machine and separating the jaws at a specified rate in accordance with ASTM test method D 638. The force required to separate the jaws divided by the minimum cross-sectional area is defined as the tensile stress. The test specimen will elongate as a result of the stress, and the amount of elongation divided by the original length is the strain.

If the applied stress is plotted against the resulting strain, a curve similar to that shown in Figure 7, is obtained for ductile polymers like polysulfones.

The initial portion of the stress/strain curve is of special interest, and is shown in Figure 8. This figure shows that strain is directly proportional to stress, up to a certain level of stress. This region is known as the “Hookean” region, and the limiting stress is known as the proportional limit. The tensile modulus is the slope of the stress/strain curve when a specimen is subjected to a tensile loading. Measuring the slope of a curved line is difficult, and some conventions have been developed to standardize the testing and reduce the variability in test results. One method uses the slope of a line drawn tangent to the curve, and another method utilizes the slope of a secant drawn through the origin and some arbitrarily designated strain level. The tangent method was used for these data.

Ductile polymers undergo “yield” prior to rupture. At the onset of jaw separation, the stress or force required to elongate the specimen is directly proportional to the elongation or strain. As the test proceeds, the specimens exhibit greater amounts of permanent deformation until the point where additional elongation is achieved with the application of less than the proportional amount of stress. This point is called “yield” and the stress level is often referred to as tensile strength at yield. The elongation is called elongation at yield or yield strain. As the test proceeds, the specimen is elongated until rupture occurs. The stress level at this point is called tensile strength at break or ultimate tensile strength. The test method used for determining tensile properties, ASTM D 638, defines tensile strength as the greater of the stress at yield or the stress at rupture.

Stress-Strain Curves

Typically, tensile property data are presented by tabulating specific data, such as tensile strength, tensile modulus, and elongation. While these data are generally adequate for most purposes, the actual stress-strain curve provides additional information about a material’s response to load that design engineers may find useful when they estimate the viability of a part design.

The following figures present the stress-strain curves for several Radel and Acudel resins. The test on unfilled resins was terminated at yield, while the tests on glass-reinforced resins were run until rupture.

Figure 7.

Typical Stress-Strain Curve

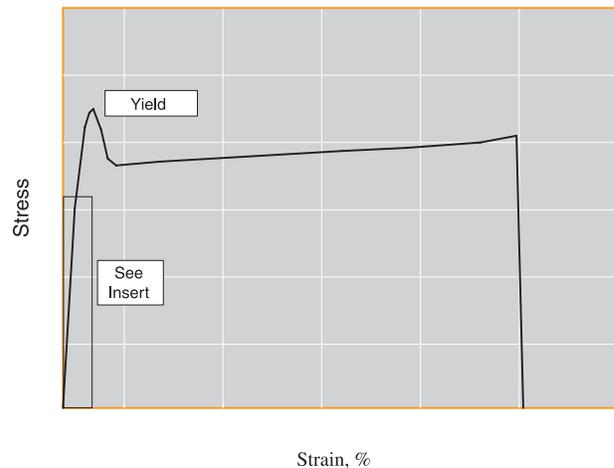
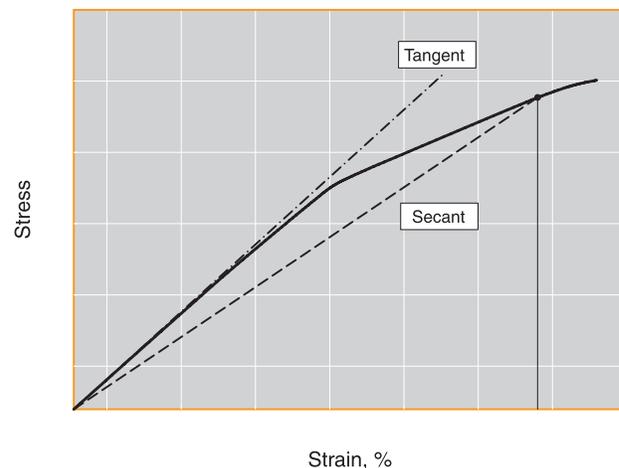


Figure 8.

Stress-Strain Curve Insert, Secant vs. Tangent Modulus



The curve for Radel A-300A is shown in Figure 9, for Radel R-5000 in Figure 10, for Acudel 22000 in Figure 11, for Acudel 25000 in Figure 12, for Radel AG-320 in Figure 13, and for Radel AG-330 in Figure 14.

Figure 9.

Radel A-300A Stress-Strain Curve to Yield

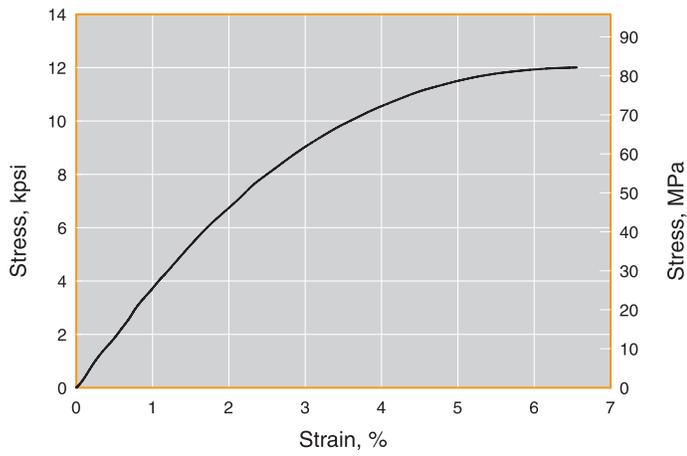


Figure 12.

Acudel 25000 Stress-Strain Curve to Yield

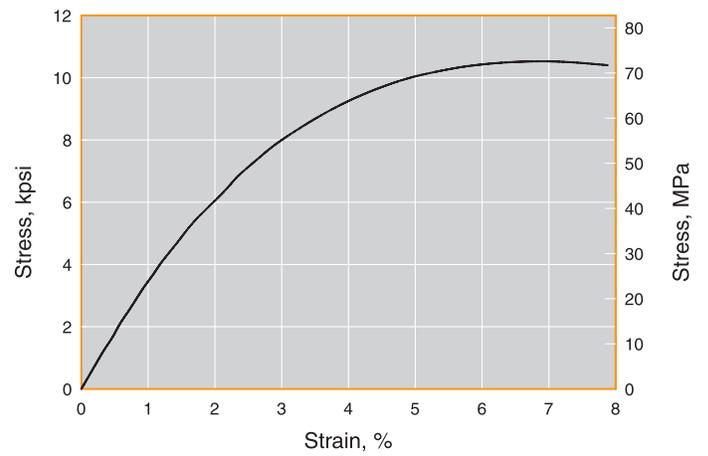


Figure 10.

Radel R-5000 Stress-Strain Curve to Yield

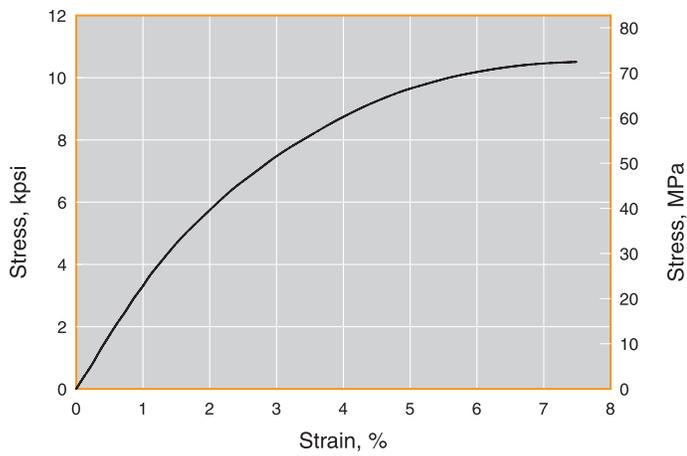


Figure 13.

Radel AG-320 Stress-Strain Curve to Break

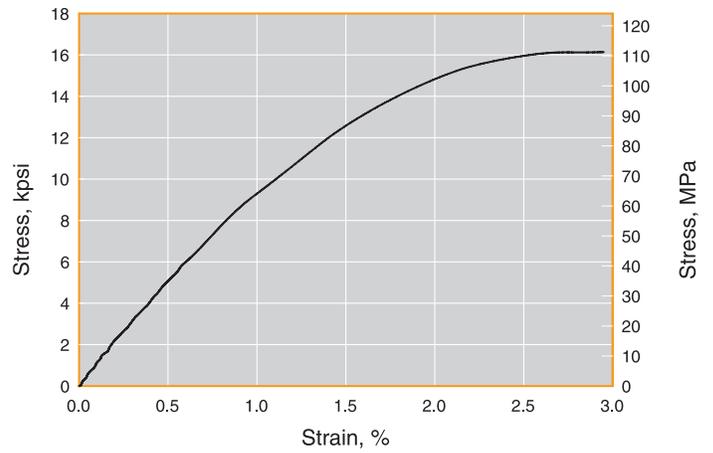


Figure 11.

Acudel 22000 Stress-Strain Curve to Yield

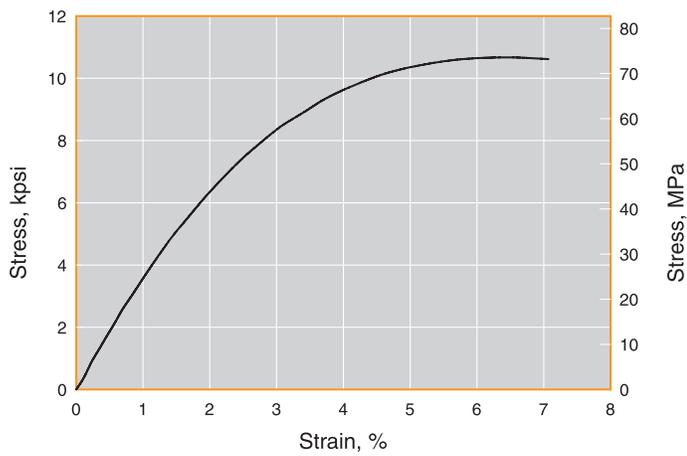


Figure 14.

Radel AG-330 Stress-Strain Curve to Break

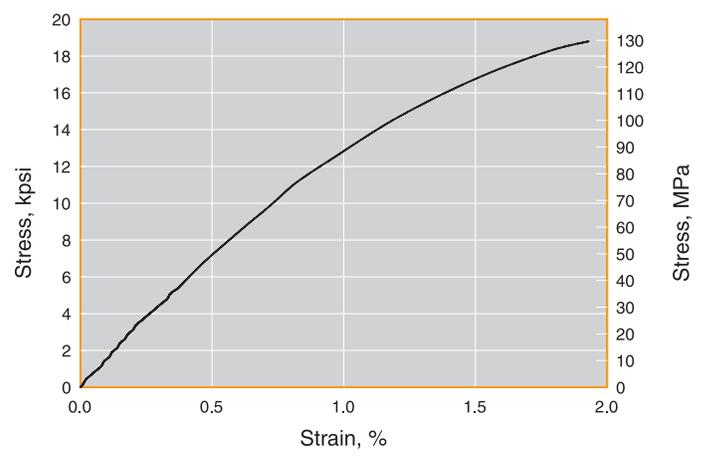


Table 10 shows that Radel A polyethersulfone has a tensile strength about 20% higher than either Udel polysulfone or Radel R polyphenylsulfone. Radel R polyphenylsulfone has greater elongation at both yield and break and a lower modulus, indicating greater ductility. This higher ductility results in greater toughness and lower sensitivity to stress concentrations.

Table 10.

Tensile Properties of Neat Resins (ASTM D638)

Grade	Strength, kpsi (MPa)	Modulus, kpsi (GPa)	Elongation at Yield, %	Elongation at Break, %
Udel	10.2 (70)	360 (2.48)	5 - 6	50 - 100
Radel A	12.0 (83)	385 (2.65)	6.5	25 - 75
Radel R	10.1 (70)	340 (2.34)	7.2	60 - 120
Acudel 22000	11.2 (77)	390 (2.69)	6.7	25 - 75
Acudel 25000	10.1 (70)	340 (2.34)	7.2	50 - 100

Figure 15 shows the room temperature tensile strength of glass-reinforced Radel A polyethersulfone. As expected, adding glass fiber reinforcement causes the tensile strength to increase.

As shown in Figure 16, the tensile modulus of Radel A polyethersulfone increases with glass content.

Flexural Properties

The flexural properties were determined in accordance with ASTM D 790 Method I using the three-point loading method shown in Figure 17. In this method, the 5.0 x 0.5 x 0.125 inch (127 x 13 x 3.2 mm) test specimen is supported on two points, while the load is applied to the center. The specimen is deflected until rupture occurs or the fiber strain reaches five percent.

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

Figure 15.

Tensile Strength of Glass-Filled Radel A

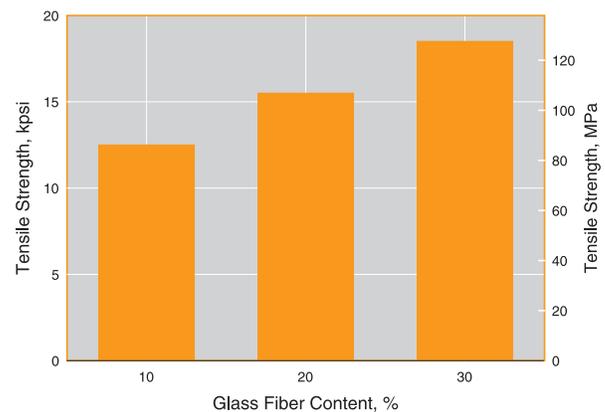


Figure 16.

Tensile Modulus of Glass-Filled Radel A

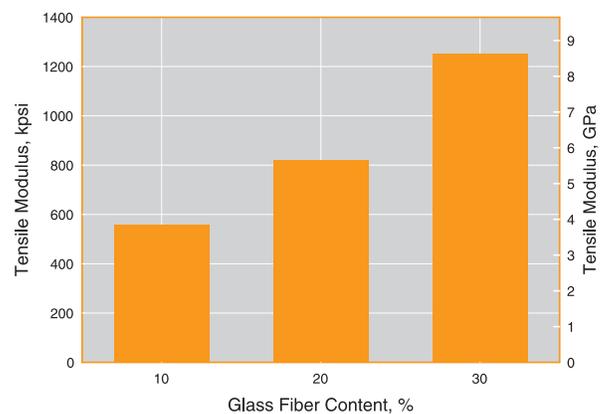
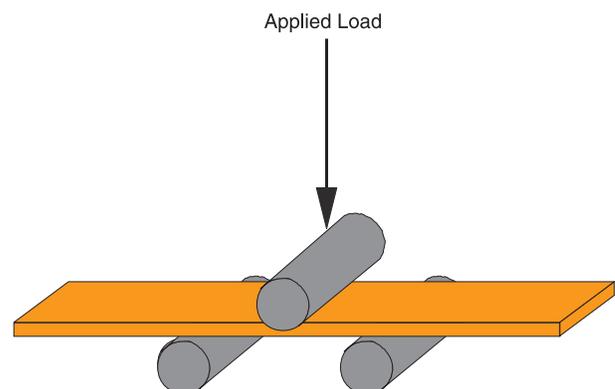


Figure 17.

Flexural Test Apparatus



As shown in Table 11, Radel A resin has the greatest flexural strength and modulus. The flexibility of Radel R resin is indicated by the lower flexural modulus.

Table 11.

Flexural Properties of Neat Resins

Resin Grade	Strength, kpsi (MPa)	Modulus, kpsi (GPa)
Udel	15.4 (106)	390 (2.69)
Radel A	16.1 (111)	420 (2.90)
Radel R	15.2 (105)	350 (2.41)
Acudel 22000	15.7 (108)	400 (2.76)
Acudel 25000	15.3 (105)	370 (2.55)

Adding glass fibers improves the flexural strength of Radel A resins, as shown in Figure 18.

Figure 19 shows that the glass-filled grades have much higher moduli than the neat materials, suggesting that glass-filled materials should be used in applications requiring higher stiffness and/or lower creep.

Compressive Properties

Compressive strength and modulus were measured in accordance with ASTM D 695. In this test, the test specimen is placed between parallel plates. The distance between the plates is reduced while the load required to push the plates together and the plate-to-plate distance is monitored. The maximum stress endured by the specimen (this will usually be the load at rupture) is the compressive strength, and the slope of the stress/strain curve is the compressive modulus.

The compressive strengths of Radel A polyethersulfone, Radel R polyphenylsulfone, and Udel polysulfone, as shown in Table 12, are similar. The compressive modulus of Radel A polyethersulfone is very close to that of Udel polysulfone. Glass fiber substantially increases the compressive strength as shown in Figure 20. The compressive modulus is similarly increased, as seen in Figure 21.

Shear Properties

Table 12.

Compressive Properties of Neat Resins

Property	Udel	Radel A	Radel R
Strength, kpsi (MPa)	13.9 (96)	14.5 (100)	14.3 (99)
Modulus, kpsi (GPa)	374 (2.6)	388 (2.7)	

Shear strength is determined in accordance with ASTM test method D 732. In this test, a plaque is placed on a plate with a hole below the specimen. A punch with a diameter slightly

Figure 18.

Flexural Strength of Glass-Filled Radel A

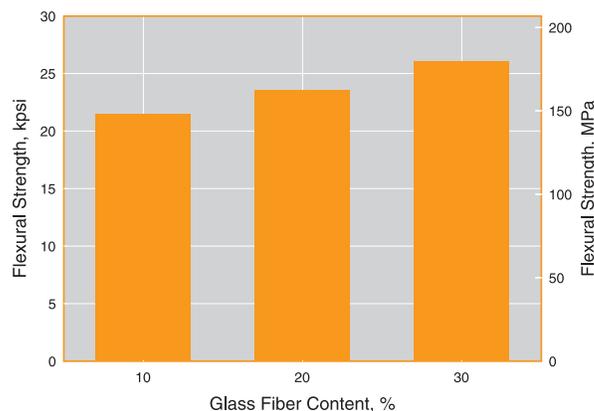


Figure 19.

Flexural Modulus of Glass-Filled Radel A

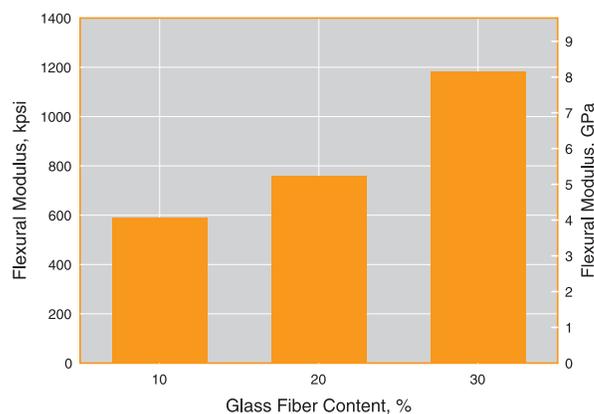
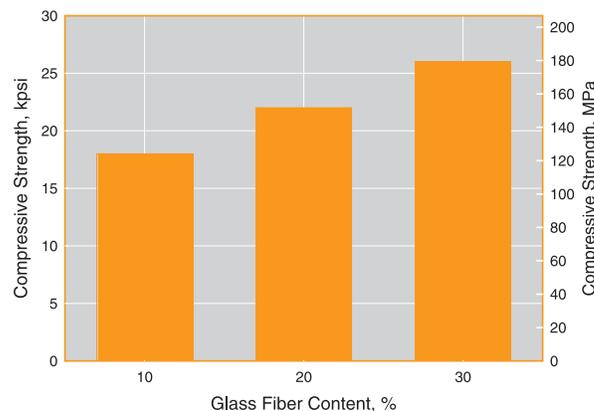


Figure 20.

Compressive Strength of Glass-Filled Radel A



smaller than the hole is pushed through the material, punching out a circular disc. The maximum stress is reported as the shear strength.

The shear strengths of the neat sulfone resins are shown in Table 13. Adding glass fiber reinforcement yields higher shear strengths, as shown in Figure 22.

Impact Properties

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

Table 13.

Shear Strength of Neat Resins

	Shear Strength	
	kpsi	MPa
Udel polysulfone	9.0	62
Radel A polyethersulfone	8.3	57
Radel R polyphenylsulfone	8.8	61
Acudel 22000 modified polyphenylsulfone	8.4	58
Acudel 25000 modified polyphenylsulfone	8.3	57

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

Notched Izod

The notched Izod test (ASTM D 256) is one of the most widely employed methods for comparing polymeric materials. In this test, a test specimen is prepared by machining in a notch with a radius of 0.010 in. (0.25 mm), a depth of 0.10 in. (2.5 mm) and an angle of 45°. The notched specimen is then struck by a swinging pendulum, as illustrated in Figure 23. After the impact the pendulum continues to swing, but with less energy due to the collision. The amount of energy lost is reported as the Izod impact strength in units of foot-pounds per inch or Joules per meter of beam thickness.

As shown in Figure 24, Radel R polyphenylsulfone exhibits exceptional impact resistance by the notched Izod method. While Udel polysulfone and Radel A polyethersulfone are

Figure 21.

Compressive Modulus of Glass-Filled Radel A

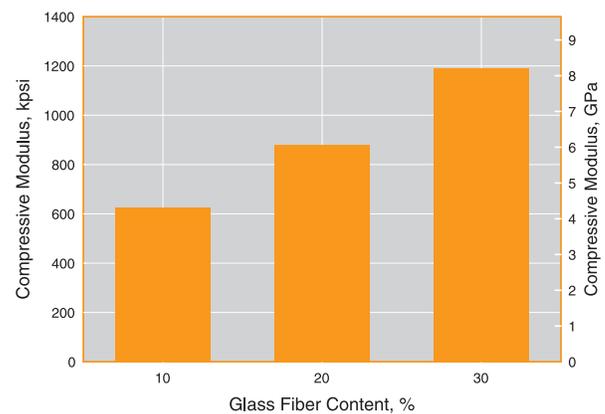


Figure 22.

Shear Strength of Glass-Filled Radel A

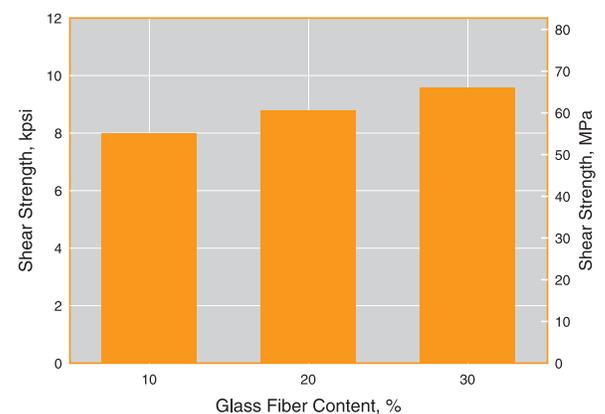
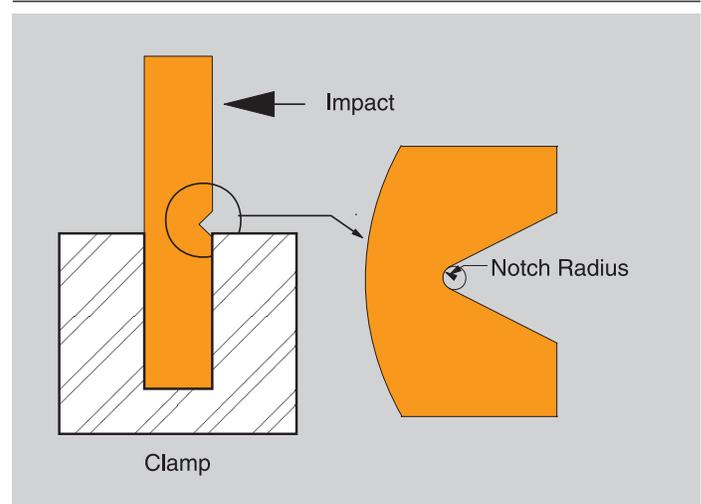


Figure 23.

Izod Impact Test Apparatus



generally considered to have good impact resistance, the impact resistance of Radel R polyphenylsulfone is an order of magnitude higher.

Failure of a material under impact conditions requires that a crack form, then propagate through the specimen. In the notched Izod test, the notch acts like a crack and the test is primarily measuring crack propagation resistance. When the test is run without a notch, a crack must first be formed, then propagate. Sulfone resins are extremely resistant to crack formation, as evidenced by the fact that none of the neat resins break in the un-notched test.

Notch Sensitivity

Another method of evaluating notch sensitivity is to measure notched Izod using varying notch radii. Materials that are very notch sensitive will show a strong negative response to sharper notches, i.e., smaller notch radii.

As shown in Figure 25, Radel R polyphenylsulfone has very good resistance to property loss due to sharp notches. In fact, it is similar to polycarbonate in this respect. Radel A polyether-sulfone is sensitive to sharp notches but shows excellent toughness when the notch radius is greater than 20 mils (0.5 mm). The Acudel modified polyphenylsulfones have good toughness when the notch radius is 15 mils (0.4 mm) or larger.

Tensile Impact

Tensile impact is similar to the Izod impact test in that a pendulum is used, but the specimen is subjected to a high speed tensile loading rather than the flexural loading of the Izod test. Also, in this test the specimens are not notched. The method described in ASTM D 1822 was followed. The results give a better indication of practical impact resistance than the Izod test.

Figure 26 shows that all three types of sulfone polymers are quite ductile by this test. The Acudel modified polyphenyl-sulfones are also quite ductile.

Figure 24.

Notched Izod of Neat Resins

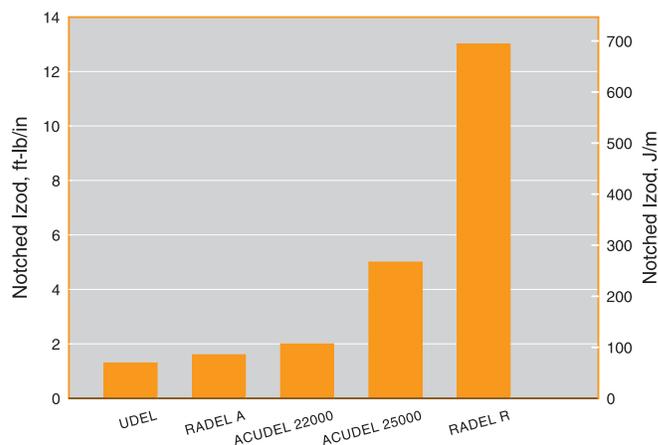


Figure 25.

Notched Izod Impact as a Function of Notch Radius

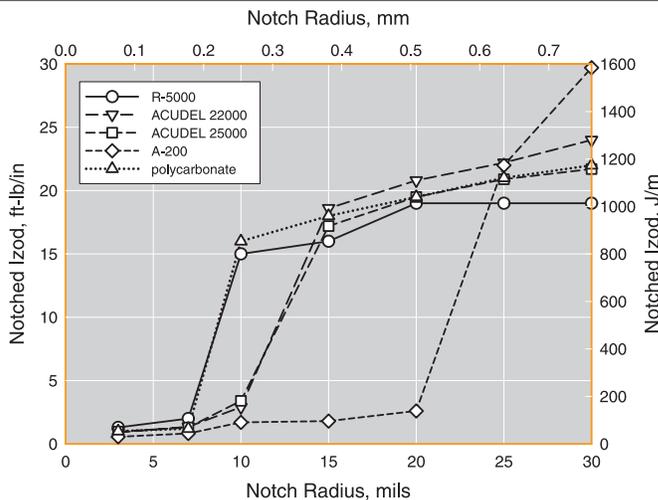
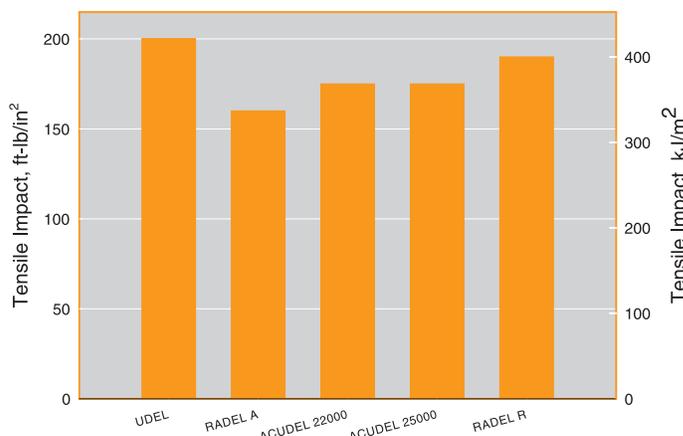


Figure 26.

Tensile Impact Strength of Neat Resins



Poisson's Ratio

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

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

The value of Poisson's ratio was measured according to ASTM test method E 132. The results are shown in Table 14.

Table 14.

Poisson's Ratios

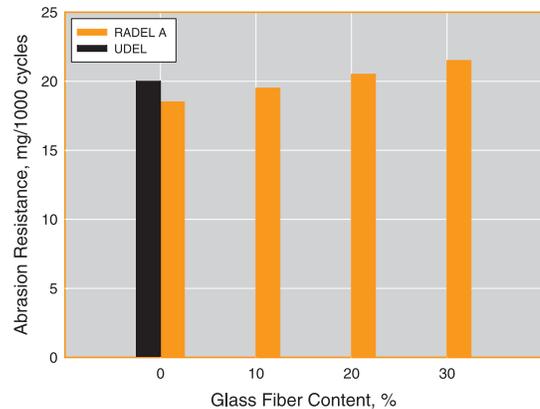
Material	ν
Udel	0.37
Radel A	0.41
Radel AG-230/330	0.42
Radel R	0.43
Acudel 22000	0.41
Acudel 25000	0.42

Wear resistance

To evaluate the relative resistance to abrasive wear, the Taber Abrasion Test was used with a CS-17 wheel and a 1,000 gram load. As shown in Figure 27, the abrasion resistance of Radel A is quite similar to that of Udel polysulfone, and the inclusion of glass fiber reinforcement has little effect.

Figure 27.

Abrasion Resistance



Long-Term Properties

The mechanical properties of materials are affected by strain rate and load application mode. These effects may be more important with polymeric materials than with metals, but the consequences are similar. The designer must be aware that constant stress will result in more deformation than expected from the short-term modulus. He must also be cognizant of the effect of cyclic loading. This section presents the available information on creep and fatigue.

Creep

When a bar made of a polymeric material is continuously exposed to a constant stress, its dimensions will change in response to the stress. This phenomenon is commonly called “creep”. In the simplest case, the tensile mode, the test bar will elongate as a function of time under stress. The term “strain” is used for the amount of length increase or elongation divided by the initial length.

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

The creep information presented in this manual was developed using the tensile mode.

Apparent or Creep Modulus

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

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

Figure 28 presents the modulus data obtained when Radel A polyethersulfone was tested at 3,000 psi (20.7 MPa) stress as a function of time. The amount of dimensional change or creep, and thus the apparent modulus, are also functions of temperature. As the test temperature is increased, the modulus is decreased.

Figure 29 shows that the addition of glass fiber reinforcement to Radel A polyethersulfone greatly increases the apparent modulus. The higher apparent modulus predicts lower deformation at equivalent stress.

Figure 28.

Apparent (Creep) Modulus Radel A-200A

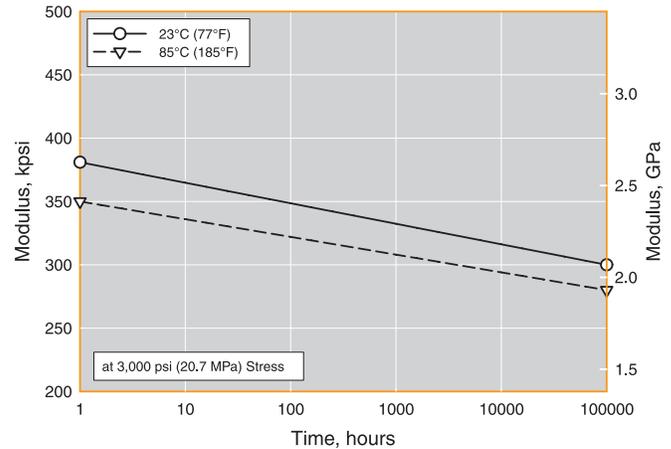


Figure 29.

Apparent (Creep) Modulus Radel AG-230

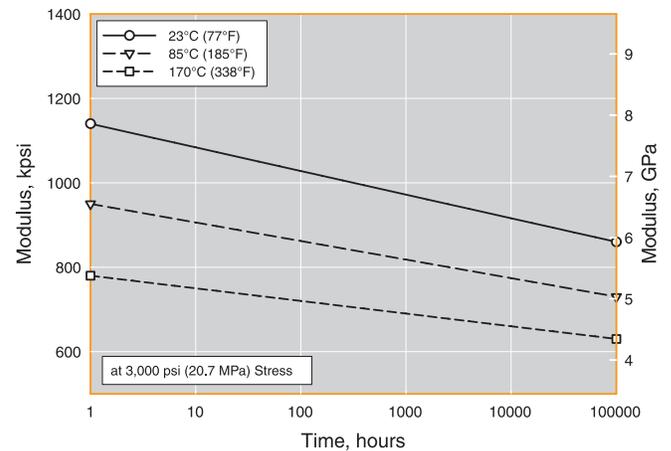
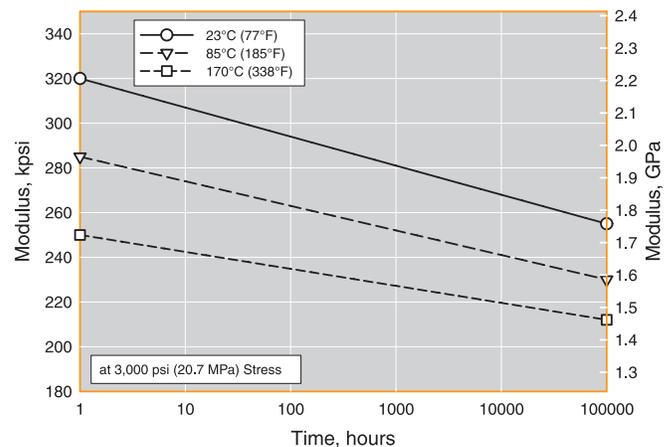


Figure 30.

Apparent (Creep) Modulus Radel R-5000



The apparent modulus data for Radel R polyphenylsulfone are shown in Figure 30. Radel R has surprisingly good creep resistance, especially at elevated temperature.

Isochronous Stress-Strain Curves

Another way of presenting creep data is the isochronous stress/strain diagram. To prepare an isochronous diagram, the strains obtained after a specified time interval are plotted. 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 strain obtained. (Please note that the figures show strain expressed in percent; actual strain is the plotted value divided by 100.)

Figure 31 shows the stress/strain curves for Radel A polyethersulfone at 100 hours of constantly applied load. The apparent modulus at any point can be calculated by dividing the stress by the indicated strain.

Figures 32 and 33 present the isochronous curves for glass-reinforced Radel A resin and for neat Radel R resin respectively.

Figure 31.

Isochronous Stress-Strain Curve Radel A-200A

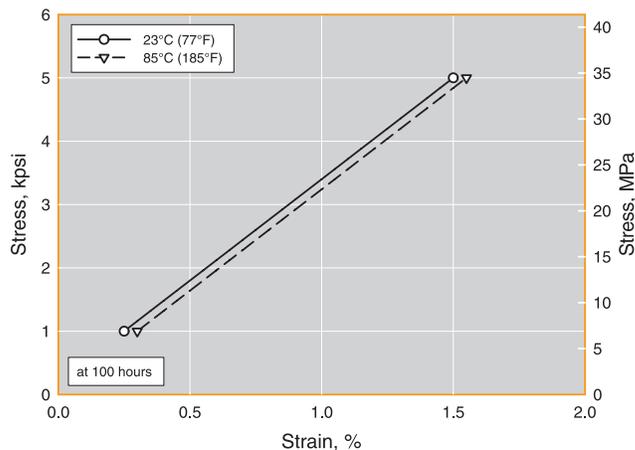


Figure 32.

Isochronous Stress-Strain Curve Radel AG-230

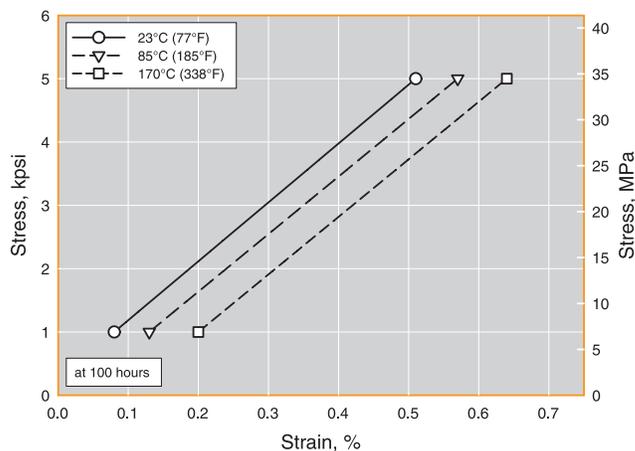
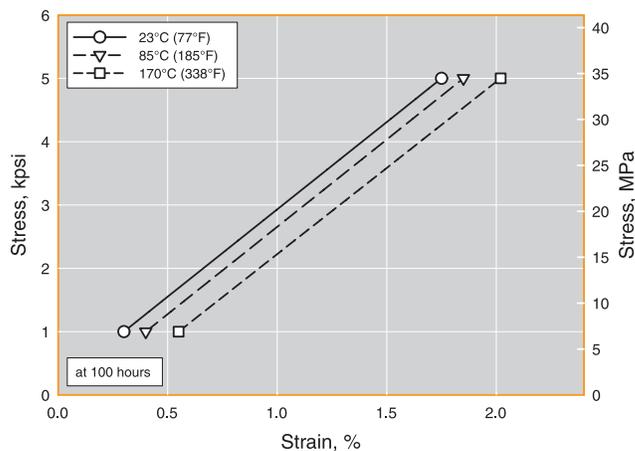


Figure 33.

Isochronous Stress-Strain Curve Radel R-5000



Fatigue

When a material is stressed cyclically, failure or rupture will occur at stress levels much lower than the short-term ultimate strength. A good example of an application involving cyclical stress is a gear. As the driving gear rotates and causes the driven gear to rotate, each tooth is subject to stress and in turn, followed by a period of time at low or zero stress until that tooth is engaged again. Many applications have a fatigue aspect, where the cyclic loading is not as evident. Other examples are bushings guiding a rotating shaft, parts subject to vibration, or any rotating part in a pump or compressor.

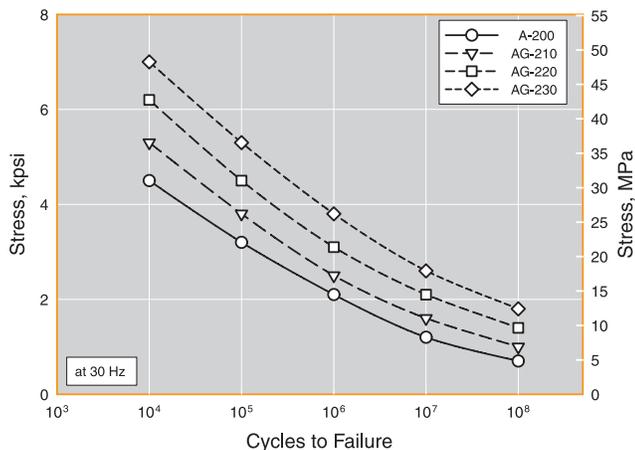
This phenomenon is well known in metals, and metallurgists have defined the term “Fatigue Endurance Limit” to represent the maximum cyclical stress that a material can be subjected to and still have infinite life. Normally, this stress level corresponds to the highest stress level that does not cause failure in 10 million (10^7) load cycles. While the term “Fatigue Endurance Limit” is sometimes used in design discussions involving plastic materials, the response of plastics to cyclical stress is more complex than the response of metals, and an endurance limit is not strictly defined.

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 endurance data were generated using test method ASTM D 671. This method uses a cantilever beam configuration with a constant amplitude of force. Specifically, the test specimen was the type “A”, the frequency was 30 Hz, and the machine was the Sontag Universal Testing Machine, Model SF-01-U.

The flexural fatigue endurance curves for both neat and glass-reinforced grades of Radel A polyethersulfone are shown in Figure 34. While these tests were run on the Radel A-200A series resins, the A-300A series resins are expected to give similar results.

Figure 34.

Flexural Fatigue Endurance Radel A



Thermal Properties

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

Glass Transition Temperature

Typically, when a polymer is heated it will become progressively less stiff until it reaches a rubbery state. The temperature at which the material goes from a glassy to a rubbery state is defined as the glass transition temperature (T_g). This temperature is important because several fundamental changes occur at this temperature. These include changes in polymer free volume, refractive index, enthalpy, and specific heat. The following table lists the glass transition temperatures of Udel polysulfone, Radel A polyethersulfone, and Radel R polyphenylsulfone. The glass transition temperatures of Radel resins are 63°F (35°C) higher than that of Udel polysulfone. This difference translates into extended thermal capability.

Table 15.

Glass Transition Temperatures

Resin	Glass Transition Temperature*	
	°F	°C
Udel	365	185
Radel A	428	220
Radel R	428	220

*Glass transition temperature is defined as the onset of change in heat capacity as measured by differential scanning calorimetry. Typically, the measured value is rounded to the nearest 5°C.

Mechanical Property Changes

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

Classification of Thermoplastic Resins

Thermoplastics are often divided into two classes: amorphous and semi-crystalline. Figure 35 shows in a generalized manner the difference in temperature response between these resin types. The modulus of amorphous resins generally decreases slowly with increasing temperature until the glass transition temperature (T_g) is reached. Amorphous resins are not normally used at ambient temperatures higher than their glass transition

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

Temperature Effects on Modulus

Udel polysulfone, Radel A polyethersulfone, and Radel R polyphenylsulfone are all amorphous resins. The effects of temperature upon their flexural moduli can be seen in Figure 36.

Figure 35.

Typical Change in Modulus with Temperature

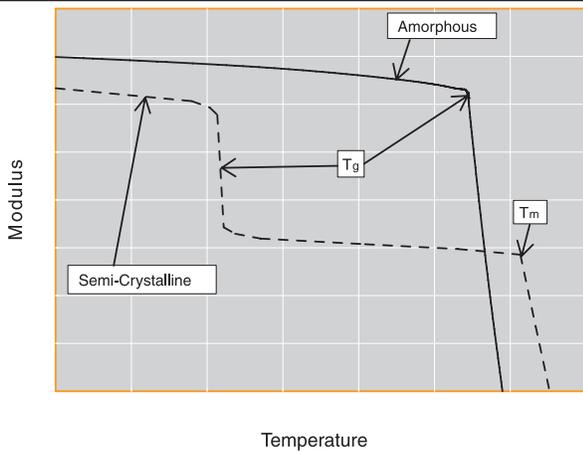


Figure 36.

Flexural Modulus vs. Temperature - Neat Resins

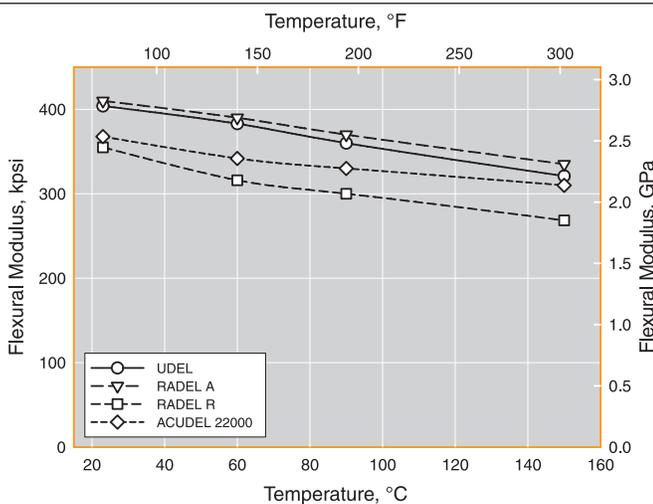


Figure 37.

Flexural Modulus vs. Temperature - GF Radel A Resins

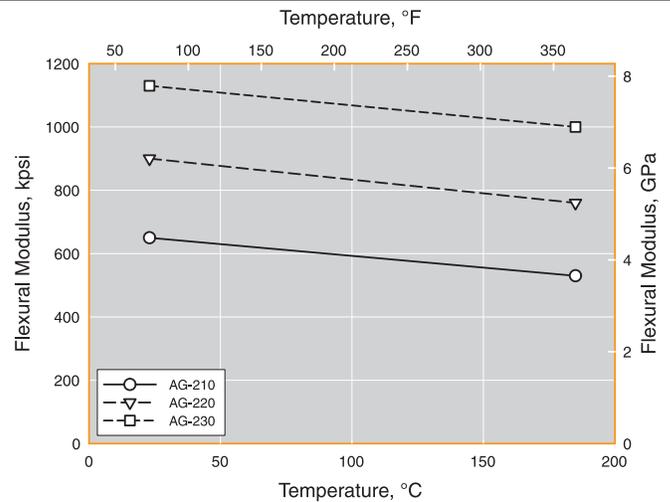


Figure 38.

Tensile Strength vs. Temperature - Neat Resins

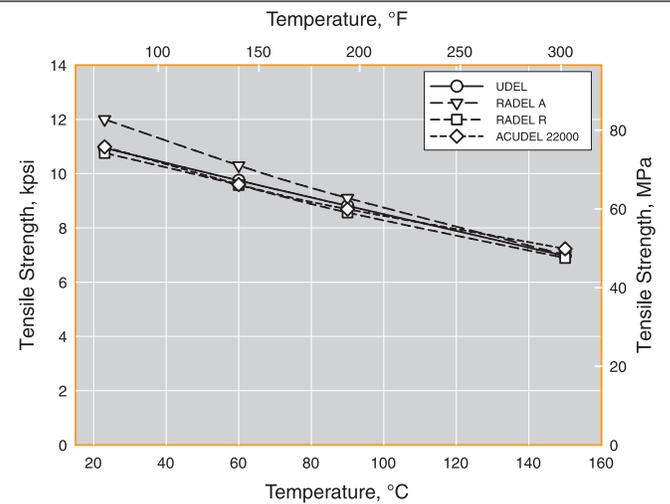
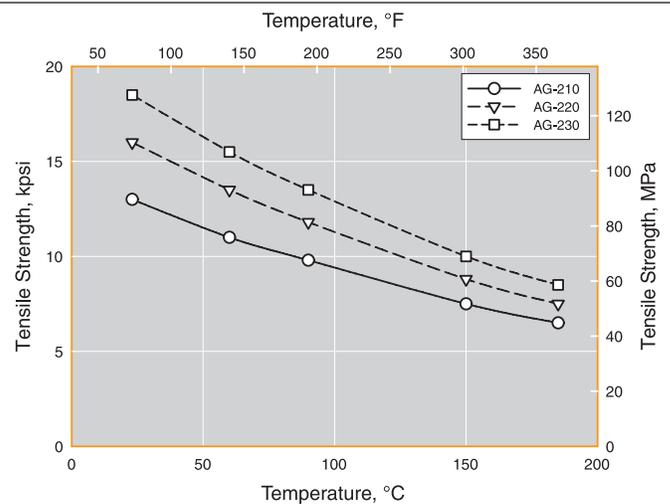


Figure 39.

Tensile Strength vs. Temperature - GF Radel A Resins



Of the three polysulfones, Radel A polyethersulfone has the highest initial modulus and also the highest modulus at elevated temperature. The effect of adding glass fiber to Radel A on the retention of flexural modulus is shown in Figure 37.

Temperature Effects on Tensile Strength

As a material loses stiffness due to rising ambient temperature, it also loses strength. Figure 38 shows the effect of temperature on the tensile strength of the neat polysulfones and Figure 39 shows this information for glass-filled Radel A.

Deflection Temperature under Load

One measure of short-term thermal capability is the deflection temperature under flexural load test described in ASTM test method D 648. In this test, a 5-inch (127 mm)-long bar is placed on supports 4 inches (102 mm) apart. The bar is loaded to a fiber stress of either 66 psi (0.45 MPa) or 264 psi (1.8 MPa). The vertical deformation is monitored while the temperature is increased at a specified rate. When the vertical deformation reaches the specified end point - 0.010 inch (0.25 mm), the temperature is noted and reported as the Deflection Temperature (also commonly referred as the heat deflection temperature). This test actually measures the temperature at which the flexural modulus is approximately 35,000 psi (240 MPa) when the test stress is 66 psi (0.45 MPa), or 140,000 psi (965 MPa) when the stress is 264 psi (1.8 MPa).

Testing Variables

Certain test parameters can have a significant influence upon the results, and the designer should be aware of these effects. These test parameters are specimen thickness and thermal history. The test specimens for this test are injection molded rectangular cross section bars, either 0.125-inch (3.2 mm) or 0.25-inch (6.4 mm) thick. The test may be performed as-molded or after heat treating or annealing. Annealing conditions are one hour at 338°F (170°C) for Udel polysulfone or 392°F (200°C) for Radel A or Radel R resins.

Molding conditions will affect molded-in stress levels, and therefore the apparent deflection temperature of the as-molded bars. Annealing relieves molded-in stress and generally causes the measured deflection temperature to increase. The difference in deflection temperature between as-molded and annealed test specimens is a function of the amount of molded-in stress, which is usually higher when the thinner bar is used. Because the measured deflection temperature varies with the amount of molded-in stress, annealing is often used to provide a more reproducible value. The annealed value more accurately reflects the thermal capability of a resin than the as-molded value.

Annealing and specimen thickness effects are seen to a greater extent with neat resins. The results obtained with glass-filled resins are less affected by these variables.

Deflection Temperature Comparisons

Both Radel A polyethersulfone and Radel R polyphenylsulfone have improved thermal capability compared to Udel polysulfone.

Table 16 contains the deflection temperature data for neat Radel A and R, and Acudel resins, and for glass-filled Radel A at both stress levels, for 0.125 in. (3.2 mm) bar thickness annealed.

Figure 40 compares the deflection temperatures of neat Udel polysulfone, Radel A polyethersulfone, Radel R polyphenylsulfone, and Acudel modified polyphenylsulfones. Both Radel resins have deflection temperatures that are about 55°F (30°C) higher than that of polysulfone. The deflection temperature of Radel R polyphenylsulfone is about 5°F (3°C) higher than that of Radel A polyethersulfone.

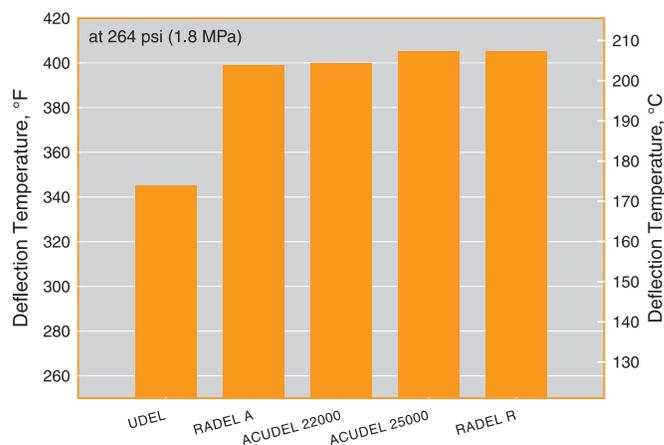
Table 16.

Deflection Temperatures of Radel Resins

Radel Grade	Stress, psi (MPa)			
	66 (0.45)		264 (1.82)	
	°F	°C	°F	°C
A-100, A-200A, A-300A	417	214	399	204
AG-320, AG-220	424	218	417	214
AG-330, AG-230	428	220	420	216
AG-340			405	207
AG-360			415	213
R-5000	417	214	405	207
RG-5030			410	210
Acudel Grade	°F	°C	°F	°C
22000			387	197
25000			405	207

Figure 40.

Deflection Temperature of Neat Resins



Thermal Expansion Coefficient

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

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

Where L_0 is the original length, and ΔL and ΔT are the change in length and temperature respectively. The coefficient of linear thermal expansion (α) was measured in accordance with ASTM D 696.

The coefficients of linear thermal expansion for Radel A polyethersulfone, Radel R polyphenylsulfone, and some common metals are shown in Table 18. Thermal stresses will be induced in assemblies when materials with different expansion coefficients are joined. The values shown in Table 18 should allow the design engineer to calculate the magnitude of any thermal stresses arising from thermal expansion.

Table 18

Coefficient of Linear Thermal Expansion*

Material	$\mu\text{in/in}^\circ\text{F}$	$\mu\text{m/m}^\circ\text{C}$
Radel A	27	49
Radel AG-210/310	20	36
Radel AG-220/320	17	31
Radel AG-230/330	17	31
Radel AG-340	23	41
Radel AG-360	11	20
Radel R	31	56
Radel RG-5030	10	18
Acudel 22000	35	63
Acudel 25000	33	59
Zinc die-casting alloy	15	27
Aluminum die-casting alloy	14	25
Stainless steel	10	18
Carbon steel	8	14

*Measured in the flow direction

Thermal Conductivity

Polymers in general are poor conductors of heat. For many applications, this is desirable because the polymer provides a measure of thermal isolation. Table 19 shows the relative thermal conductivities, as measured by ASTM test method E 1530, of Radel and Udel engineering resins as well as some other common materials.

Table 19.

Thermal Conductivity

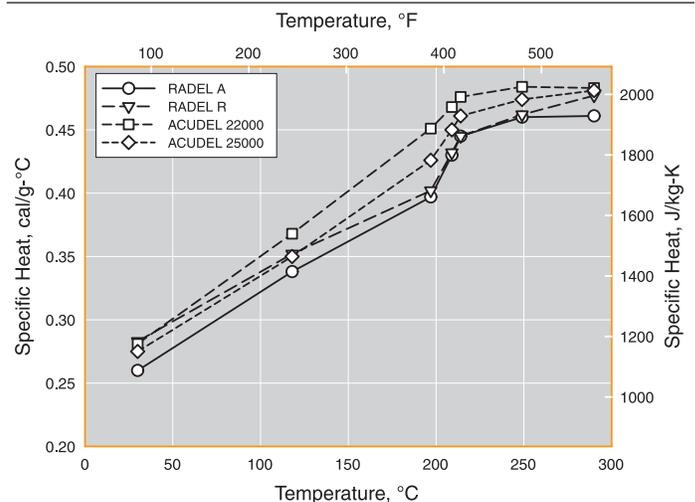
Material	Thermal Conductivity,	
	Btu-in/hrft ² F	(W/mK)
Udel	1.80	0.26
Radel A	1.66	0.24
Radel AG-230/330	2.08	0.30
Radel R	2.08	0.30
Acudel 22000	1.66	0.24
Acudel 25000	1.66	0.24
Stainless steel	140-250	20-36
Carbon	36-60	5-9
Wood (Particle Board)	12	1.7
Rubber	1.00	0.14

Specific Heat

Specific heat is defined as the amount of heat required to change the temperature of a unit mass one degree. This property was measured using ASTM test method E-1269. Figure 41 shows that the specific heat of Radel A and R resins is a function of temperature, and that the specific heat changes significantly at the glass transition temperature. The specific heat of the Acudel modified polyphenylsulfones also changes with temperature but because these are blends the change is more gradual.

Figure 41.

Specific Heat



Combustion Properties*

UL 94

Radel A neat resins are rated 94 V-0 at a specimen thickness of 0.062 inch (1.6 mm). The glass-reinforced grades are rated 94 V-0 at a specimen thickness of 0.031 inch (0.8 mm). Radel R grades R-5000, R-5100, and R-5500 are all rated 94 V-0 at a specimen thickness of 0.031 inch (0.8 mm).

Oxygen Index

The oxygen index is defined by ASTM D 2863 as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will support flaming combustion of a material initially at room temperature under the conditions of this method.

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

Radel A polyethersulfone, Radel R polyphenylsulfone, and the Acudel modified polyphenylsulfones are inherently flame resistant as shown by the oxygen indices in Table 20.

Table 20.

Oxygen Indices of Radel Resins

Grade	Oxygen Index
A-100	39
10% GR resins	40
20% GR resins	40
30% GR resins	40
R-5000	44
Acudel 22000	38
Acudel 25000	38

Self-Ignition Temperature

The self-ignition temperature of a material is defined as the lowest ambient air temperature at which, in the absence of an ignition source, the self-heating properties of the specimen lead to ignition or ignition occurs of itself, as indicated by an explosion, flame, or sustained glow. This property was measured using ASTM D 1929.

The self-ignition temperature of Radel A polyethersulfone is 936°F (502°C).

Smoke Density

When a material burns, smoke is generated. The quantity and density of the generated smoke is important in many applications. ASTM test method E 662 provides a standard technique for evaluating relative smoke density. This test was originally developed by the National Bureau of Standards (NBS), and is often referred to as the NBS Smoke Density test.

The data presented in Table 21 were generated using the flaming condition. A six-tube burner was used to apply a row of flamelets across the lower edge of the specimen. A photometric system aimed vertically is used to measure light transmittance as the smoke accumulates. The specific optical density (D_s) is calculated from the light transmittance. The maximum optical density is called D_m .

These data show that both Radel A polyethersulfone and Radel R polyphenylsulfone are extremely low smoke generators.

Thermal Stability

Thermogravimetric Analysis

Table 21.

Smoke Density

Measurement	Radel A	Radel R
D_s @ 1.5 minutes	0	0.3
D_s @ 4.0 minutes	1.0	0.4
D_m	5-15	35

Specimen thickness - 0.063 in. (1.6 mm)

One method for evaluating the thermal stability of a material is thermogravimetric analysis. In this test, a small sample of the test material is heated while its weight is constantly monitored. The test is usually run with both an inert nitrogen atmosphere and in air. The difference in the results indicates the importance of oxygen in causing degradation.

Figures 42 and 43 show the thermogravimetric analysis results obtained using a heating rate of 18°F (10°C) per minute for Udel polysulfone, Radel A polyethersulfone, and Radel R polyphenylsulfone in nitrogen and in air respectively. The results show that all five resins have exceptional thermal stability. There is no significant weight loss below 427°C (800°F) which is over 28°C (50°F) higher than the maximum recommended processing temperature. Table 22 gives the temperature at which the listed weight losses were recorded. These data clearly show that Radel R polyphenylsulfone has the best thermal stability of the resins tested.

Figure 42.

Thermogravimetric Analysis in Nitrogen

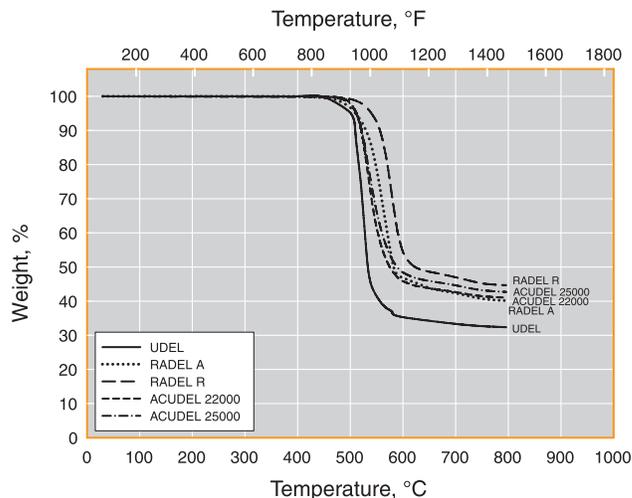


Figure 43.

Thermogravimetric Analysis in Air

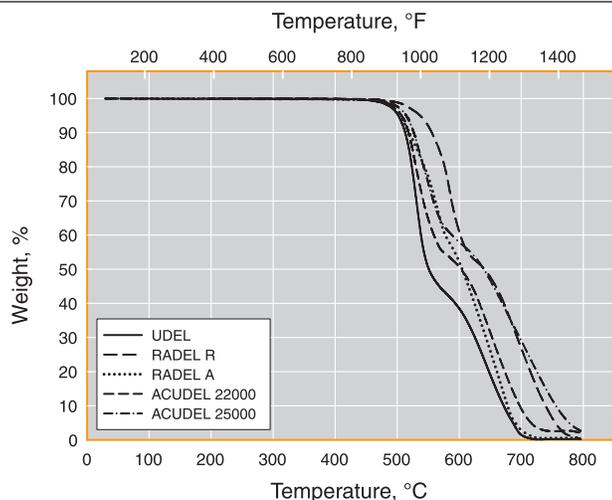


Table 22.

Thermogravimetric Analysis Details

Temperature, °C (°F) in Nitrogen

Material	Weight Loss, %			
	1	2	5	10
Udel	480 (896)	489 (912)	500 (932)	509 (948)
Radel A	472 (882)	487 (909)	511 (952)	530 (986)
Radel R	504 (939)	519 (966)	541 (1006)	556 (1033)
Acudel 22000	491 (916)	498 (928)	512 (954)	521 (970)
Acudel 25000	487 (909)	498 (928)	512 (954)	522 (972)

Temperature, °C (°F) in Air

Udel	470 (878)	487 (909)	502 (936)	513 (955)
Radel A	472 (882)	487 (909)	506 (943)	525 (977)
Radel R	496 (925)	514 (957)	537 (999)	558 (1036)
Acudel 22000	476 (888)	491 (916)	508 (946)	519 (966)
Acudel 25000	481 (898)	497 (927)	515 (959)	527 (981)

Thermal Aging

Thermo-oxidative stability limits the acceptable long-term use temperature of polymers. To evaluate the long-term effects of elevated ambient temperatures on the properties of Radel A polyethersulfone, test specimens were oven aged at several different temperatures. Bars were periodically removed and tested at room temperature for tensile strength. Figure 44 shows the results of this testing on neat Radel A. Data on polyetherimide (PEI) are included for comparison. Radel A polyethersulfone is more thermally stable than polyetherimide.

The evaluation of the thermal aging characteristics of Radel R resins is in progress. The results obtained so far are shown in Figure 45. It is evident that the greater thermal stability of Radel R polyphenylsulfone seen in TGA is also seen in these aging tests.

Figure 44.

Thermal Aging of Radel A PES and PEI

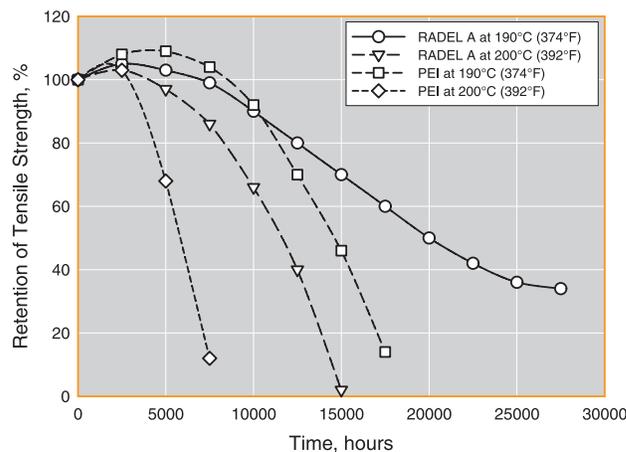
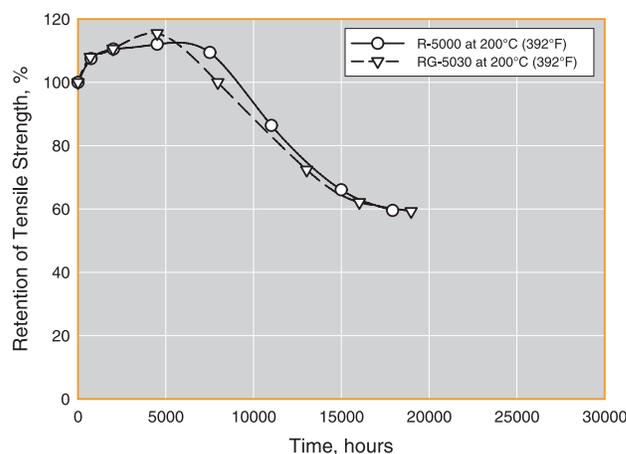


Figure 45.

Thermal Aging of Radel R Polyphenylsulfone



UL Thermal Index (RTI)

Thermal aging data similar to that appearing in the previous section are used to establish Relative Thermal Indices per Underwriters' Laboratories Standard 746B. This method determines the temperature to which a material can be exposed for 100,000 hours and still retain fifty percent of its original properties. The index temperature is frequently considered the maximum continuous use temperature. Table 23 gives the indices that have been assigned to Radel A by Underwriters' Laboratories. For the most current and complete information, please consult the Underwriters' Laboratories website at www.ul.com.

Table 23.

Relative Thermal Indices per UL 746B*

Radel Grades	Thickness, mm (in)	Electrical	Mechanical with impact	Mechanical without impact
A-100	0.75 (0.030)	180		
A-100 A-200A A-300A	1.5 (0.059) 3.0 (0.118)	180	180	180
AG-110 AG-210 AG-310	0.75 (0.030)	190		
AG-110 AG-210 AG-310	1.5 (0.059) 3.0 (0.118)	190	190	190
AG-120 AG-220 AG-320	0.75 (0.030)	190		
AG-120 AG-220 AG-320	1.5 (0.059) 3.0 (0.118)	190	190	190
AG-130 AG-230 AG-330	0.75 (0.030)	190		
AG-130 AG-230 AG-330	1.5 (0.059) 3.0 (0.118)	190	190	190

*Values are °C

Electrical Properties

Many applications for thermoplastic resins depend upon their ability to function as electrical insulators. Several tests have been developed to provide the designer with measures of how well a particular resin can perform that function.

Table 24.

Electrical Properties of Radel Resins

Grade	Dielectric Strength (D 149)	Volume Resistivity (D 257)	Dielectric Constant (D 150)			Dissipation Factor (D 150)		
			60 Hz	1 KHz	1 Mhz	60 Hz	1 KHz	1 Mhz
A-100, A-200A, A-300A	380 (15)	1.7×10^{15}	3.51	3.50	3.54	0.0017	0.0022	0.0056
AG-220, AG-320	440 (17)	$>10^{16}$	3.84	3.84	3.88	0.0015	0.0018	0.0081
AG-230, AG-330	440 (17)	$>10^{16}$	4.11	4.11	4.17	0.0019	0.0018	0.0094
AG-340	418 (16)	1.9×10^{16}			3.81			0.0103
R-5000, R-5100, R-5500, R-5800	380 (15)	9×10^{15}	3.44	3.45	3.45	0.0006		0.0076
Acudel 22000	470 (18)	$>9 \times 10^{15}$			3.40			0.0080
Acudel 25000	514 (21)	8×10^{15}			3.40			0.0090
Units (SI)	volts/mil (kV/mm)	ohm-cm						

Dielectric Strength

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

Volume Resistivity

Volume resistivity is defined as the resistance of a unit cube of material. The test is run by subjecting the material to 500 volts for 1 minute and measuring the current. The higher the volume resistivity, the more effective a material will be in electrically isolating components.

Dielectric Constant

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

Dissipation Factor

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

UL 746A Short-Term Properties

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

High-Voltage, Low-Current Dry Arc Resistance (D 495)

This test measures the time that an insulating material resists the formation of a conductive path due to localized thermal and chemical decomposition and erosion. The test is intended to approximate service conditions in alternating-current circuits operating at high voltage with currents generally limited to less than 0.1 ampere.

Comparative Tracking Index (CTI)

This test determines the voltage that causes a permanent electrically conductive carbon path when 50 drops of electrolyte is applied to the specimen at the rate of one drop every 30 seconds. This test is used as a measure of the susceptibility of an insulating material to tracking.

High-Voltage Arc-Tracking Rate (HVTR)

This test determines the susceptibility of an insulating material to track or form a visible carbonized conducting path over the surface when subjected to high-voltage, low-current arcing. The high-voltage arc-tracking rate is the rate in millimeters per minute at which a conducting path can be produced on the surface of the material under standardized test conditions.

Hot Wire Ignition (HWI)

This test determines the resistance of plastic materials to ignition from an electrically heated wire. Under certain operational or malfunctioning conditions, components become abnormally hot. When these overheated parts are in intimate contact with the insulating materials, the insulating materials may ignite. The intention of the test is to determine the relative resistance of insulating materials to ignition under such conditions.

High-Current Arc Ignition (HAI)

This test measures the relative resistance of insulating materials to ignition from arcing electrical sources. Under certain conditions, insulating materials may be in proximity to arcing. If the intensity and duration of the arcing are severe, the insulating material can ignite.

Table 25.

Electrical Properties of Radel resins per UL 746A

Performance Level Class (0 = best) shown in ()						
Radel Grade	Thickness, in (mm)	D 495, arcs	CTI, volts	HVTR, mm/min	HWI, sec	HAI, arcs
A-100, 200, 300	0.031 (0.8)			147 (3)	13 (4)	13 (4)
	0.062 (1.6)			99 (3)	25 (3)	11 (4)
	0.125 (3.2)	94 (6)	155 (4)	97 (3)	85 (1)	20 (3)
AG-210, AG-310	0.031 (0.8)				13 (4)	4 (4)
	0.062 (1.6)				25 (3)	4 (4)
	0.125 (3.2)	94 (6)	140 (4)	97 (4)	85 (1)	4 (4)
AG-220, AG-320	0.031 (0.8)				13 (4)	4 (4)
	0.062 (1.6)				25 (3)	4 (4)
	0.125 (3.2)	94 (6)	140 (4)	97 (4)	85 (1)	4 (4)
AG-230, AG-330	0.031 (0.8)				48 (2)	4 (4)
	0.062 (1.6)				77 (1)	4 (4)
	0.125 (3.2)	121 (6)	140 (4)	203 (4)	96 (1)	4 (4)
R-5000	0.031 (0.8)				>150 (0)	>150 (0)
	0.125 (3.2)	135 (5)	62 (5)	0 (0)		

Environmental Resistance

Hydrolytic Stability

Hydrolytic stability can be defined as resistance to hydrolysis, or attack by water. Therefore, hydrolytic stability is a specific instance of chemical resistance. Hydrolytic stability has special importance because water is ubiquitous and is very aggressive to many polymers. A quick test for hydrolytic stability is immersion in boiling water. As shown in Table 26, polysulfones have excellent resistance to hydrolysis. Of the polysulfones, Radel R polyphenylsulfone has exceptional performance.

Hydrolytic stability is very important in plumbing applications and a longer-term study of the effects of prolonged hot water exposure on Radel R-5000 polyphenylsulfone and the modified polyphenylsulfone Acudel 22000 was conducted. Mechanical properties of the two resins as molded were determined. Test specimens molded from these materials were then exposed to 140°F (60°C) and 194°F (90°C) water for periods up to 8,000 hours (333 days). After exposure, the mechanical properties of these specimens were tested. The percent retention of each property was calculated by dividing the final value by the value before exposure and multiplying by 100.

The results of this study are summarized in Table 27. The properties of both Radel R-5000 and Acudel 22000 were generally unaffected by the hot water exposure. The only property showing a significant decrease is elongation at break, which could be interpreted as an indication of embrittlement. However, the tests of impact strength show good retention of impact strength indicating that practical toughness is maintained.

Steam Sterilization Analysis

Because steam autoclaves are widely used to sterilize medical devices, resistance to steam sterilization is important for applications in medical devices.

To evaluate this property in a manner consistent with actual practice, morpholine was added to the steam to simulate the presence of typical boiler additives, and the test bars were strained in a cantilever beam arrangement to an outer fiber stress of 1,000 psi (6.9 MPa) to simulate residual or molded-in stresses commonly found in most components.

The testing was conducted in a steam autoclave at 27 psig (2 bar) steam which has a temperature of 270°F (132°C). The steam contains morpholine at a concentration of 50 ppm. The specimens were molded bars with dimensions of 5 x 0.5 x 0.125 inch (127 x 13 x 3 mm).

The results of the evaluation are shown in Table 28.

Table 26.

Resistance to Boiling Water

Retention of Properties after 10 days, %

Resin	Tensile Strength	Tensile Elongation
Udel	113	21
Radel A	94	8
Radel R	99	105

Table 27.

Effects of Prolonged Hot Water Exposure

Retention of Property after 16,000 hr, %	Acudel 22000		Radel R-5000	
	140°F (60°C)	194°F (90°C)	140°F (60°C)	194°F (90°C)
Tensile Strength	100.0	104.7	97.2	99.9
Tensile Modulus	90.2	91.9	95.7	94.1
Elongation @ Yield	92.5	85.0	92.5	85.0
Elongation @ Break	56.9	34.7	100.8	30.9
Flexural Strength	100.9	105.5	102.0	105.3
Flexural Modulus	108.2	111.6	103.9	106.0
Notched Izod	64.3	53.6	100.8	117.6
Instrumented Drop Impact	112.9	114.5	102.9	102.9

Table 28.

Steam Autoclave Resistance

Resin	Cycles to Craze	Cycles to Rupture
Udel	80	150
Radel A	100	275
Radel R	>1,000*	>1,000*

*Testing stopped at 1,000 cycles, neither crazing nor rupture occurred.

Chemical Resistance

In general, polysulfone resins have reasonably good chemical resistance, especially to aqueous systems. Table 29 gives a general indication of the relative chemical resistance to a variety of common reagents. The resistance of both the polysulfone family of resins and polyetherimide resin to aqueous acids is excellent. The polysulfones also resist aqueous caustic solutions which severely attack polyetherimide.

Radel R polyphenylsulfone also exhibits excellent resistance to chlorinated water at elevated temperatures. Exposure to a 90°C (194°F) re-circulating water environment with 5 ppm free chlorine for 1500 hours did not produce any reduction in resin tensile strength or in the weight of the test bars. Other engineering resins, including nylon 6,6 and an aliphatic polyketone showed substantial weight losses under similar testing.

Some chlorinated hydrocarbons are solvents for the sulfone polymers and polyetherimide, while others can cause environmental stress cracking to varying degrees. In general this class

of chemicals is incompatible with these resins. However, Radel R polyphenylsulfone offers the best resistance profile.

Aromatic solvents and oxygenated solvents, such as ketones and ethers, can cause stress cracking in both the polysulfones and the polyetherimide. Radel R polyphenylsulfone exhibits the best resistance within this group of resins. Glass fiber reinforced grades of Radel R can often be used in many of these environments without stress cracking.

Table 29.

General Indication of Chemical Resistance*

Reagent	Udel polysulfone	Radel A polyethersulfone	Radel R polyphenylsulfone	Acudel 25000	PEI
n-Butane	G	E	E	E	E
Iso-octane	G	E	E	E	E
Benzene	P	P	F	F	P
Toluene	P	P	F	F	P
Ethanol	G	E	E	E	E
Methyl Ethyl Ketone	P	P	P	P	F
2-Ethoxyethanol	P	P	G	F	F
1,1,1-Trichloroethane	P	P	G	F	F
Carbon Tetrachloride	P	G/E	E	G	E
Hydrochloric Acid (20%)	E	E	E	E	E
Acetic Acid (20 %)	E	E	E	E	E
Sulfuric Acid (20 %)	E	E	E	E	E
Sodium Hydroxide (10 %)	E	E	E	E	P

Exposure - immersion for seven days at room temperature.

Rating System

E	Excellent	Little or no effect
G	Good	No serious loss of properties
F	Fair	Some negative effects, some useful properties retained
P	Poor	Severe attack or rupture

Radel R Chemical Resistance

Because screening tests indicate that Radel R polyphenylsulfone has exceptional chemical resistance, more extensive testing was performed. Samples of Radel R polyphenylsulfone were immersed in a variety of reagents for seven days at room temperature. The effects of the exposure were monitored by measuring any change in weight and noting any change in

appearance. The results of that evaluation are shown in Table 30. To summarize these data, Radel R polyphenylsulfone is not seriously affected by organic chemicals, except for ketones. Of the inorganic chemicals tested, only concentrated strong acids had a deleterious effect. Several functional fluids common in transportation were tested. Of these only Skydrol® 500B aircraft hydraulic fluid showed crazing.

Table 30.

Chemical Resistance of Radel R Resin by Immersion*

Reagent	Concentration, %	Weight Change, %	Comments
Organic Chemicals			
1,1,1 Trichloroethane	100	+0.0	no change
Acetone	100	+9.0	surface softened
Benzene	100	+0.7	cloudy
Butanol	100	-0.0	no change
Butyl Acetate	100	+0.0	no change
Carbitol Solvent	100	-0.0	no change
Carbon Tetrachloride	100	+0.0	no change
Cyclohexane	100	+0.0	no change
Ethanol	100	+0.3	dark spots
Ethyl Acetate	100	+3.7	edges whitened
Ethylene Glycol	100	-0.4	no change
Formaldehyde	40	+0.4	no change
Glycerol	100	-0.0	no change
Methanol	100	+0.9	cloudy
Toluene	100	+0.8	whitened
Acetic Acid - Glacial	100	+0.0	slight attack
Acetic Anhydride	100	+1.0	crazed
Citric Acid	100	+0.5	no change
Formic Acid	10	+0.6	no change
Inorganic Chemicals			
Hydrochloric Acid	20	+0.2	no change
Hydrochloric Acid	37	+0.2	bleached
Nitric Acid	20	+0.5	no change
Nitric Acid	71	+26.9	opaque cracked
Oleic Acid	100	0.0	no change
Potassium Hydroxide	10	+0.5	no change
Sodium Hydroxide	10	+0.5	no change
Sulfuric Acid	50	+0.1	no change
Sulfuric Acid	97	-11.3	etched
Functional Fluids			
Brake Fluid	100	-0.2	cloudy
Gasoline	100	+0.1	no change
Hydraulic Oil LO-1	100	+0.0	no change
Jet Fuel JP-4	100	+0.0	cloudy
Kerosene	100	+0.0	no change
Motor Oil 10W-40	100	+0.0	cloudy

*7 days at room temperature

Stress Crack Resistance

To evaluate the resistance of Radel resins to environmental stress cracking, test specimens five inches (127 mm) long, one-half inch (13 mm) wide, one-eighth inch (3.2 mm) thick were clamped to curved fixtures. The radius of the fixture induces a strain in the specimen. The corresponding stress was calculated from the tensile modulus of the material. The reagents were then applied to the central portion of the fixtured test specimen. After 24 hours of exposure, the specimens were examined for evidence of attack and rated. Table 31 defines the ratings that appear in the subsequent environmental stress crack resistance tables.

The results of this testing in automotive fluids is shown in Table 32 on page 30. Testing of organic chemicals is shown in Table 33 on page 31. Inorganic chemical results are in Table 34 and aviation chemical results are in Table 35 on page 32.

The variables of importance in environmental stress cracking are temperature, stress level, time, and reagent. If a reagent causes stress cracking at a given time, temperature, and stress level, the following generalizations usually apply. At lower stress levels, cracking may not occur unless the exposure time is much longer or the temperature is higher. Higher temperatures generally speed cracking. Diluting the reagent may or may not eliminate stress cracking, depending upon the reagent and its miscibility with the diluent.

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

Table 31.

Key to Environmental Stress Cracking Tables

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

Table 32.

Environmental Stress Cracking Resistance to Automotive Fluids

24 Hours

Reagent	Concentration, %	Temperature		Radel Grade	Stress Level, psi (MPa)			
		°F	°C		none	1,000 (6.9)	2,000 (13.8)	4,000 (27.6)
Antifreeze (Prestone®)	50	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
	100	73	23	R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
				A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
		212	100	R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Gasoline - Unleaded	100	73	23	A-200A	OK	OK	OK	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	C
				RG-5030	OK	OK	OK	OK
Gasohol - 15% Methanol	100	73	23	A-200A	OK	OK	OK	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Motor Oil 10W-40	100	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
Power Steering Fluid	100	73	23	R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
				A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
		212	100	R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Reference Fuel C	100	73	23	A-200A	OK	OK	C	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	C
				RG-5030	OK	OK	OK	OK
Transmission Fluid	100	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
Windshield Washer Concentrate	50	73	23	R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
				A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK

Table 33.

Environmental Stress Cracking Resistance to Organic Chemicals

24 Hours

Reagent	Concentration, %	Temperature,		Radel Grade	Stress Level, psi (MPa)			
		°F	°C		none	1,000 (6.9)	2,000 (13.8)	4,000 (27.6)
Methyl Ethyl Ketone	100	73	23	A-200A	R	R	R	R
				AG-230/330	D	D	D	D
				R-5000	D	R	R	R
				RG-5030	D	D	D	D
Trichloroethane 1,1,1	100	73	23	A-200A	OK	C	R	R
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Toluene	100	73	23	A-200A	C	R	R	R
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	C	C
				RG-5030	OK	OK	OK	OK
Methylene Chloride	100	73	23	A-200A	D	D	D	D
				AG-230/330	D	D	D	D
				R-5000	D	D	D	D
				RG-5030	D	D	D	D
Methanol	100	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Isopropanol	100	73	23	A-200A	OK	OK	C	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Acetone	100	73	23	A-200A	R	R	R	R
				AG-230/330	D	D	D	D
				R-5000	D	C	C	C
				RG-5030	D	D	D	D
Cellsolve (2-ethoxyethanol)	100	73	23	A-200A	C	C	C	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	C	C
				RG-5030	OK	OK	OK	OK
Carbitol (Diethylene glycol monoethyl ether)	100	73	23	A-200A	C	C	R	R
				AG-230	OK	OK	OK	OK
				R-5000	OK	OK	C	C
				RG-5030	OK	OK	OK	OK

Table 34.

Environmental Stress Cracking Resistance to Inorganic Chemicals

24 Hours

Reagent	Concentration, %	Temperature,		Radel Grade	Stress Level, psi (MPa)			
		°F	°C		none	1,000 (6.9)	2,000 (13.8)	4,000 (27.6)
Sodium Hydroxide	20	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Hydrochloric Acid	20	73	23	A-200A	OK	OK	OK	R
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A		C	C	C
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Sulfuric Acid	50	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
		212	100	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK

Table 35.

Environmental Stress Cracking Resistance to Aviation Fluids -

24 Hours

Reagent	Concentration, %	Temperature		Radel Grade	Stress Level, psi (MPa)			
		°F	°C		none	1,000 (6.9)	2,000 (13.8)	4,000 (27.6)
Hydraulic Fluid (Skydrol® 500B)	100	73	23	A-200A	C	R	R	R
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Jet Fuel A	100	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK
Aircraft Deicer	100	73	23	A-200A	OK	OK	OK	OK
				AG-230/330	OK	OK	OK	OK
				R-5000	OK	OK	OK	OK
				RG-5030	OK	OK	OK	OK

Radiation Resistance

Radel A-200A polyethersulfone was exposed to gamma radiation at dosages of 4, 6, and 8 megarads. The properties of the exposed specimens were measured and compared to the properties of unexposed specimens. Radel A resin was virtually unaffected by the radiation, as shown in Figure 46.

The gamma radiation resistance of Radel R polyphenylsulfone was similarly evaluated using dosages of 5, 7.5, and 10 megarads. As shown in Figure 47, the radiation had virtually no effect on the Radel R even though higher dosage was used.

Figure 46.

Radiation Resistance of Radel A

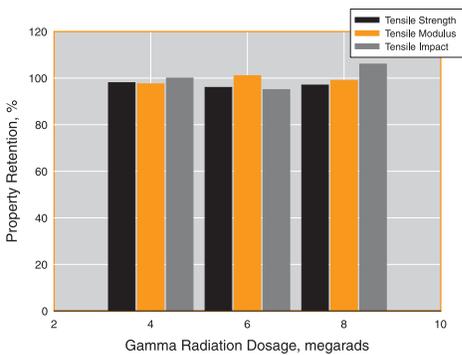
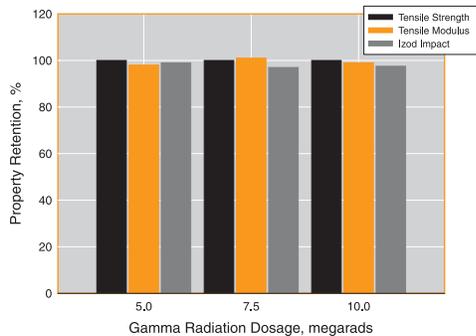


Figure 47.

Radiation Resistance of Radel R



Physical Properties

Density

Plastic resins are sold by unit weight, but used volumetrically. The property that defines the relationship of volume and weight is density. The term specific gravity refers to a material's density compared to the density of water, which at 4°C is defined as 1.0000 g/cc. Figure 48 shows that the resin volume per unit weight is inversely related to the resin's specific gravity. In other words, the lower the specific gravity, the greater the number of items that can be produced from a pound. Table 36 lists the specific gravities of Radel A and R resins.

Water Absorption

Most polymers absorb some water from the environment, but they vary significantly in the rate of water absorption and the amount of water absorbed. Figure 49 shows the water absorption versus time curves for Udel, Radel A, Radel R, and Acudel resins generated using specimens with a thickness of 0.125 inch (3.2 mm).

Udel polysulfone is well known for its low water absorption, Radel R absorbs a slightly greater amount, and Radel A absorbs somewhat more. The water absorption of Acudel resin is higher than that of Udel resin but less than that of Radel R resin.

Figure 48.

Resin Volume Varies Inversely with Specific Gravity

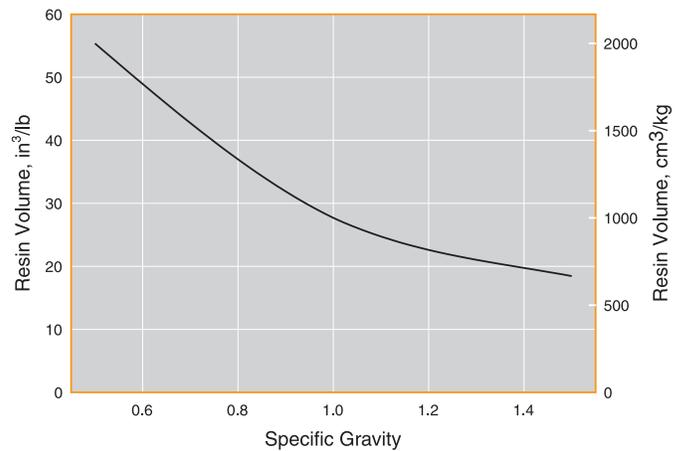


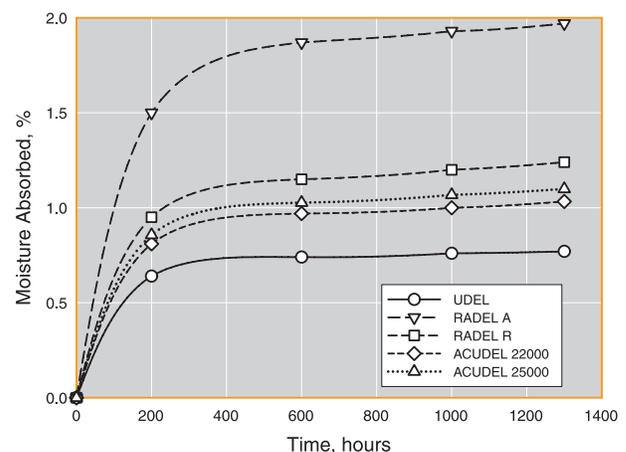
Table 36.

Specific Gravity of Radel Resins

Material Type	Grade	Specific Gravity
Neat Resins	A-100, 200, 300	1.37
	Acudel 22000, 25000	1.28
	R-5000, 5100, 5500, 5800	1.29
Glass-Filled Resins	AG-210	1.43
	AG-220/320	1.51
	AG-230/330	1.58
	AG-340	1.45
	RG-5030	1.53

Figure 49.

Water Absorption by Immersion at 77°F (23°C)



Design Information

This section presents basic design principles and general recommendations that the design engineer may find useful in developing new components. The goal of plastic part design is to achieve a design that meets the physical strength and deformation requirements of the application with a minimum volume of material, without neglecting the effects of stresses caused by assembly, temperature changes, environmental factors, and processing.

Mechanical Design

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

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

Stress Levels

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

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

Stress-Strain Calculations

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

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.
4. The part has no residual or molded-in stresses.

A variety of parts can be analyzed using a beam bending model. Table 37 lists the equations for maximum stress and deflection for some selected beams. The maximum stress occurs at the surface of the beam furthest from the neutral surface, and is given by:

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

where

M = bending moment, inch pounds

c = distance from neutral axis, inches

I = moment of inertia, inches⁴

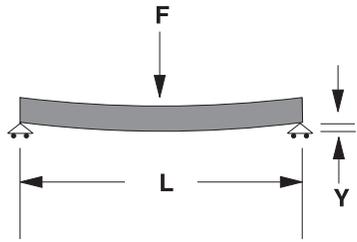
$Z = \frac{I}{c}$ = section modulus, inches³

Table 38 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.

Table 37.

Maximum Stress and Deflection Equations

Simply Supported Beam
Concentrated Load at Center



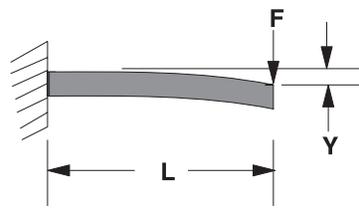
$$\sigma = \frac{FL}{4Z}$$

(at load)

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

(at load)

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



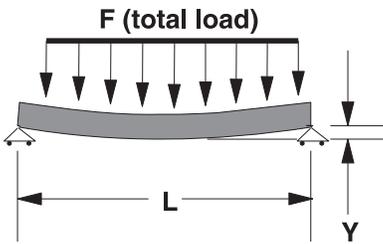
$$\sigma = \frac{FL}{Z}$$

(at support)

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

(at load)

Simply Supported Beam
Uniformly Distributed Load



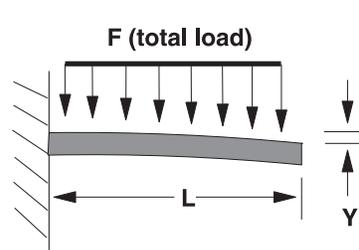
$$\sigma = \frac{FL}{8Z}$$

(at center)

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

(at center)

Cantilevered Beam (One End Fixed)
Uniformly Distributed Load



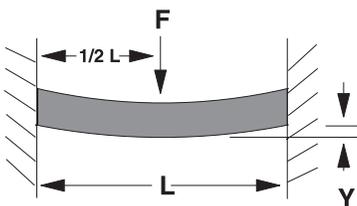
$$\sigma = \frac{FL}{2Z}$$

(at support)

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

(at support)

Both Ends Fixed
Concentrated Load at Center



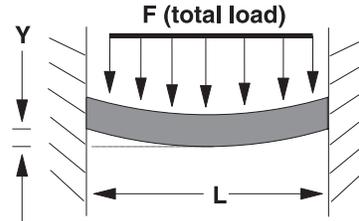
$$\sigma = \frac{FL}{8Z}$$

(at supports)

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

(at load)

Both Ends Fixed
Uniformly Distributed Load



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

(at supports)

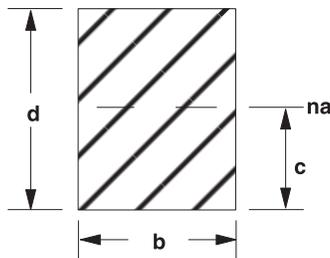
$$Y = \frac{FL^3}{384EI}$$

(at center)

Table 38.

Area and Moment Equations for Selected Cross Sections

Rectangular



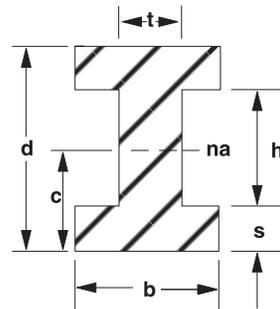
$$A = bd$$

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

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

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

I-Beam



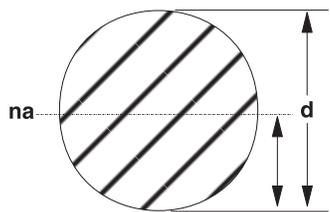
$$A = bd - h(b - t)$$

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

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

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

Circular



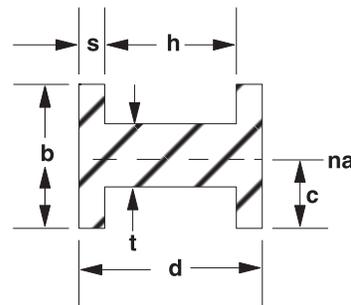
$$A = \frac{\pi d^2}{4}$$

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

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

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

H-Beam



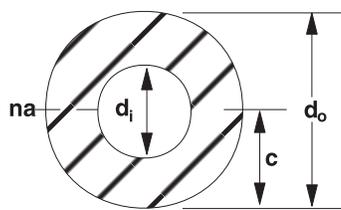
$$A = bd - h(b - t)$$

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

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

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

Tube



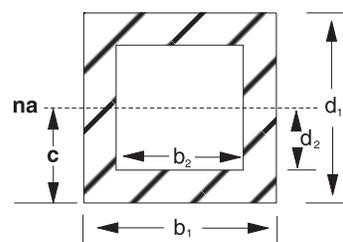
$$A = \frac{\pi (d_o^2 - d_i^2)}{4}$$

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

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

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

Hollow Rectangular



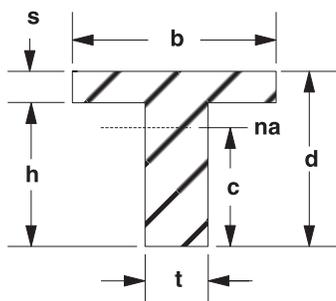
$$A = b_1d_1 - b_2d_2$$

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

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

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

T-Beam or Rib



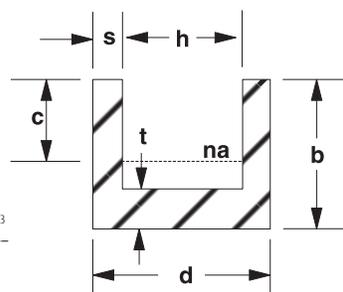
$$A = bs + ht$$

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

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

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

U-Beam



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

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

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

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

Design Limits

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

The term “design allowable” has been coined for an estimate of a material’s strength which incorporates the appropriate safety factors for the intended loading pattern. Table 39 presents the design allowables for short-term intermittent loading. Table 40 provides the design allowable stresses for constant loading where creep is a major design consideration. These tables do not consider any environmental factors other than temperature. The presence of chemicals may lower the design allowables dramatically.

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

Stress Concentrations

Stress concentrations may lead to premature failure, particularly under impact or fatigue. 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 half of the nominal wall thickness. A fillet radius of 0.020 inch (0.5 mm) should be considered minimum.

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 50 shows the effect of radius on the stress concentration factor.

Table 39.

Allowable Design Stresses¹ for an Intermittent Load, psi (MPa)

Grade	73°F (23°C)	200°F (93°C)	350°F (177°C)
A-100, 200, 300	6,100 (42)	4,570 (32)	2,640 (18)
AG-210, 310	6,600 (46)	4,820 (33)	3,550 (24)
AG-220, 320	7,710 (53)	5,840 (40)	3,810 (26)
AG-230, 330	9,140 (63)	6,850 (47)	4,160 (29)
R-5000, 5100, 5500, 5800	5,180 (36)	3,300 (23)	2,540 (18)

¹ Environmental factors may lower allowable stress levels

Table 40.

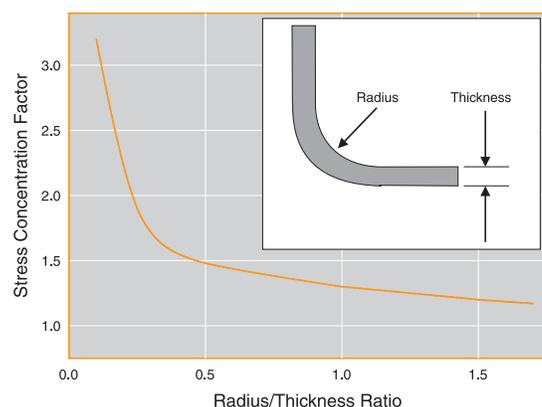
Allowable Design Stresses¹ for a Constant Load, psi (MPa)

Grade	73°F (23°C)	200°F (93°C)	350°F (177°C)
A-100, 200, 300	3,000 (21)	2,250 (16)	1,300 (9)
AG-210, 310	3,250 (22)	2,375 (16)	1,750 (12)
AG-220, 320	3,800 (26)	2,875 (20)	1,875 (13)
AG-230, 330	4,500 (31)	3,375 (23)	2,050 (14)
R-5000, 5100, 5500, 5800	2,550 (18)	1,625 (11)	1,250 (9)

¹ Environmental factors may lower allowable stress levels

Figure 50.

Stress Concentration Factor at Inside Corners



Designing for Injection Molding

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

Wall Thickness

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

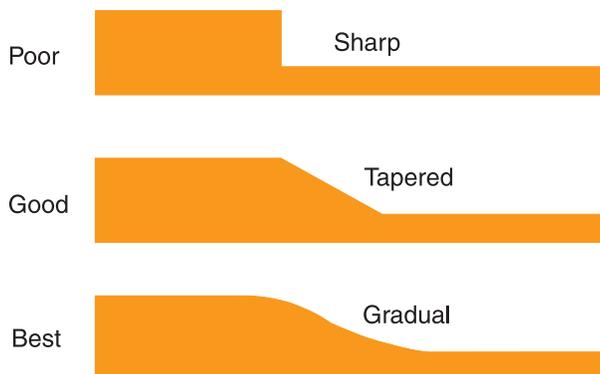
Occasionally, wall thicknesses greater than those required by the mechanical design analysis are required for molding. The flow of Radel resins, like other thermoplastics, depends upon the wall thickness as well as the mold design and process variables, such as injection rate, mold temperature, melt temperature, and injection pressure. The practical limits of wall thickness generally lie between 0.030 inches and 0.250 inches (0.7 mm and 6.5 mm). Wall sections of 0.010 inches (0.25 mm) can be molded if flow lengths are short. Specific information regarding flow length versus wall thickness of the various Radel grades can be found on page 46.

Wall Thickness Variation

While uniform wall thicknesses are ideal, varying wall thickness may be required by structural, appearance, and draft considerations. When changes in wall section thickness are necessary, the designer should consider a gradual transition, such as the 3 to 1 taper ratio shown in Figure 51. Sharp transitions can create problems in appearance and dimensional stability due to cooling rate differentials and turbulent flow.

Figure 51.

Wall Thickness Transition



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

Draft Angle

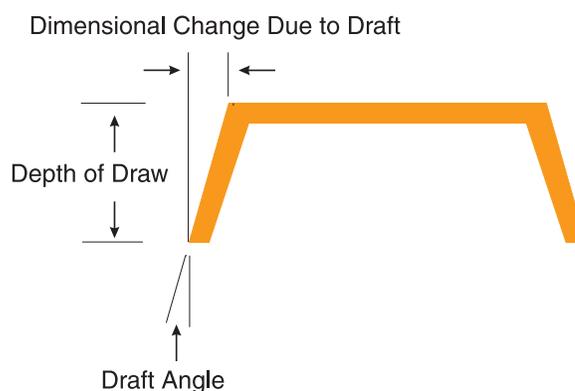
To aid in the release of the part from the mold, parts are usually designed with a taper in the direction of mold movement. The taper creates a clearance as soon as the mold begins to move, allowing the part to break free. The taper is commonly referred to as “draft”, and the amount of taper referred to as “draft angle”. The use of draft is illustrated in Figure 52.

Adequate draft angle should be provided to allow easy part removal from the mold. Generally, the designer should allow a draft angle of 1 to 2° per side for both inside and outside walls for Radel resins. In some special cases, smaller draft angles 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 52.

Draft - Designing for Mold Release



Ribs

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

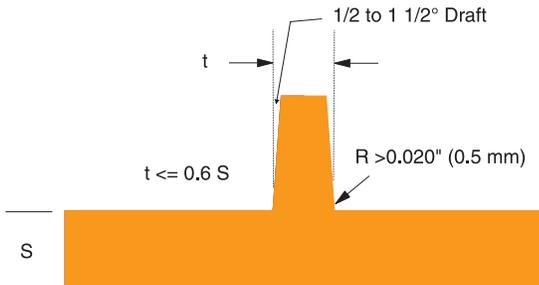
In general, these guidelines should be followed when designing with ribs. The thickness at the rib base should be equal to one-half the adjacent wall thickness. When ribs are opposite appearance areas, the width should be kept as thin as possible. If there are areas in the molded part where structure is more important than appearance, then ribs are often 75%, or even

100%, of the outside wall thickness. Whenever possible, ribs should be smoothly connected to other structural features such as side walls, bosses, and mounting pads. Ribs need not be constant in height or width, and are often matched to the stress distribution in the part. All ribs should have a minimum of $1/2^\circ$ of draft per side and should have a minimum radius of 0.020 inch (0.5 mm) at the base.

Figure 53 shows recommended rib size relationships.

Figure 53.

Recommended Rib Design



Coring

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

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

Cores that extend into the cavity are subject to high pressure. For blind cores with diameters greater than 1/16" (1.6 mm), the core lengths should not exceed three times the diameter; blind cores with diameters less than 1/16" (1.6 mm) the core length should not exceed twice the diameter. These recommendations may be doubled for through cores. Draft should be added to all cores and all tooling polished for best ejection.

Bosses

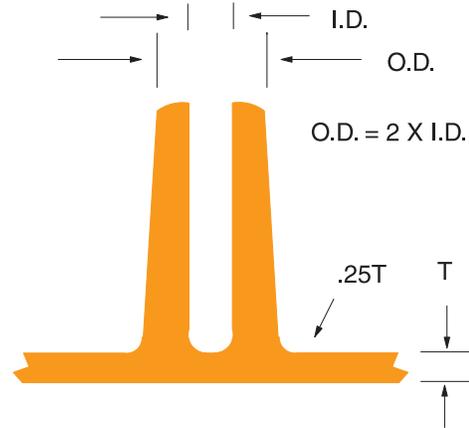
Bosses are protrusions off the nominal wall of a part that will eventually be used as mounting or fastening points. The design of bosses is largely dependent upon their role in a given part. Cored bosses can be used with press fits, self-tapping screws, or ultrasonic inserts. These fasteners exert a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

As a general guideline, the outside diameter of each boss should be twice the inside diameter of the hole, and the wall thickness of each boss should not exceed that of the part. Figure 54 illustrates these guidelines.

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

Figure 54.

Boss Design General Guidelines



Fabrication

The fabrication methods used for Radel and Acudel resins are injection molding, extrusion, and blow molding.

Drying

Radel A polyethersulfone, Radel R polyphenylsulfone, and Acudel modified polyphenylsulfones should be dried completely prior to melt processing. Although these polymers are hydrolytically stable and not subject to molecular weight degradation, incomplete drying will result in cosmetic defects in the formed part, ranging from surface streaks to severe bubbling. However, such parts may be recovered as regrind.

Pellets of Radel resin can be dried on trays in a circulating air oven or in a hopper dryer. Minimum drying times are: 2.5 hours at 350°F (177°C), 4 hours at 300°F (150°C), or 4.5 hours at 275°F (135°C). Drying below 275°F (135°C) is not recommended because drying times would be excessive. Dried resin should be handled carefully to prevent resorption of moisture from the atmosphere by using dry containers and covered hoppers.

The recommended maximum moisture content is 500 ppm for injection molding and 100 ppm for extrusion.

Typical drying curves for Radel A polyethersulfone, Radel R polyphenylsulfone, Acudel 22000 resin, and Acudel 25000 are shown in Figures 55 through 58.

Figure 55. Drying of Radel A Resin in a Circulating Air Oven

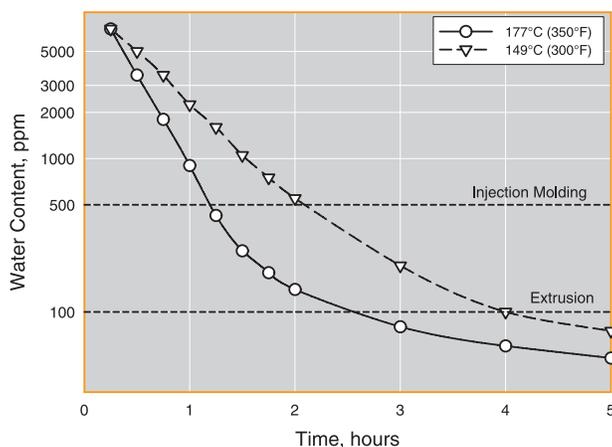


Figure 56. Drying of Radel R Resin in a Circulating Air Oven

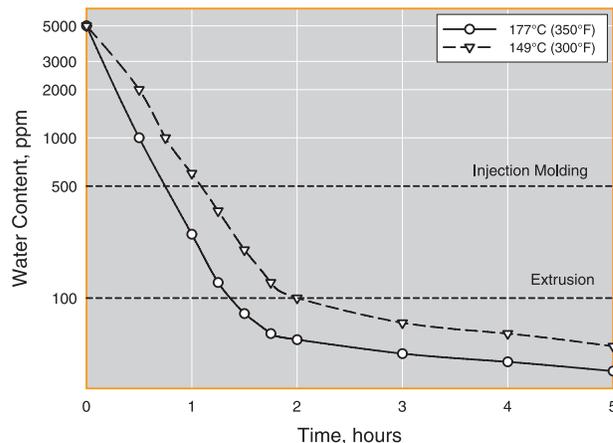


Figure 57. Drying of Acudel 22000 Resin in a Circulating Air Oven

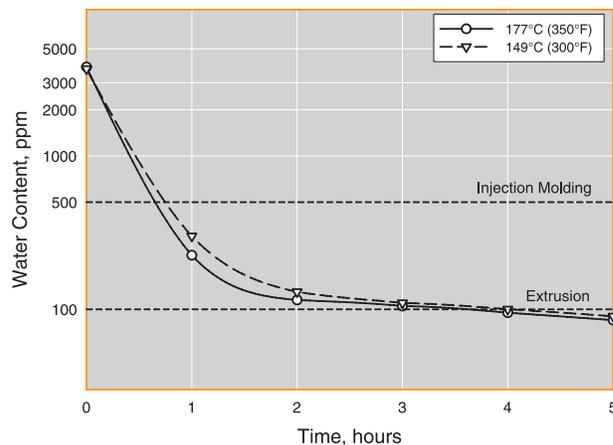
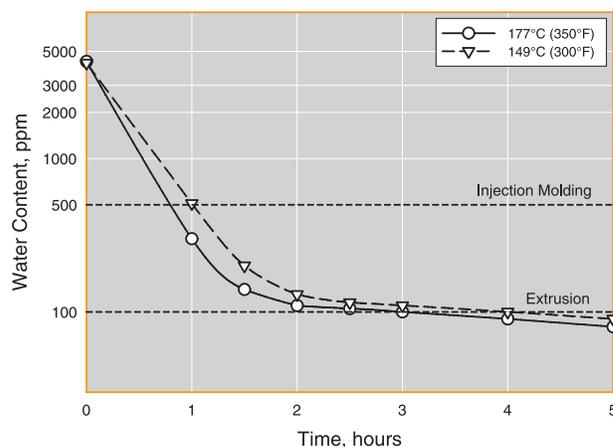


Figure 58. Drying of Acudel 25000 Resin in a Circulating Air Oven



Rheology

To assist the fabricator in the proper design of tools and processing equipment, the rheology of the Radel resins has been measured under a variety of conditions. The viscosity versus shear rate data are shown in Tables 41 and 42.

Table 41.

Shear Rate - Viscosity Data Radel R

Radel Grade	Temp., °C (°F)	Shear Rate, sec ⁻¹	True Viscosity, Poise
R-5000/ R-5100	340 (644)	30	32,810
		100	30,474
		500	15,293
		1,000	9,465
		3,000	3,803
	360 (680)	30	16,996
		100	16,000
		500	10,244
		1,000	6,780
		3,000	3,084
	380 (716)	30	9,669
		100	9,317
		500	6,723
		1,000	4,864
		3,000	2,446
	400 (752)	30	6,808
		100	6,451
		500	4,767
		1,000	3,637
		3,000	2,000
R-5800	340 (644)	30	24,224
		100	22,725
		500	12,948
		1,000	8,225
		3,000	3,549
	360 (680)	30	11,972
		100	11,499
		500	8,071
		1,000	5,613
		3,000	2,699
	380 (716)	30	7,165
		100	7,109
		500	5,297
		1,000	3,995
		3,000	2,133
	400 (752)	30	4,936
		100	4,768
		500	3,661
		1,000	2,914
		3,000	1,724

Table 42.

Shear Rate - Viscosity Data Radel A

Radel Grade	Temp., °C (°F)	Shear Rate, sec ⁻¹	True Viscosity, Poise
A-200A	345 (653)	100	9,756
		1,000	4,660
		10,000	1,496
	365 (689)	100	6,695
		1,000	3,198
		10,000	1,027
	385 (725)	100	4,595
		1,000	2,195
		10,000	705
AG-230	345 (653)	100	21,080
		1,000	7,505
		10,000	2,170
	365 (689)	100	13,648
		1,000	4,859
		10,000	1,400
	385 (725)	100	8,835
		1,000	3,145
		10,000	910
A-300A	340 (644)	23	34,686
		104	28,173
		499	16,070
		1507	7,589
		3514	3,380
	360 (680)	23	17,982
		104	14,864
		499	10,065
		1507	5,781
		3514	2,886
	380 (716)	23	12,640
		104	10,132
		499	6,905
		1507	4,281
		3514	2,347
	400 (752)	23	7,449
		104	6,086
		499	4,539
1507		3,184	
3514		2,100	
AG-330	340 (644)	23	32,271
		104	25,071
		499	13,818
		1507	7,499
		3514	3,373
	360 (680)	23	19,337
		104	13,460
		499	7,933
		1507	4,672
		3514	2,476
	380 (716)	23	12,941
		104	8,511
		499	5,284
		1507	3,346
		3514	2,027
	400 (752)	23	9,536
		104	6,869
		499	4,241
1507		2,832	
3514		1,872	

The rheology data for Radel A-200A are plotted in Figure 59, for Radel A-300A in Figure 60, for glass-filled Radel AG-230 in Figure 61, and for Radel AG-330 in Figure 62.

Figure 59.

Rheology of Radel A-200A Resin

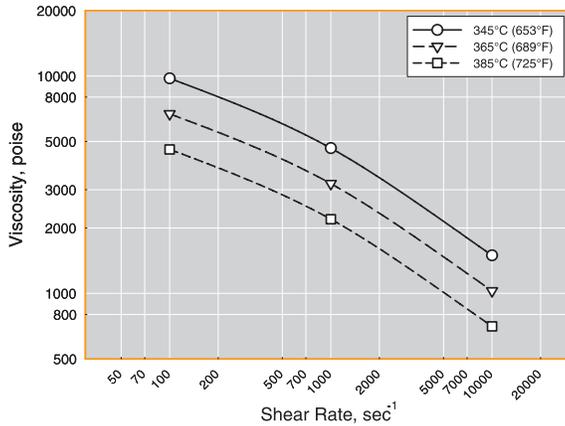


Figure 60.

Rheology of Radel A-300A Resin

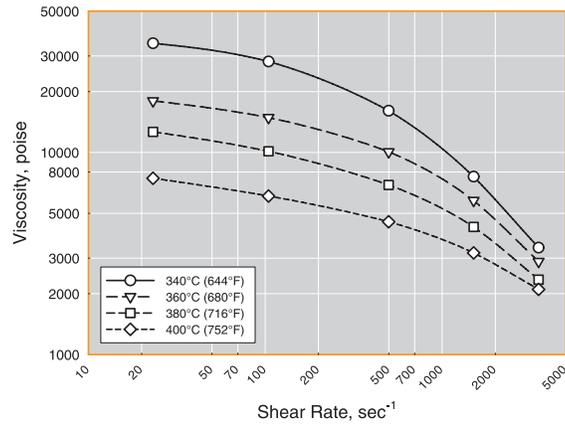
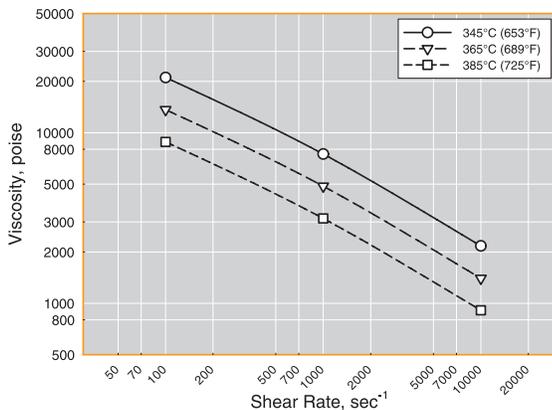


Figure 61.

Rheology of Radel AG-230 Resin



The rheology data for Radel R-5000 are shown in Figure 63, and for Radel R-5800 in Figure 64.

Figure 62.

Rheology of Radel AG-330 Resin

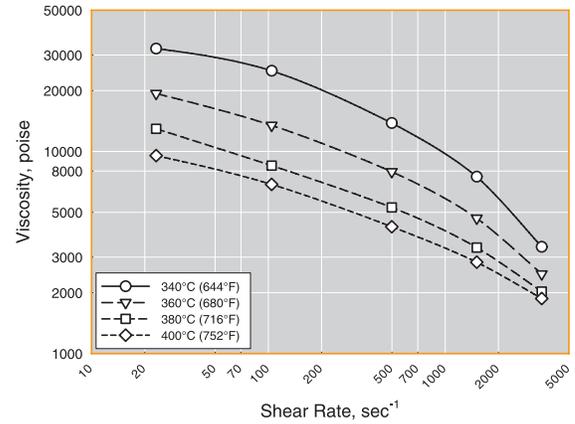


Figure 63.

Rheology of Radel R-5000 Resin

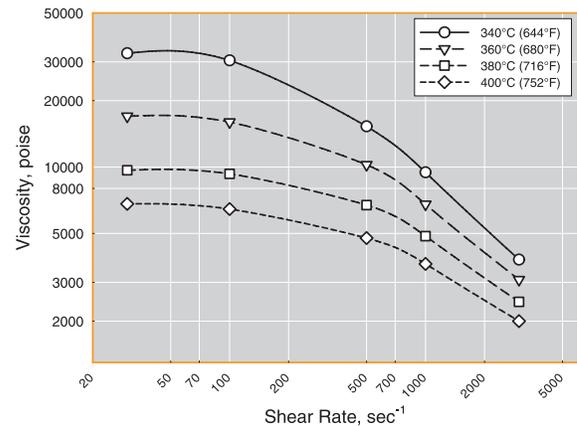
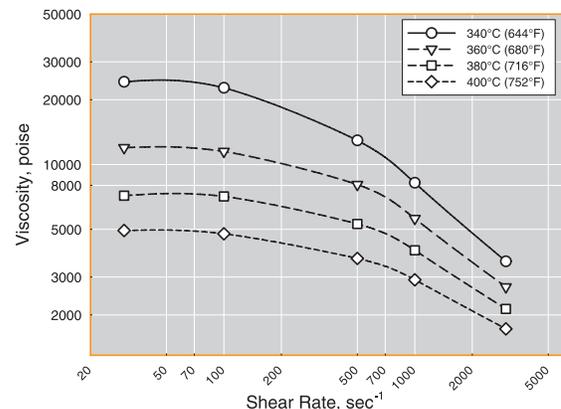


Figure 64.

Rheology of Radel R-5800 Resin



Melt Processing Parameters

The increased use of computer modeling for predicting flow and cooling has created a need for certain material constants or parameters. These parameters for Radel resins are shown in Table 43.

Table 43.

Melt Processing Parameters

Property	Units	Radel Grade		
		A-200A A-300A	AG-230 AG-330	R-5000
Melt Thermal Diffusivity	cm ² /s	9.72 x 10 ⁻⁴	9.02 x 10 ⁻⁴	1.66 x 10 ⁻³
Melt Specific Heat	cal/g-C	0.438	0.408	0.480
Melt Density @ 10,000 psi	g/cm ³	1.3432	1.5963	1.2855
No Flow Temperature	°C	220.0	219.7	219.7
Freezing Temperature	°C	206.0	214.0	215.0
Solid density	g/cm ³	1.3554	1.5633	1.2900
Glass Transition Temperature				
Onset	°C	220	220	220
End	°C	225.9	227.3	221.0

Injection Molding

Injection Molding Equipment

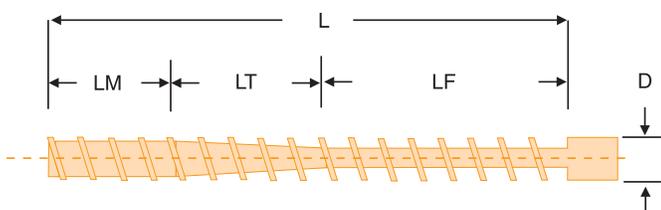
The molding characteristics of Radel resins are similar to those of Udel polysulfone resin. Radel resins can be readily injection molded with most screw injection machines.

Screw Design

The typical general-purpose screw will perform satisfactorily with Radel resins. A typical screw design for processing the Radel engineering resins is shown in Figure 65.

Figure 65.

Screw Design for Injection Molding



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

Screw Tips and Check Valves

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

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

Nozzles

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

Molds

Standard guidelines for mold design are appropriate for the Radel resins.

Draft and Ejection

In general, the injection molds designed for Radel resins should have 1 to 2° draft. The contact area of ejector pins or stripper plates should be as large as possible to prevent part deformation or penetration during ejection.

Gates

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

Venting

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

Mold Temperature Control

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

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

Machine Settings

Injection Molding Temperatures

The injection molding melt temperatures recommended for various Radel resins are listed in Table 44. In general, higher temperatures should not be used, because of the risk of thermal degradation. As a fundamental rule, injection molding melt temperatures higher than 740°F (395°C) should be avoided.

Mold Temperatures

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

The mold temperature for Radel is usually set in the range of 250-320°F (120-160°C). The only products that require higher temperatures to achieve an optimum finish are the glass-reinforced Radel grades. Table 44 lists the recommended mold temperatures for the individual Radel grades.

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

Barrel Temperatures

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

The band heater control system should be monitored. For instance, a timely alarm may prevent screw breakage if a heater fails in one of the barrel sections. The feeding of the pellets can often be improved by maintaining the temperature in the vicinity of the hopper at about 175°F (80°C).

Table 44.

Molding Conditions - Starting Point

Radel Grade	Melt Temperature, °F (°C)	Mold Temperature, °F (°C)	Shrinkage, %
A-200A	690-730 (365-390)	280-320 (138-160)	0.6 - 0.7
A-300A	660-730 (350-390)	280-320 (138-160)	0.6 - 0.7
AG-210	680-730 (360-390)	280-320 (138-160)	0.5
AG-320	680-730 (360-390)	280-320 (138-160)	0.4
AG-330	680-730 (360-390)	280-320 (138-160)	0.3
R-5000/5100	690-740(365-393)	300-325 (150-163)	0.6 - 0.7
Acudel	690-740(365-393)	300-325 (150-163)	0.6 - 0.7

Residence Time in the Barrel

The length of time the plastic remains in the plasticizing cylinder has a significant effect on the quality of the injection molding. If it is too short, the pellets will not be sufficiently melted. If it is too long, thermal degradation is likely and is indicated by discoloration, dark streaks, and even burned particles in the molded parts. Frequently, the residence time can be reduced by fitting a smaller plasticizing unit. Acceptable residence times will be obtained if the shot size is 30-70 % of the barrel capacity. At the melt temperatures listed in Table 44, all the Radel resins withstand a residence time of 10 - 20 minutes.

Molding Process

Feed Characteristics

Radel pellets can be conveyed smoothly along the barrel and homogeneously plasticized at the recommended temperatures by screws of the design shown in Figure 65 on page 44.

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

Back Pressure

Back pressure is usually employed to maintain a constant plasticizing time, to avoid air entrainment, and to improve the homogeneity of the melt. While some back pressure is generally beneficial, back pressure that is too high can result in high frictional heating.

Screw Speed

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

Injection Rate and Venting

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

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

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

Demolding

Radel parts can be readily demolded and do not stick to the walls of the mold, even when they are hot. As a rule, the draft on injection molds for Radel resins should be 1 to 2°. A somewhat larger draft is required for the glass-reinforced products, because of their lower shrinkage. The area of ejectors or stripper plates should be as large as possible. Ejector pins must not be too thin, or they may press into the parts and deform them during rapid cycling or at high mold temperatures.

Shrinkage

Shrinkage is defined as the difference between the dimensions of the mold and those of the molded part at room temperature. It is primarily a property of the thermoplastic resin and results from the contraction in volume that occurs when the molding compound cools within the mold. Other factors that effect the magnitude of the shrinkage are the geometry of the part, the wall thickness, the size and location of the gates, and the processing parameters. The interaction of all these factors makes it difficult to predict shrinkage exactly, but close estimates of typical values appear in Table 44.

Resin Flow Characteristics

One method of characterizing a material's flow is the measurement of the length of flow in a spiral cavity at various thicknesses, temperatures, and molding pressures. These data have been generated for Radel A-200A, A-300A, AG-210, and AG-230. The results for Radel A-200A are shown in Figure 66, Radel AG-210 in Figure 67, for Radel A-300A in Figure 68, and for Radel AG-230 in Figure 69. Spiral flow data for Radel R-5000 are shown in Figure 70 and for Radel R-5800 in Figure 71.

Figure 66.

Spiral Flow of Radel A-200A

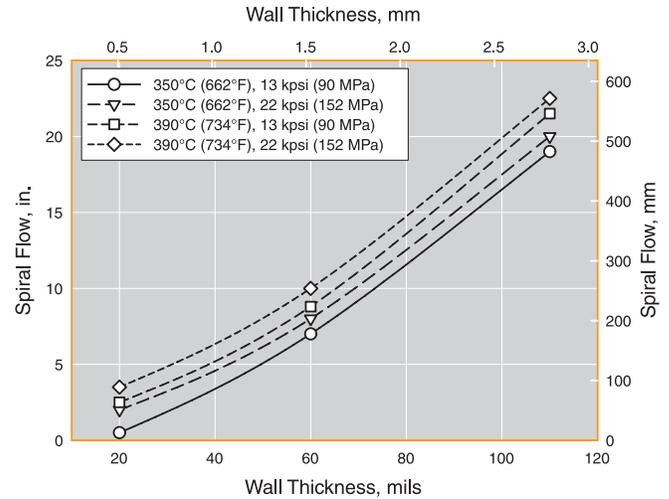


Figure 67.

Spiral Flow of Radel AG-210

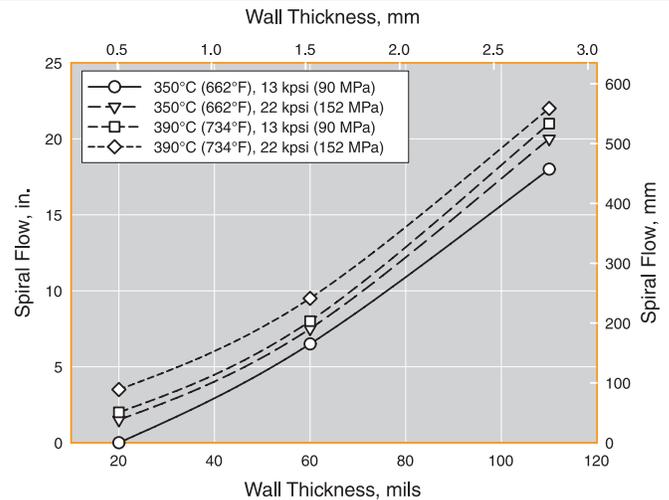


Figure 68.

Spiral Flow of Radel A-300A

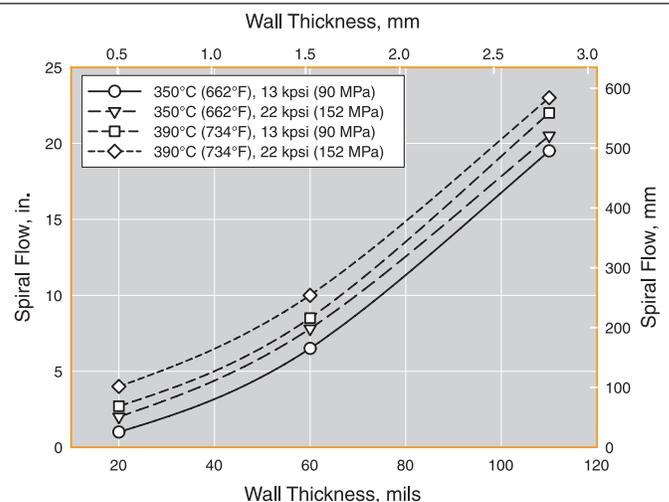


Figure 69.

Spiral Flow of Radel AG-230

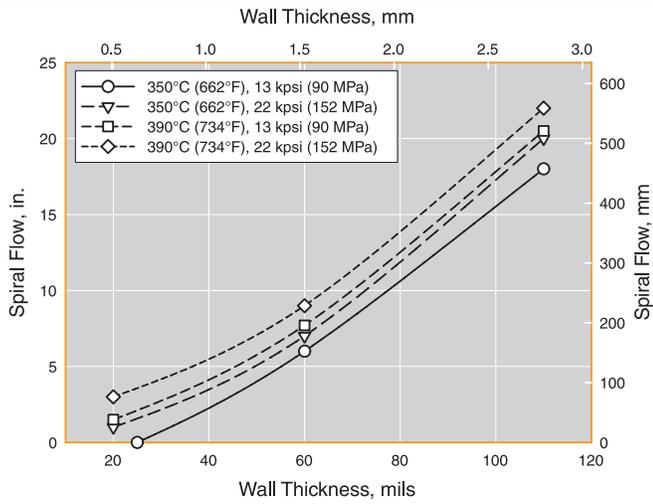


Figure 70.

Spiral Flow of Radel R-5000

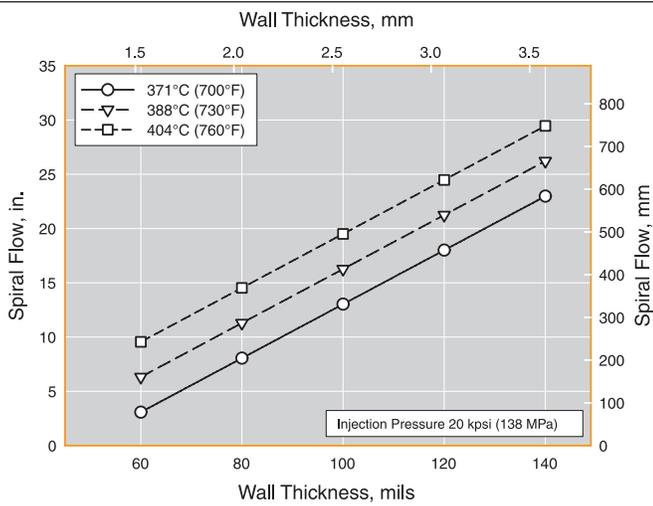
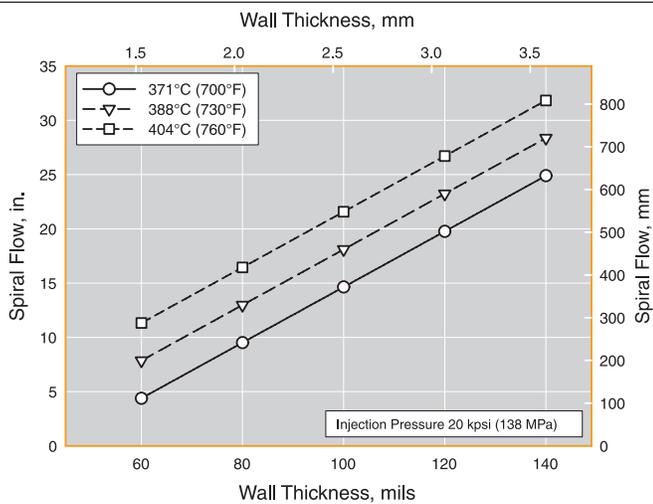


Figure 71.

Spiral Flow of Radel R-5800



Measuring Residual Stress

When thermoplastics are injection molded, the process induces residual or molded-in stresses in the molded articles. While stresses induced in plastic parts by mechanical and thermal loads may be calculated by conventional means, there is no reliable method for predicting residual stress levels. Many performance parameters are affected by the level of residual stress present in a part. Since these stresses cannot be calculated, it is important to be able to measure them.

A method for measuring the residual stress level in parts molded from unfilled Radel resin has been developed. It involves the exposure of finished parts to chemical reagents which are known to produce cracking or crazing of the material at specific stress levels. Exposure of parts to these reagents under no load conditions allows the quantification of the residual stress levels.

The following table details the reagents used for this testing and the stress levels at which they are known to cause the material to crack. This information was generated at room temperature at 100% reagent concentration with a one-minute exposure time.

The exposure time required for these reagents to produce cracking at the noted stress level is one minute. This exposure time was employed to facilitate rapid testing and to limit the possibility of errors due to over or under exposure. Exposure for longer time periods produces cracking at stress levels lower than those specified.

To determine the residual stress level of a molded Radel part, choose the list appropriate for the Radel grade from Table 45, and follow the procedure shown, starting with the first reagent in the list.

Table 45.

Residual Stress Test Parameters

Reagents	Minimum Stress Level To Produce Failure, psi (MPa)
Radel A polyethersulfone	
2-Ethoxyethanol (Cellosolve)	2,200 (15)
Ethyl Acetate (EA)	1,200 (8)
50%* MEK / 50%* EA	800 (6)
Methyl Ethyl Ketone (MEK)	400 (3)
Radel R polyphenylsulfone	
Ethyl Acetate (EA)	1,750 (12)
Methyl Ethyl Ketone (MEK)	1,200 (8)
5%* N-Methyl pyrrolidone / 95%* MEK	800 (6)

*% by volume

Procedure for Residual Stress Determination

1. Allow the parts to cool to room temperature then rinse with isopropyl alcohol.
2. Expose the part to reagent for one minute, then rinse with water.
3. Inspect the part for cracked or crazed regions under strong light. Hairline fractures may be difficult to see.
4. If the part has no cracks or crazes, the residual stress level is lower than the stress level shown in Table 45 for that reagent. Proceed to the next reagent and repeat steps 2 and 3.

The stress level in the part lies between the stress level shown for the reagent which induces cracking and the one directly above it in Table 45.

Determining stress levels through the use of reagent exposure is approximate in nature. Small differences in the test conditions (ambient temperature, exposure time, or reagent concentration, etc) may cause slight variations in the test results. Results should be within 20% of the actual stress level.

Residual stress levels depend on numerous molding parameters that may be in flux at the time of molding. For this reason, individual samples may exhibit variations in stress levels. Therefore, testing multiple parts is recommended.

The determination of the acceptable molded-in stress level for an individual part should be made from its end use application, in particular, the chemical environment to which the part will be exposed. Radel resins are amorphous thermoplastics that are considered to have good chemical resistance. Parts whose residual stress levels are below 800 psi (5 MPa) may typically be considered well molded.

Health and Safety Considerations

Consult your supplier's Material Safety Data Sheet before handling the specific reagents selected for testing and follow the manufacturer's instructions for handling precautions.

All testing should be conducted in a ventilated laboratory hood, or in a well ventilated area. The reagents are flammable organic chemicals, and should be stored in closed containers away from open flames, sparks, or locations where elevated temperatures may be expected. Disposal of these materials must be in accordance with applicable federal, state, or local regulations.

Extrusion

Both Radel A polyethersulfone and Radel R polyphenylsulfone can be readily extruded on conventional extrusion equipment.

Predrying

Radel resins must be thoroughly dried prior to extrusion to prevent bubbles in the extrudate. Resin should be dried until the moisture content is below 100 ppm. Appropriate drying times and temperatures are shown in Figures 55 and 56 on page 40. Hopper drying requires sufficient insulation and minimal system leakage. Inlet air temperature must be high enough and inlet air moisture content low enough for polymer pellets to be maintained above 300°F (150°C) in air with a -40°F (-40°C) dew-point. This condition must be sustained long enough for the polymer moisture content to drop to below 100 ppm.

Extrusion Temperatures

Depending upon the specific extrusion operation, the melt temperature of the extruded stock should be in the range of 650 to 750°F (343 to 400°C).

Actual barrel temperature settings of 625-700°F (330-370°C) at the feed end of the extruder and 625-700°F (330-370°C) at the head are recommended for most operations. These temperature settings along the barrel should yield the required extruded stock temperature if maintained uniformly in the range of 650 to 750°F (340 to 400°C).

Higher barrel settings may be necessary if a screw with a relatively shallow metering section is used to better control the operation within the pressure and power limitations of the equipment.

Screw Design Recommendations

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

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

As a rule, screw designs intended for polyolefins will not give acceptable results with Radel resins.

Die Design

The die heaters must be capable of reaching and maintaining temperatures of 800°F (430°C). Since the viscosity of Radel resins is temperature-sensitive, die temperature must be closely controlled to provide a uniform extrudate.

Streamlined dies should always be used. Streamlining the flow channel and incorporating purge plates (i.e., bleeder plugs) in the ends of sheeting dies eliminate the possibility of hang-up in the die and melt stagnation.

Dies should be capable of operating continuously at pressures up to 3,500 psi (240 bar). Flow channels, die lips, and lands should be highly polished and chromium-plated for optimum extrudate appearance.

Extruded Product Types

Wire

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

Film

The high melt strength of Radel resins provides excellent drawdown properties for the production of thin film. Slot-cast film possesses high modulus, good impact strength, and good electrical properties over a wide temperature range. The film is heat sealable and can be printed without pre-treatment.

Typical film extrusion conditions for a 2.5-inch (64-mm) extruder are:

Die: Standard film dies of coat hanger design and straight manifold-choker bar design are satisfactory. Die lip openings of 0.025 to 0.040 in. (1 to 1.5 mm) should be used for 1 to 10 mil film. Dies must be capable of continuous operation at 3,500 psi (240 bar).

Breaker Plates/Screenpacks: Breaker plates are not required and can cause “die lines”, but when used in conjunction with a screenpack can result in a consistent, defect-free extrudate. Alternatively, a sleeve can also seal the die adapter to the extruder.

Casting Roll: An 8.5-inch (215-mm) diameter roll at 350°F (180°C) is required to prevent wrinkling of the film.

Sheet

Standard round and teardrop manifold sheet dies with choker bars are satisfactory. Typically, die openings are 10 to 20 percent larger than the desired final thickness. In sheet extrusion, the take-off roll temperature must be maintained high enough to prevent curl and to minimize strains in the sheet. Either an "S" wrap technique or straight-through calendaring technique is satisfactory, providing that roll temperatures of 350 to 450°F (180 to 230°C) can be obtained. Calendaring also requires that a small bank (melt bead) be maintained at the roll nip.

A power shear has been used to cut the sheet to length for sheet thicknesses up to 0.100 inches (2.5 mm). For greater thicknesses, sawing is recommended.

Pipe and Tubing

Radel resins can be extruded into pipe and tubing using standard pin and spider assemblies. Control of stock temperature is critical to achieving high-quality extrudate. Stock temperatures of 650 to 700°F (340 to 370°C) are suggested.

Sizing plate and vacuum tank methods of dimensional control are satisfactory. For best melt control, the extrusion die should be 70 to 100 percent larger than the sizing die.

For high-quality extrusion, stress due to processing must be minimized. This is accomplished by minimizing the level of cooling in the vacuum-sizing bath while maintaining dimensional requirements. To this end, a short water bath (1/4th to 1/5th the length of that typically used for polyethylene) is desirable.

Start-Up, Shut-Down, and Purging

Start-Up Procedure

Feed warm pre-dried resin to the preheated extruder with the screw speed set to 15-20 rpm. As soon as the feed section is full, decrease speed to 5-10 rpm until material begins to exit the die. Adjust screw speed to desired extrusion rate.

Shut-Down Procedure

If a shut-down is required during an extrusion run, certain precautions should be taken. It is not good practice to allow resin to sit stagnant in an extruder for prolonged periods of time at extrusion temperatures. Some decomposition is likely to occur, and it may prove difficult to start again and properly purge the machine.

If the shut-down is of a short duration (two hours or less), purge the extruder with Udel polysulfone. Run the extruder dry, and then restart using starve feed. For longer shut-downs, the extruder should be purged with Udel polysulfone, and then run dry. The extruder heaters should be turned off and allowed to cool to room temperature. To start-up the next day, turn on the die heaters at least one hour, but preferably two hours, before turning on the extruder heaters. Once the extruder reaches 600

to 650°F (315 to 343°C), the screw can be rotated periodically until extrusion temperatures are reached. Start by starve feeding at low screw speeds until material comes out of the die.

Purging

Radel resins can be purged from extrusion processing equipment by a variety of techniques. Because Radel resins are tough, stable, high-temperature materials, the most effective purging procedures replace the Radel resin with a lower temperature plastic that is more easily removed. The generally recommended purging material is polyethylene, but suitable commercial purging compounds can also be used.

The most effective procedure is a step-wise purge, beginning with a natural polysulfone resin, such as Udel P-1700, and following with a low-melt-flow, high-density polyethylene. The polysulfone should be fed until it is running clear at the die. The extruder barrel temperatures may be lowered 30 to 50°F (15 to 25°C) as the polysulfone replaces the Radel resin. The polysulfone can then be purged by adding polyethylene to the machine while it is at 625 to 650°F (330° to 340°C) and running until the extrudate appears to be mainly polyethylene. When that point has been reached, the die, adapter, and breaker plate can be removed and cleaned of the polyethylene as it cools, and machine purging can continue. When no more polysulfone is visible in the extruder purge, the temperature may be safely lowered to 300°F (150°C). Various cleaning compounds may then be used, if desired.

An alternative procedure would be to follow the Radel resin directly with the low-melt-index, high-density polyethylene purge. Upon completion of the Radel resin extrusion, the machine should be run dry of material and the polyethylene introduced and extruded until no Radel compound is evident in the extrudate. The die, adapter, and breaker plate can be removed and cleaned. Polyethylene purging can then be continued until no evidence of Radel resin is seen in the extrudate, at which point the temperatures can be lowered to 300°F (150°C).

When purging is complete and the extruder has been run to an empty condition, the screw can be removed and both the barrel and screw brushed clean. If residual Radel resin can not be removed by brushing, it can be burned off using proper care. An alternative technique is soaking the parts in N-methyl pyrrolidone (NMP) until the residual resin is softened enough for easy removal.

Secondary Operations

Machining

Radel resins may be machined with normal metal working tools. Because of their high softening temperatures, relatively high cutting speeds can be used without gumming. The inherent toughness of these materials allows deep, smooth cuts to be made without chipping or shattering. If cooling is required, water spray works well.

Drilling and Tapping

Standard high-speed twist drills are recommended. Cutting speeds of 300 ft/min (90 m/min) at feed rates of 0.005 to 0.015 in/rev (0.15 to 0.40 mm/rev) are recommended. Tapping should be done with 2-flute or 3-flute high-speed steel spiral point taps.

Sawing

Standard band saws with blades containing ten teeth per inch operated at 3,000 to 5,000 ft/min (900 to 1,500 m/min) sawing rates work well, but other wood cutting configurations can also be used.

Turning

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

Cutting speeds of 500 to 2000 ft/min (150 to 600 m/min) with feed rates from 0.002 to 0.010 in/rev (0.05 to 0.25 mm/rev) can be used.

Milling and Routing

Milling and routing are readily accomplished at high speeds without coolants or lubricants. Tools for aluminum work well. For example, a groove 0.5 inches (13 mm) wide, 0.100 inches (2.5 mm) deep can be end milled at 1,750 rpm with a feed rate of 4.5 in/min (115 mm/min).

Finishing and Decorating

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

Painting

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

Good adhesion with no embrittlement is a critical paint requirement. For proper paint adhesion, removal of foreign matter, such as dirt, oil, grease, and mold release, from the part surface

is critical. When contaminants are present, parts should be cleaned first. Properly handled parts may not need any cleaning and can be painted without such treatment.

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

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

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

Electroplating

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

Hot Stamping

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

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

Printing

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

Printing inks suitable for use on Radel resin can include a variety of air-dry, plural-component, and ultraviolet-radiation curing inks.

Reinforced grades of Radel resin are acceptable for laser marking.

Vacuum Metallizing

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

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

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

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

Cathode Sputtering

The high heat resistance of Radel resins allows the use of cathode sputtering. Metals with low vapor pressures like copper and silver are used most frequently. Other acceptable metals are platinum, palladium and gold.

Cathode sputtering permits precise control of the metallic coating thickness and provides improved adhesion of the coating to the part. Both are critical for applications such as sub-miniaturized electrical circuitry.

Flame/Arc Spraying

Flame and arc spraying of metallic coatings may successfully be used with Radel resin.

This technique involves the use of pure aluminum, copper, or zinc powder metered into a special spray gun. The metal powder is melted by a flame or electric arc and sprayed onto the part, producing a hard, dense coating.

Assembly and Joining

Ultrasonic Bonding

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

The principle involved in ultrasonic joint design is to concentrate the energy in an initial small contact area. The high frequency vibration melts the material, pressure is maintained

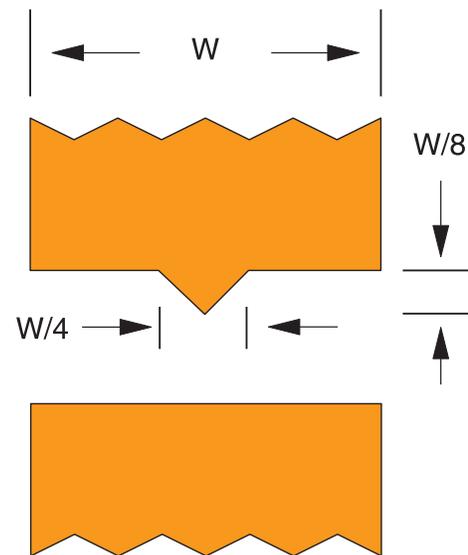
when the vibrations stop and the melt solidifies. The bond which is now formed may be as strong as the strength of the original material.

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

The basic butt joint with energy director is shown in Figure 73. The V-shaped energy director concentrates the ultrasonic energy to this area, which quickly melts and creates a melt pool as the parts are pressed together. A mating flow channel is preferred in cases where an hermetic seal is desired.

Figure 73.

Energy Director Design



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

- The welding horn should have a suitable contact area.
- The joint/weld area should be located as close as possible to the point where the welding horn will contact the plastic part.
- Large mating surfaces and close fit joints should be avoided.
- Allow for adequate flow of molten material.

Spin Welding

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

Adhesive Bonding

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

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

It is also critical that the surface is free of any contaminants, such as grease, oil, fingerprints and mold release, which can weaken the bond. In some cases, the surfaces of the materials to be bonded must be chemically etched or mechanically roughened to allow the adhesive to gain a firm grip. Clamping

pressure should be sufficient to insure good interface contact, but not so high that the parts are deformed or that solvent is forced from the joint.

The joint area should be designed so that the two parts fit precisely together. Figure 74 shows recommended joint designs for adhesive bonding. Parts should be molded with low residual stresses and to accurate dimensions.

Mechanical Fasteners

Fasteners frequently used with injection molded plastic parts include screws, bolts, nuts, lock washers, and lock nuts. When using metal mechanical fasteners, good design practice should be used to prevent the plastic parts being assembled from becoming over stressed.

The most obvious procedure for preventing a high-stress assembly is to control the tightening of the mechanical fasteners with adjusted torque-limiting drivers. When torque cannot be controlled, as might be the case with field assembly, shoulder screws can limit compression on the plastic part. Other alternatives are the use of flange-head screws, large washers, or shoulder washers. Figure 75 presents some preferred designs when using mechanical fasteners.

Figure 74.

Joint Designs for Adhesive Bonding

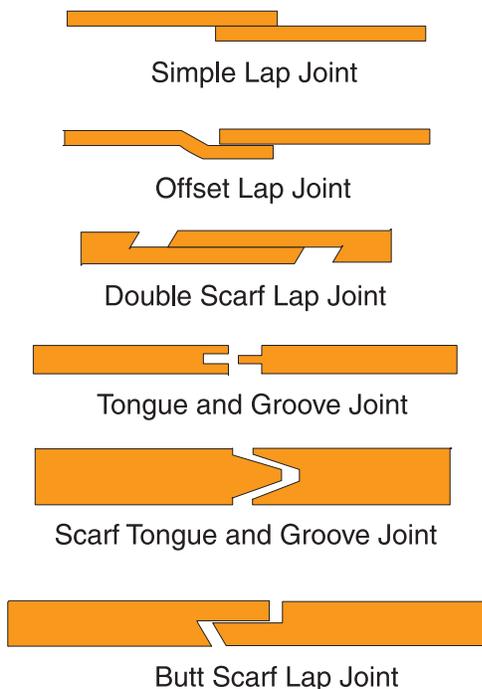
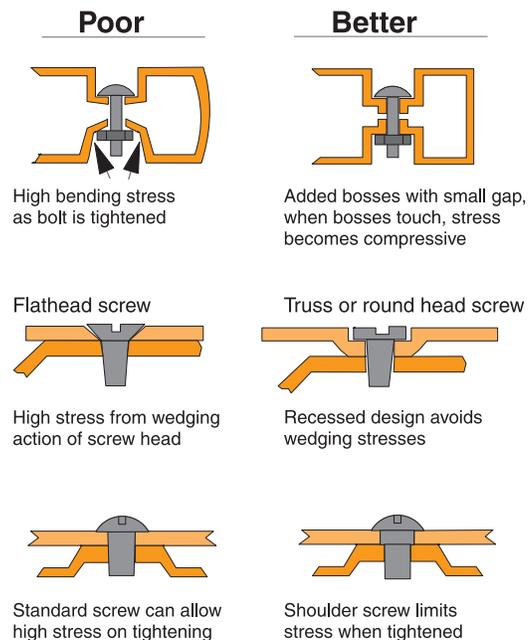


Figure 75.

Designing for Mechanical Fasteners



Molded-In Threads

With molded-in threads mating male and female threads are molded into the parts to be assembled. Molded internal threads usually require some type of unscrewing or collapsing mechanism in the tool as shown in Figure 76. In some case external threads can be molded by splitting them across the parting line as shown in Figure 77. Molding very fine threads which exceed 28 pitch is usually not practical.

Figure 76.

Internal Threads

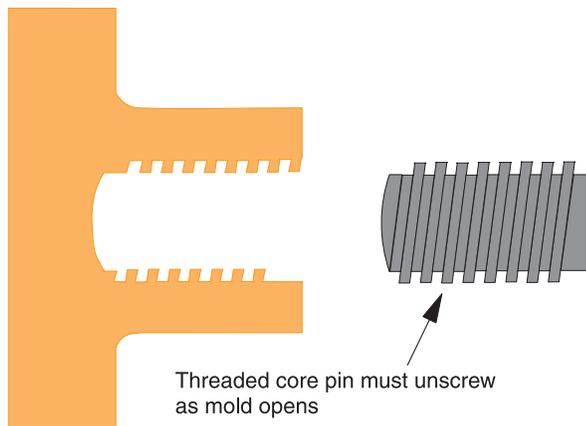
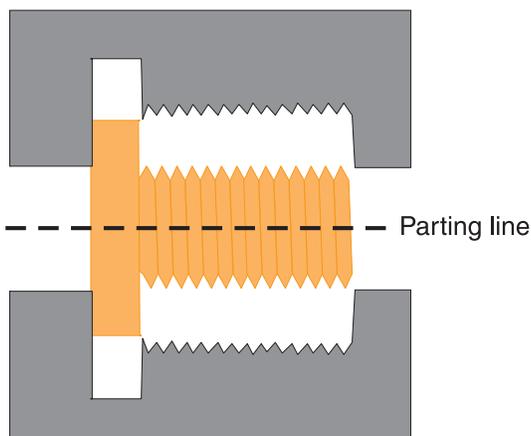


Figure 77.

External Threads



Threaded Inserts

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

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

Besides female threads, inserts can be threaded male styles, locating pins and bushings. The recommendations on installation procedures and boss dimensions can be provided by the insert supplier and resin manufacturer.

Self-Tapping Screws

Self-tapping screws are suitable for use with Radel A and Radel R resins. Self-Tapping screws provide an economical method for joining plastics because they eliminate the need for molding an internal thread or a separate tapping operation.

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

Figure 78.

Boss Design for Self-Tapping Screws

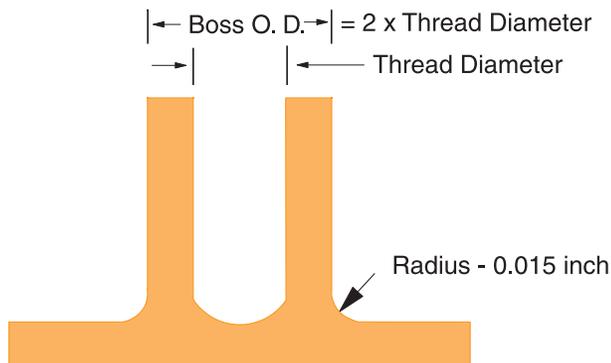


Figure 78 illustrates the basic guidelines for designing with self-tapping screws. These include:

- Use a hole diameter equal to the pitch diameter of the screw for the highest ratio of stripping to driving torque.
- The standard boss diameter recommendation is 2 times the screw diameter. Too thin a boss may crack and no increase in stripping torque may be achieved with thicker bosses.
- Stripping torque increases rapidly with increasing length of engagement and levels off when the engaged length is about 2.5 times the pitch diameter of the screw.
- To avoid stripping or high-stress assemblies, torque-controlled drivers should be used on assembly lines.
- Repeated assembling and disassembling should be avoided when using self-tapping screws. If repeated assembly is required, thread forming screws are recommended.

Ultrasonic Inserts

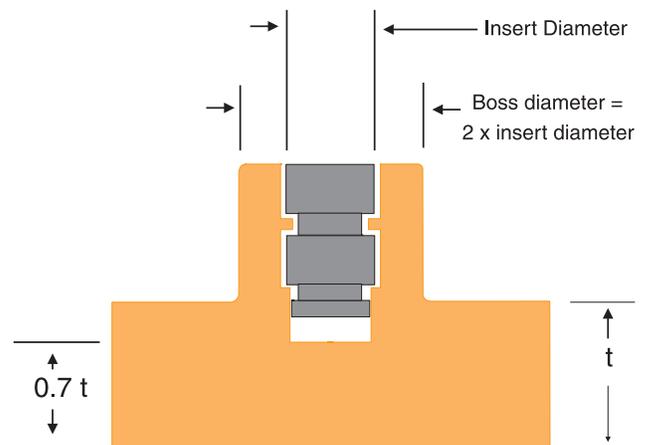
Metal parts can be ultrasonically inserted into parts of plastic as an alternative to molded-in or pressed-in inserts. With proper design, ultrasonic insertion results in lower residual stresses compared to other methods of insertion.

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

Figure 79 depicts the recommended insert and boss designs for use with Radel resin.

Figure 79.

Boss Design for Ultrasonic Inserts



Snap-Fits

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

The two most common types of cantilever beam snap-fits are straight beam and tapered beam. Figure 80 and Figure 81 show these typical snap-fit designs and the corresponding equations for calculating the maximum strain during assembly. The proportionality constants for a tapered beam design are shown in Figure 82. The design should not have a maximum strain greater than the permissible strain shown in Table 46.

Table 46.

Maximum Permissible Strains For Snap-Fit Designs

Radel Grade	Maximum Permissible Strain
A-200A	6.0
AG-310	3.0
AG-320	1.5
AG-330	1.0
R-5000/5100/5200	6.7

Figure 80.

Snap-Fit Design Using Straight Beam

$$\text{Maximum Strain } \epsilon = \frac{3Yh_0}{2L^2}$$

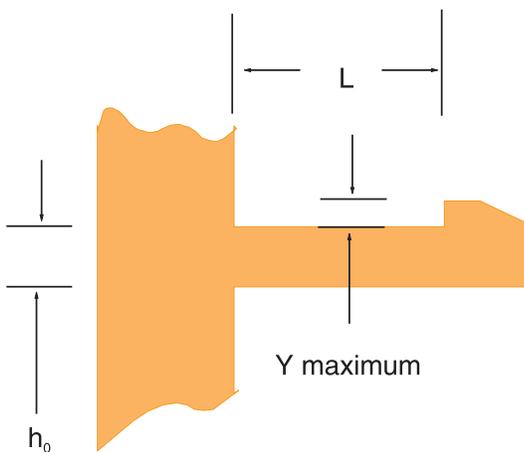


Figure 81.

Snap-Fit Design Using Tapered Beam

$$\text{Maximum Strain } \epsilon = \frac{3Yh_0}{2L^2K}$$

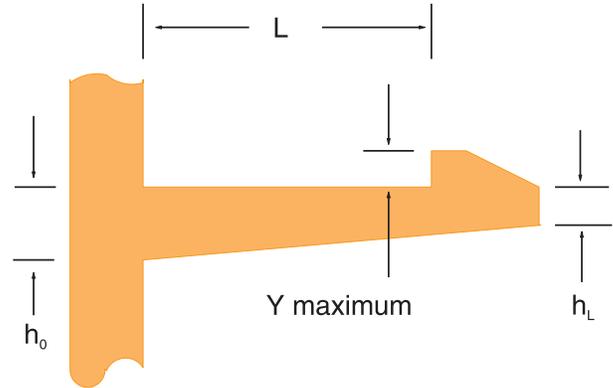
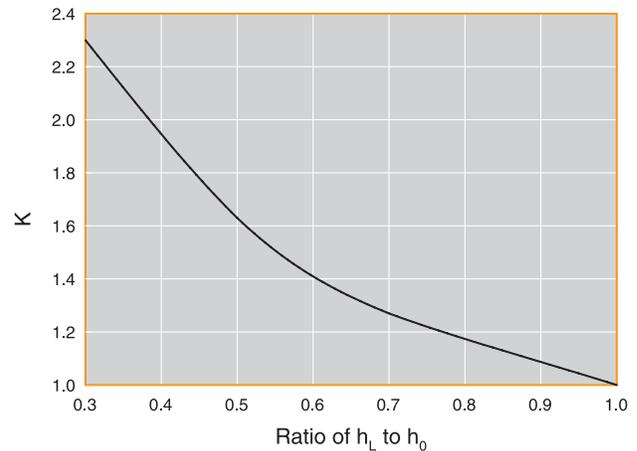


Figure 82.

Proportionality Constant (K) for Tapered Beam



It is recommended that the snap-fit fingers be located away from sharp corners, gates or knitlines. If a large number of assembly cycles is expected, fatigue life could be a consideration and a lower strain limit may be required.

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Notes

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