DuPont™ Vespel® S Line

Design Handbook

Contents

Introduction

General

A number of innovations in both product development and fabrication technology have led to a family of polyimide products that offer the design engineer practical, cost-competitive solutions to difficult problems in high performance applications.

Commercial for more than 50 years, DuPont™ Vespel® SP Parts and Shapes are particularly adapted to applications where thermal stability, electrical properties, wear and friction behavior are required in mechanical components.

Vespel® SCP further increases the already excellent thermal stability and mechanical properties of the Vespel® family.

From these polyimide resins DuPont fabricates Vespel® parts to customers' exact specifications. Stock shapes such as rods, tubes and plaques are also available for machining prototypes.

Today's competitive markets place a high premium on the role of the design engineer, both in designing new products and redesigning existing ones. Vespel® parts, like all plastic parts, are governed by the same rules for good design and by the same physical laws as other materials. The purpose of this manual is to help designers apply these principles to the selection, testing and specification of Vespel® parts.

This design manual contains comprehensive physical property and performance data on the SP and SCP polyimide resins from which Vespel® parts are made. Selection of data for this manual has been based to some extent on discussion with customers' design engineers involved with applications of Vespel® parts. All of the data in the sections that follow are the result of extensive physical property research in DuPont laboratories around the world. Nevertheless, end-use testing is always recommended.

Vespel® Parts meet ASTM D6456-10 Standard Specification for Finished Parts Made from Polyimide Resin for applicable grades.

Today Vespel® parts and shapes are produced in Newark, DE and Valley View, OH, USA; Utsunomiya, Japan; Tuas, Singapore; and Mechelen, Belgium.

Chemistry

Polymer—Vespel® SP is a condensation type polyimide produced from pyromellitic dianhydride (PMDA) and 4,4' diamino diphenyl ether (ODA).

Vespel® SP has no observable glass transition temperature or melting point below a decomposition temperature that is well in excess of 400 °C (752 °F).

This lack of glass temperature or melting point is a key feature in product performance. Therefore Vespel® performs like thermosets.

Figure 1. Chemical Structure of Vespel® SP
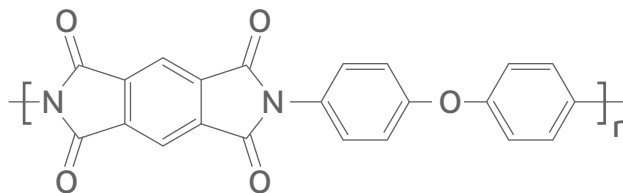
The major advantage of Vespel® SCP polyimide is increased thermal oxidative resistance. Like Vespel® SP, SCP resins perform over a large range of temperatures from cryogenic to extreme heat. Along with improved thermal and chemical resistance, SCP resins also exhibit increased mechanical properties such as strength and toughness.

Fabrication Methods

DuPont fabricates Vespel® precision parts by several basic production methods. The method ultimately chosen is based on a number of considerations — end-use requirements, customer specifications, part geometry and economics. All standard metalworking techniques can be employed, and very close tolerances can be held. For detailed fabrication instructions, reference the Vespel® Machining Guide.

Larger quantities of parts, geometry permitting, can be direct-formed by a technique similar to powder metallurgy. Direct-formed parts usually can be produced at substantially lower prices than machined parts from shapes. Where specific part tolerances or complexity exceed the capability of the direct-forming method, a combination of direct forming and secondary machining is often used.

Properties versus Direction

In common with most plastics, DuPont™ Vespel® parts exhibit anisotropy or differences in properties depending on the direction of force used in fabrication. For example, properties such as tensile strength and elongation are higher and thermal expansion lower in the plane perpendicular (⊥) to the molding force than in the direction parallel (||) with the force.

Vespel® parts machined from ISO shapes usually do not show this effect.

The typical properties of machined parts were obtained from samples prepared from isotropic material. The material is formed so that properties are uniform throughout regardless of direction.

Direct-formed parts are produced with the pressure applied unidirectionally, resulting in some anisotropy, or directionality, of properties. Directionality is increased with the addition of fillers. The highest strength and elongation and the lowest

thermal expansion are found in the direction perpendicular to the pressing direction in most parts. The data presented here for direct-formed parts, except for compressive properties and thermal conductivity, were obtained in the perpendicular direction.

It is very important, testing Vespel® in an application, to use the material (either shape or direct formed) that will be used commercially. For this reason, DuPont offers direct formed material (slugs) for prototyping.

Establishing Specifications

The establishing of specifications usually follows several other key steps in developing a new application for DuPont™ Vespel® precision parts. Defining the end-use requirements is a necessary first step such as temperature, pressure and mechanical properties.

Drafting the preliminary design, preparation of prototypes and testing the design are steps that normally follow. The design engineer should always be aware that designing plastic parts usually requires higher tolerances than metal.

The various fabrication techniques for producing Vespel® precision parts make possible great flexibility in meeting customer specifications.

This manual presents typical property values (Appendix B) for direct formed parts and parts machined out of shapes. Because these published values are averaged, it is suggested not to base specifications on the maximum values.

Quality

Vespel® parts are custom-made by DuPont to meet the stringent quality requirements of the world's most demanding original equipment manufacturers — part to part and order to order. Our Statistical Process Control (SPC) procedure makes it possible to produce consistently high-quality parts at lower cost compared with conventional process control methods. The accuracy of SPC even permits some customers to eliminate their own inspection of incoming parts — for substantial cost savings.

Procedures include both laser inspection and digital microscopy for dimensional tolerances and uniformity, and ultrasonic testing for material integrity.

Because the production details of every order are kept on file, finished product can be traced all the way back to the original resin batch, if required.

All Vespel® production sites are certified ISO 9001, IATF 16949 and AS/EN 9100.

As an example for our highest quality commitment the DuPont™ Vespel® Mechelen site is rated as preferred supplier by Rolls Royce Aero Engines Company.

Worldwide, DuPont has implemented the total quality management system to ensure top quality under all aspects. For parts this means quality assurance from the incoming raw material to the finished part delivered in time to the customer.

DuPont's quality production follows the idea to avoid errors instead of eliminating tasks. We are committed to continuous improvement following the Six Sigma, the VDA (Verband der Automobilindustrie E.V.) guidelines as well as all the other quality requirements specified by our customers, using the IATF16949 core tools.

All items to ensure quality are listed in the quality handbook which is continuously updated.

Definitions/Abbreviations

Abbreviations

FMEA	Failure Mode Error Analysis
MSA	Measurement System Analysis
APGP	Advanced Product Quality Planning
PPAP	Production Part Approval Process
SPC	Statistical Process Control
RMI	Raw Material Inspection
RMD	Risk Management Documentation
PITA	Production and Inspection Tool Administration
MOS_2	Molybdenum Disulfide
CTE	Coefficient of Thermal Expansion
PV	Pressure Velocity
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
RH	Relative Humidity
CO	Carbon Monoxide
TOS	Thermal Oxidative Stability

Definitions

ISO: Parts machined out of isostatic shapes material (Class M in ASTM standard).

DF: Parts obtained by Direct Forming process (Class D in ASTM standard).

Perpendicular: Measured perpendicular to the forming direction.

Parallel: Measured parallel to the forming direction.

Plaque: Parts machined out of our plaque process (hot compression)

Compositions and Properties

Selector Guide

Grades	Typical End-Use Applications	Polyimide Compositions

DuPont™ Vespel® SP precision parts are available in a number of standard and special purpose compositions. Some compositions contain fillers to enhance the performance of the polyimide material in one or two key characteristics.

Graphite is added, for example, to reduce friction and wear and fluoropolymer to lower static friction or reduce abrasion against soft metals. A brief description of DuPont's polyimide compositions follows.

Vespel® SP for Demanding Applications

Grades	Typical End-Use Applications	Polyimide Compositions
SP-1	Mechanical and electrical parts at elevated temperatures. Valve seats, seal, insulators.	Unfilled base resin. Maximum strength and elongation: lowest modulus and thermal conductivity: optimum electrical properties.
SP-21	For lubricated or non-lubricated, low friction and wear applications. Valve seats, seals, bearings, washers, seal rings.	Contains graphite. Enhances inherent wear resistance, improves long term thermal stability.
SP-22	Applications in which low thermal expansion is more important than strength (which is slightly reduced). Bearings (bushings, washers, etc.).	Contains graphite. Gives low coefficient of thermal expansion. Maximum creep resistance.
SP-211	For low friction and wear applications in moderate temperature and PV environments. Bearings (bushings, washers, etc.).	Contains graphite and fluoropolymer. Lowest static friction.
SP-3	For friction and wear applications in vacuum or inert gases. Bearings, piston rings and seals.	Contains MoS_2. For friction and wear applications in vacuum or inert gases.
SP-2515	Designed for wear against aluminum, low coefficient of friction in dry environments.	Contains graphite. High thermal conductivity, low CTE (matches aluminum).
SP-202	Electronics handling. Low wear rates for long part life and cleaner environments.	Conductive. With advanced filler technology materials needed for electronics handling.

DuPont developed Vespel® SCP as the next generation of polyimide, fulfilling the need for materials which can withstand even more demanding applications. Vespel® SCP builds on decades of experience using polyimides in the most challenging applications, while offering the following advantages over Vespel® SP:

• Increased thermal stability • Better chemical resistance • Improved wear and friction performance • Improved mechanical properties

As with Vespel® SP, multiple grades of Vespel® SCP are available to service specific application needs:

Vespel® SCP: Next Generation Polyimide for Highest Thermal Oxidative Resistance and Strength

Grades	Typical End-Use Applications	Polyimide Compositions
SCP-5000	Aerospace applications, electronics (wafer inspection disk). Best performance at the highest temperatures for the longest times.	Unfilled SCP polyimide resin.
SCP-5009	Ball bearing retainers, bushings, washers	Advanced filler technology. Excellent combination of physical properties, such as high compressive strength and low tendency to creep, even under extreme conditions.
SCP-50094	Valve seats, test sockets, bearings and bushings.	Advanced filler technology. Highest PV limit of any grade. Excellent combination of physical properties, wear resistance and temperature resistance.
SCP-5050	CTE matches steel and cast iron.	Advanced filler technology. Lowest CTE. Unsurpassed wear resistance and thermal stability.

All the above information is subject to the disclaimer printed on the back page of this document.

We hope this publication stimulates ideas on how Vespel® SP and SCP can help you solve your design challenges. If you have any questions, comments, or need additional information contact your local DuPont™ Vespel® technical service engineer before you begin your design. They will be happy to provide information on Vespel® parts, to discuss similar applications and to help you obtain Vespel® materials for testing and prototyping.

Physical Properties

Vespel® SP and SCP precision parts, formed from DuPont polyimide resins, possess a unique combination of physical properties that add new dimensions to the plastic engineering materials currently available. These properties include:

- An operating range from cryogenic temperatures to 500 °C (932 °F) for many applications

- Continuous service temperature up to 300 °C (572 °F) in air

- Very high PV (dry pressure velocity limits to 12 MPa m/s and even higher with lubrication) values for bearing applications

- High dielectric strength

- Excellent mechanical strength and solvent resistance

- Low outgassing and high resistance to ionizing radiation

Summaries of typical properties are presented in Tables 1, 2, 3 and 4 in Appendix B. The graphs and tables that follow provide specific details.

DuPont Vespel® SP-202 was developed as a conductive material for electronics handling applications. This grade, available in plaque form, has a combination of capabilities for these applications:

- Electrostatic charge removal. Vespel® SP-202 is a conductive plastic grade with surface and volume resistivity values in the range of 10^{-1} to 10^{1} (ohm, ohm-cm).

- Vespel® SP-202 has the thermal resistance to maintain tolerances in high heat applications and through multiple thermal cycles.

- Lower wear rates on contact surfaces generate longer part life and cleaner environments.

- Vespel® SP-202 can be machined to tight tolerances with relative ease.

Vespel® SP Resins—Effect of Temperature

Since SP polyimides do not melt and have no glass transition temperature (Tg) or softening point as measured by the usual methods, strength and moduli decrease with temperature in a nearly linear manner. This contrasts to the usual engineering thermoplastic which shows a large decrease in these properties as the Tg is approached. Figures 2 through 5 illustrate typical changes in tensile strength and modulus of elasticity with temperature for machined and direct-formed parts.

The upper use temperature of SP and polyimides is limited by their rate of degradation, not by a softening point where they would lose their load-carrying capability. Parts may be used continuously in air up to 300 °C (572 °F) and for short excursions to as high as 500 °C (932 °F).

Figure 6 illustrates usefulness at high temperatures in terms of time to 50% reduction in initial tensile strength. For example,

after 100 hr continuous exposure to air at 370 °C (698 °F), SP-1 polyimide will retain half its initial strength. The graphite filler in SP-21 and SP-22 polyimide imparts some physical stability to the parts which is manifested in a greater retention of properties with time. SP-21 requires about 200 hours at 370 °C (698 °F) and SP-22 350 hours to reach the 50% strength level (see Figure 6).

The loss in properties with time at temperatures up to about 400 °C (752 °F) is due almost entirely to oxidative degradation. At temperatures up to at least 340 °C (644 °F), SP parts will perform in inert environments such as nitrogen or vacuum with negligible loss of properties with time.

Naturally, the data in Figure 6 should only be used as a guide, since the useful service life of DuPont™ Vespel® parts is usually much greater. This is because the temperatures encountered are often intermittent instead of continuous, and because the parts are generally covered to some extent by a housing or retainer. Seldom are Vespel® parts totally exposed to air in high-temperature applications.

Vespel® SCP Resins—Effect of Temperature

Like Vespel® SP polyimide, Vespel® SCP does not melt. Vespel® SCP shows a more linear decrease in strength and moduli compared to large decreases seen in thermoplastics due to thermal transitions. Rather than an upper temperature limit determined by a melting or softening point, Vespel® SCP is limited instead by thermal degradation. One of the most outstanding improvements offered by Vespel® SCP is in this area of thermal degradation, specifically increased thermal oxidative resistance. Because Vespel® SCP does not melt, extreme temperature excursions are possible [>450 °C (842 °F)] for short periods of time. At temperatures where other polymers have melted, Vespel® SP and Vespel® SCP can operate continuously, or for hundreds or thousands of hours and maintain stiffness.

Mechanical Properties

Figures 7 and 8 are typical stress/strain curves for machined plaque samples. The curves for a given composition differ between the two forms because of the lower density of the direct-formed parts.

Figures 9 through 14 provide data on stress-strain in compression. While you can load most SP/SCP polyimide compositions in compression to high strains (>30%) without reaching ultimate strength, in practice this would result in a grossly deformed part. The curves showing low strains (up to 5%) illustrate the practical limits of loading without significantly exceeding the elastic limits of the materials. Unlike thermosetting materials, polyimides can be compressed several percent before reaching this deformation level. The materials are quite compliant and useful in forming seals of many types.

Figure 2. SP/SCP polyimide ISO shapes. Typical ultimate tensile strength vs. temperature, ASTM D1708
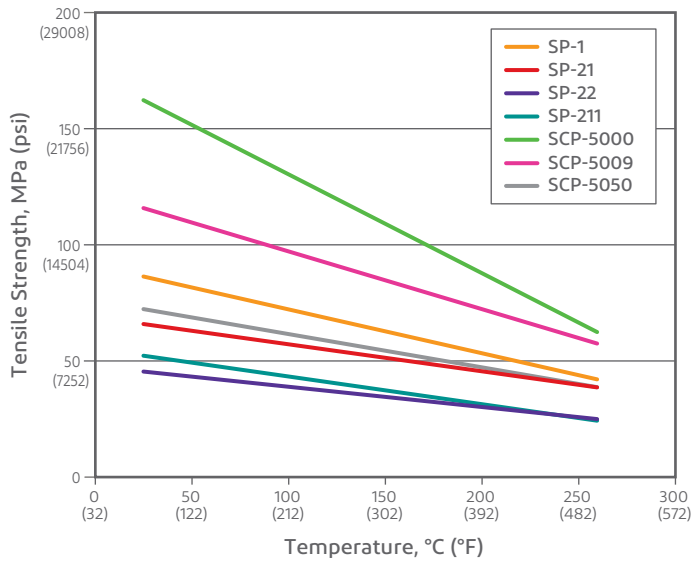

Figure 4. SP/SCP polyimide ISO shapes. Typical modulus of elasticity (flexural modulus) vs. temperature, ASTM D740
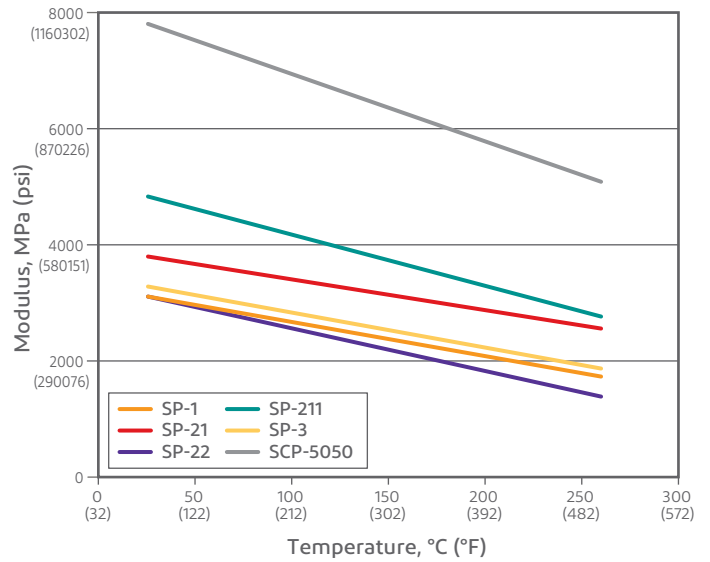

Figure 3. Direct formed SP/SCP polyimide. Typical ultimate tensile strength vs. temperature, ASTM E8
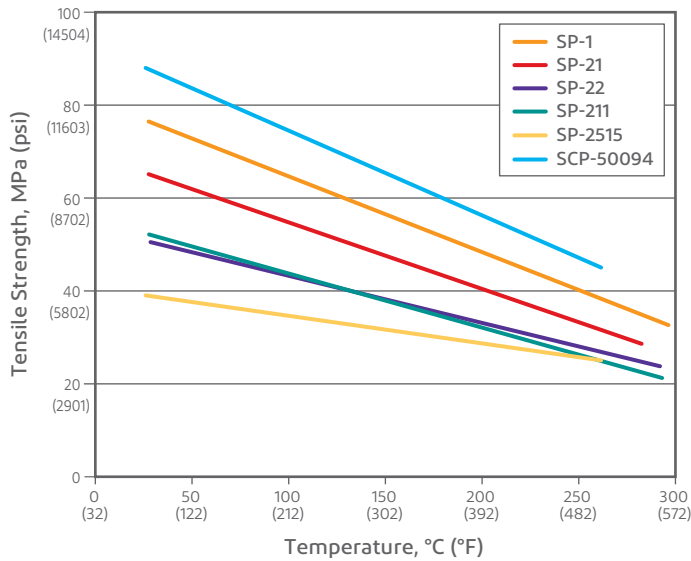

Figure 5. Direct formed SP/SCP polyimide. Typical modulus of elasticity (flexural modulus) vs. temperature, ASTM D790
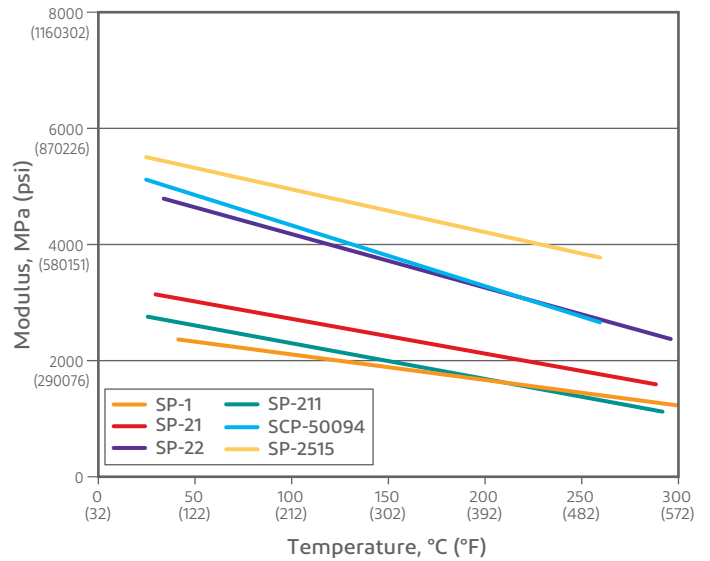

Figure 6. SP polyimide exposure to air at elevated temperature. Approximate time to 50% reduction in tensile strength vs. temperature
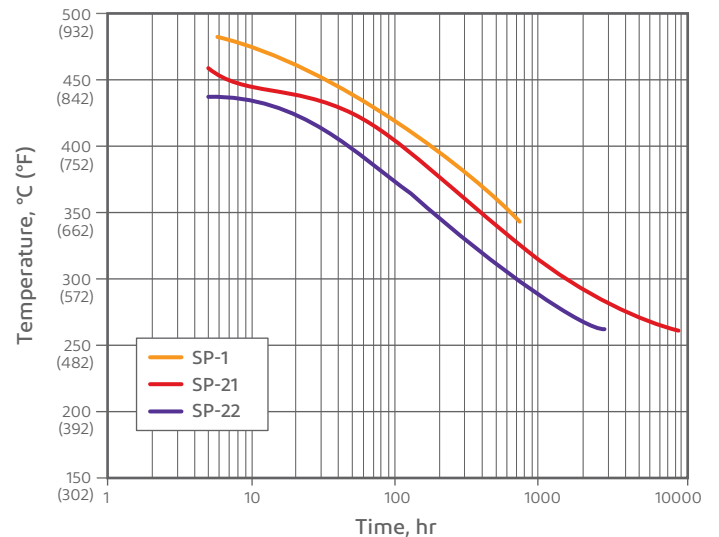

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Figure 7. Plaque SP/SCP polyimide. Typical stress/strain in tension at 23 °C (73 °F), ASTM E8 (⊥ to forming)
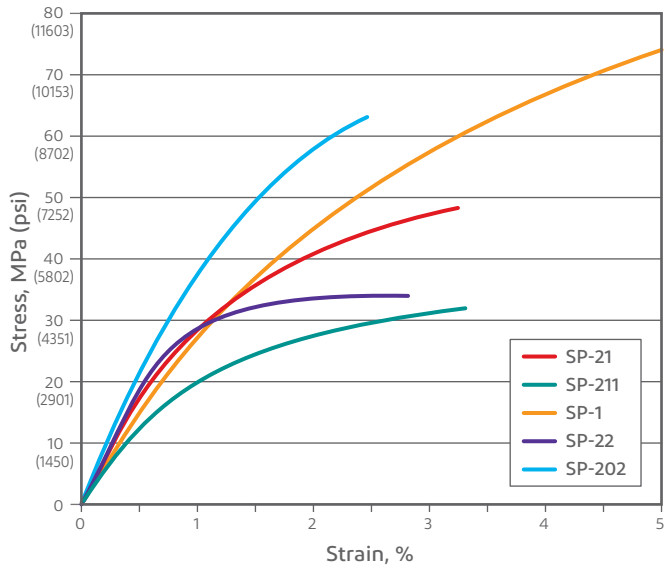

Figure 8. Plaque SP/SCP polyimide. Typical stress/strain in tension at 260 °C (500 °F), ASTM E8 (⊥ to forming)
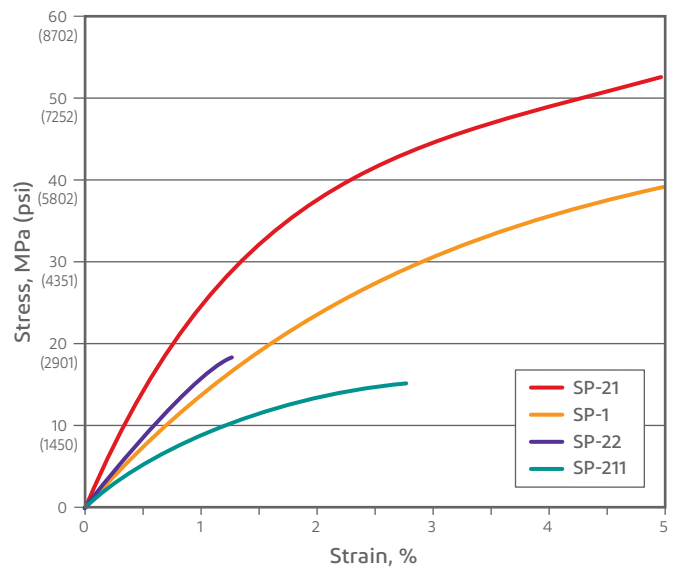

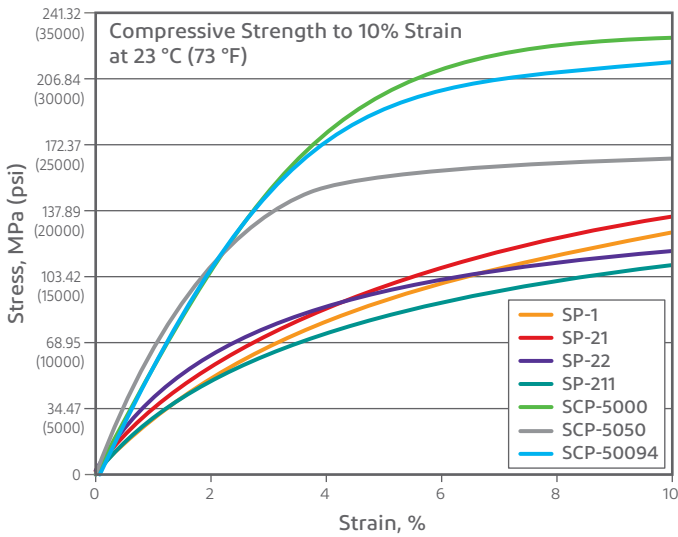**Figure 9. Machined SP/SCP polyimide ISO shapes in compression at 23 °C (73 °F), ASTM D695**

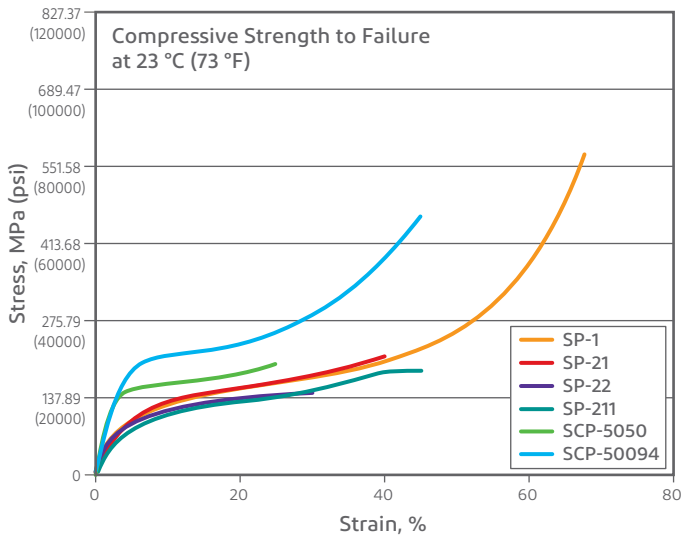**Figure 10. Machined SP/SCP polyimide ISO shapes in compression at 23 °C (73 °F), ASTM D695**

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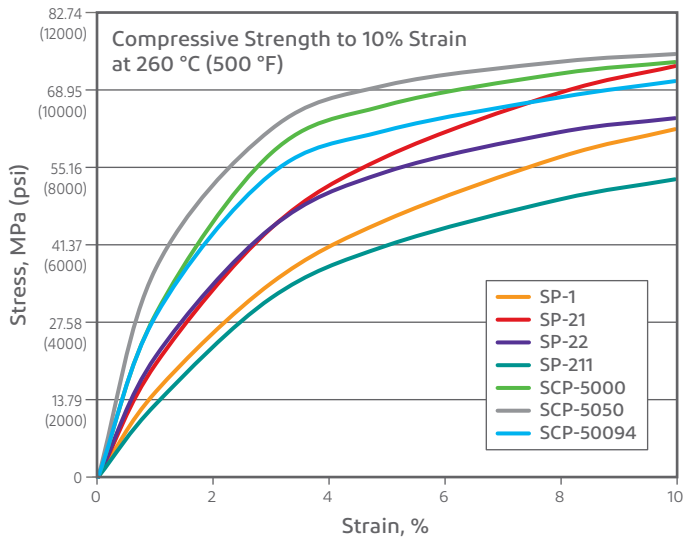**Figure 11. SP/SCP polyimide ISO shapes in compression at 260 °C (500 °F), ASTM D695**

Compressive Strength to 10% Strain at 260 °C (500 °F)

Legend:
- SP-1
- SP-21
- SP-22
- SP-211
- SCP-5000
- SCP-5050
- SCP-50094

Stress, MPa (psi) vs Strain, %

Figure 13. Direct-formed SP/SCP polyimide. Typical stress/strain in compression at 260 °C (500 °F), ASTM D695 (⊥ to forming)

Compressive Strength to 10% Strain at 260 °C (500 °F)

Legend:
- SP-1
- SP-21
- SP-22
- SP-211
- SCP-5050
- SP-2515
- SCP-50094

Stress, MPa (psi) vs Strain, %
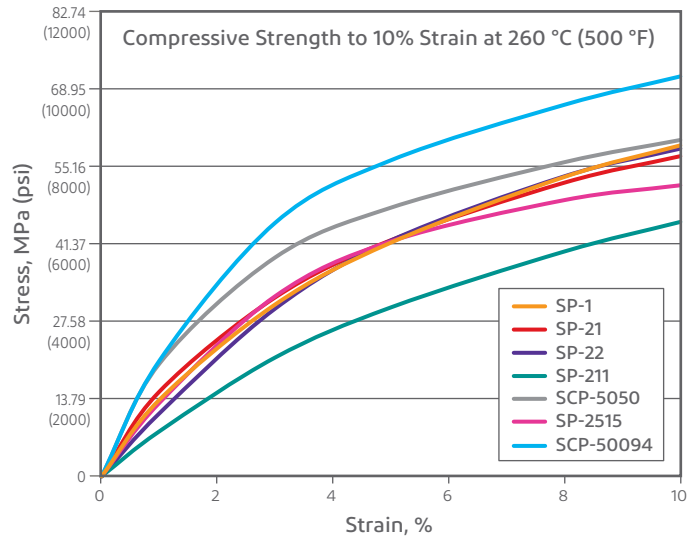
Figure 12. Direct-formed SP and SCP polyimide. Typical stress/strain in compression at 23 °C (73 °F), ASTM D695 (⊥ to forming)

Compressive Strength to 10% Strain at 23 °C (73 °F)

Legend:
- SP-1
- SP-21
- SP-22
- SP-211
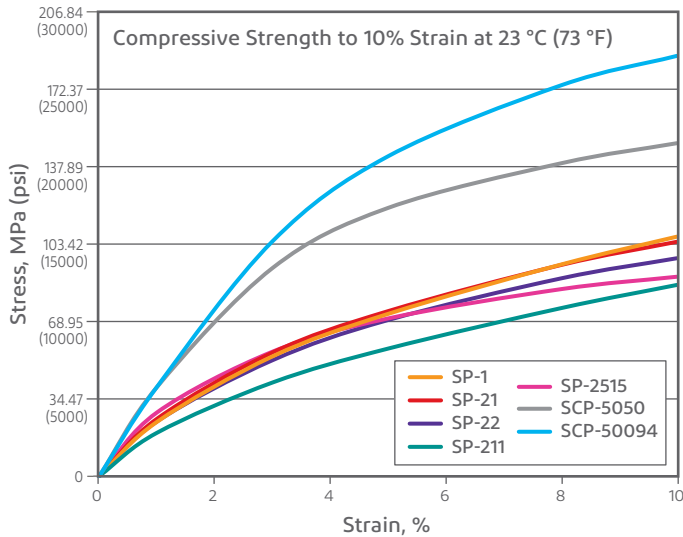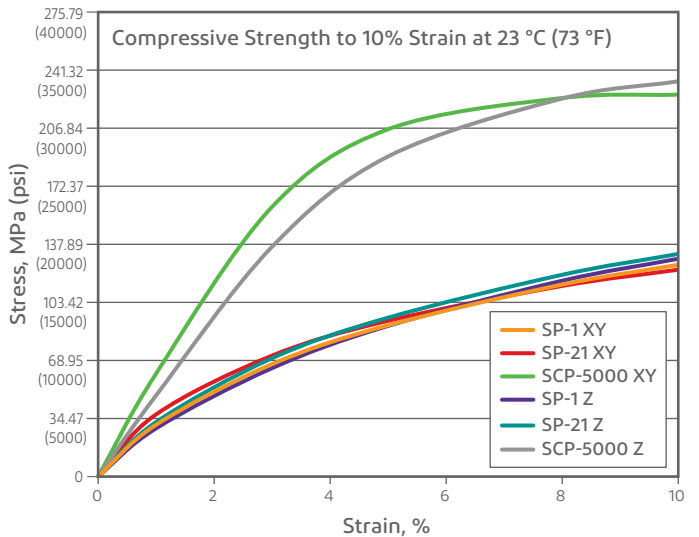- SP-2515
- SCP-5050
- SCP-50094

Stress, MPa (psi) vs Strain, %

Figure 14. Plaque SP and SCP polyimide. Typical stress/strain in compression at 23 °C (73 °F), ASTM D695 (⊥ to forming)

Compressive Strength to 10% Strain at 23 °C (73 °F)

Legend:
- SP-1 XY
- SP-21 XY
- SCP-5000 XY
- SP-1 Z
- SP-21 Z
- SCP-5000 Z

Stress, MPa (psi) vs Strain, %

Creep and Stress Relaxation

The time-dependent deformation which occurs in a plastic material under constant stress is called creep.

Creep at a given time is the difference between the total strain at that time and the initial instantaneous strain experienced on loading.

The time-dependent decrease in the stress needed to maintain a constant strain is called stress relaxation.

Figures 15, 16 and 17 show total deformation or strain vs. time under 10.3 and 17.2 MPa (1494 and 2495 psi) for machined ISO SP-1, SP-21 and SP-22 polyimide at two temperatures.

Since SP polyimide doesn't soften and is thermally resistant, it can carry loads at temperatures beyond the reach of most plastic materials and do so while exhibiting extremely low creep. Creep resistance is further enhanced in the graphite-filled compositions, SP-21 and SP-22. For example, Figure 17 shows that creep for SP-22 polyimide at 17.2 MPa (2495 psi) and 300 °C (572 °F) is only 0.9% after 1000 hours.

Figures 18 through 20 give the change in apparent modulus of elasticity with time corresponding to Figures 15 through 17. Substituting the appropriate time-dependent apparent modulus for elastic modulus in standard engineering equations will allow prediction of the effects of creep and stress relaxation.

Figure 21 gives data on creep testing for Vespel® SCP. Again, the improved strength of Vespel® SCP builds on the already excellent creep resistance of Vespel® SP. This is true for temperatures from cryogenic to extreme heat, making Vespel® SCP a flexible solution for a diverse range of applications.

Figure 16. SP-21 polyimide ISO shapes. Total deformation under load vs. time

Figure 17. SP-22 polyimide ISO shapes. Total deformation under load vs. time

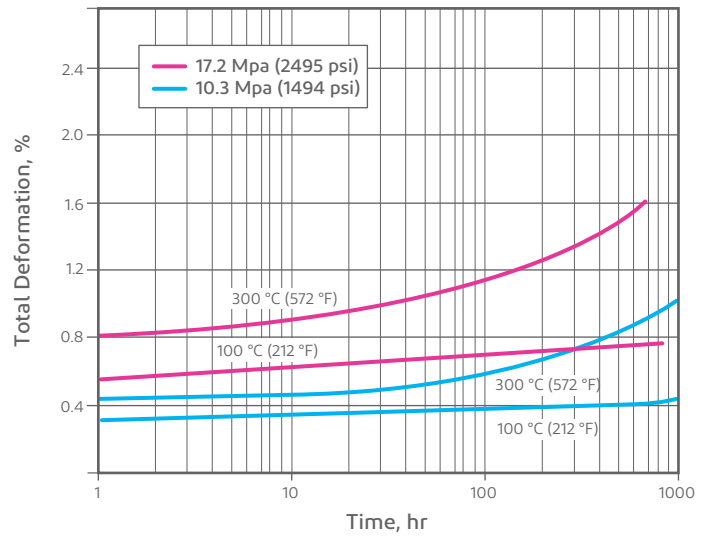**Figure 15. SP-1 polyimide ISO shapes. Total deformation under load vs. time**
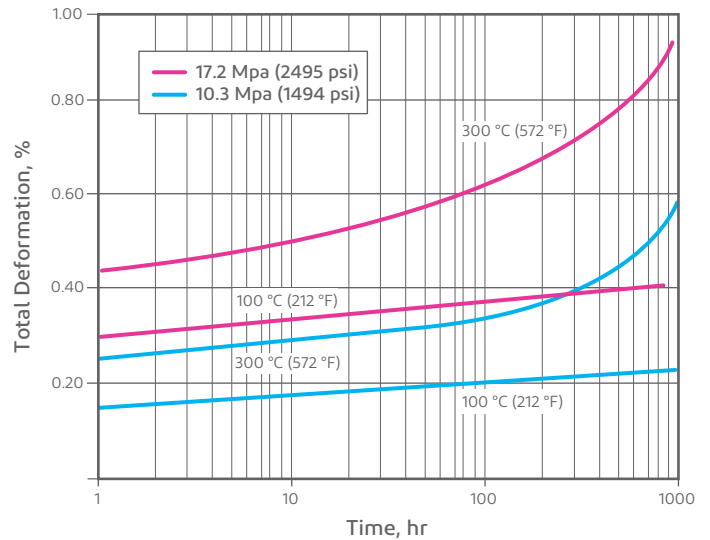
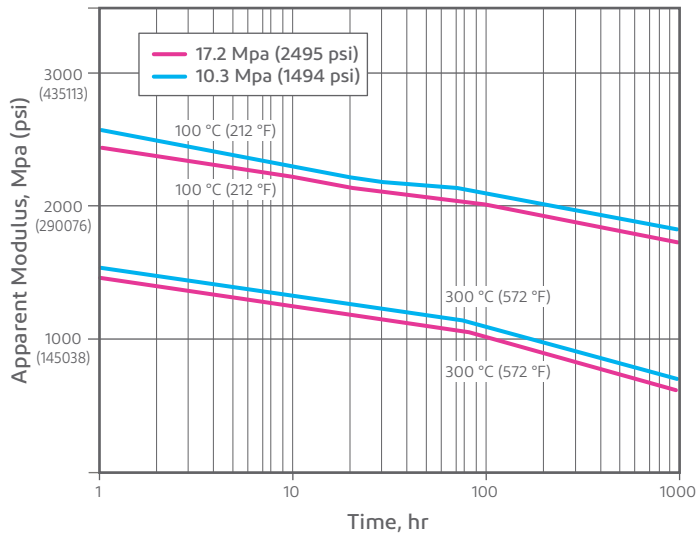**Figure 18. SP-1 polyimide ISO shapes. Apparent modulus vs. time under load**

Figure 20. SP-22 polyimide ISO shapes. Apparent modulus vs. time under load
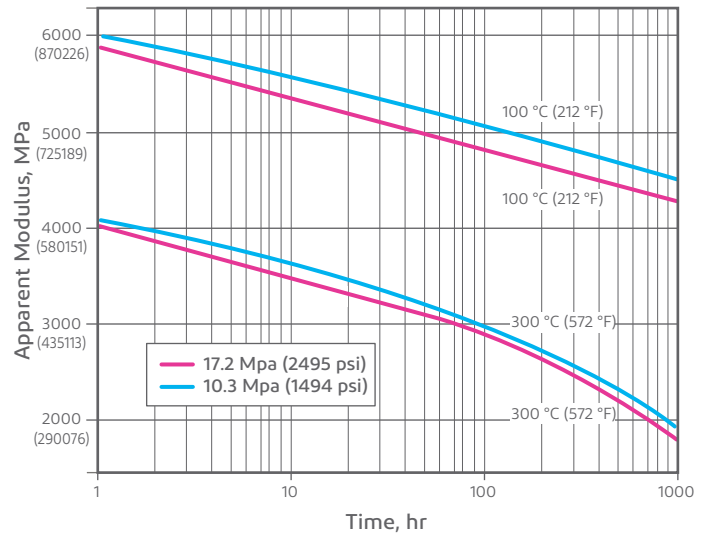

Figure 19. SP-21 polyimide ISO shapes. Apparent modulus vs. time under load
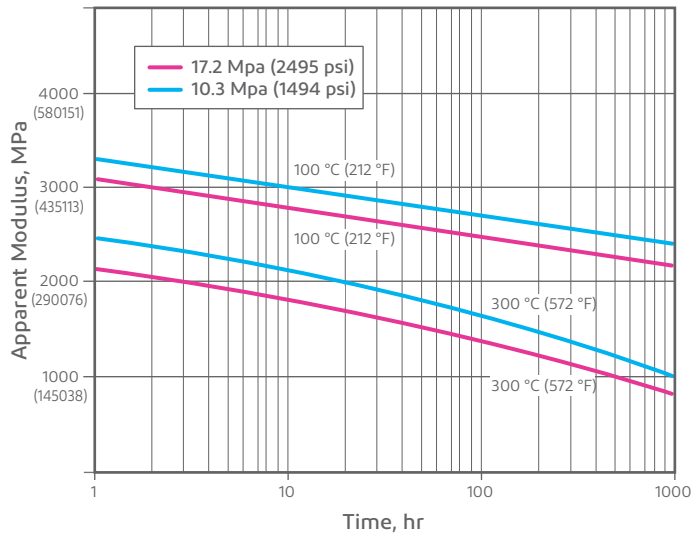
Figure 21. Creep comparison
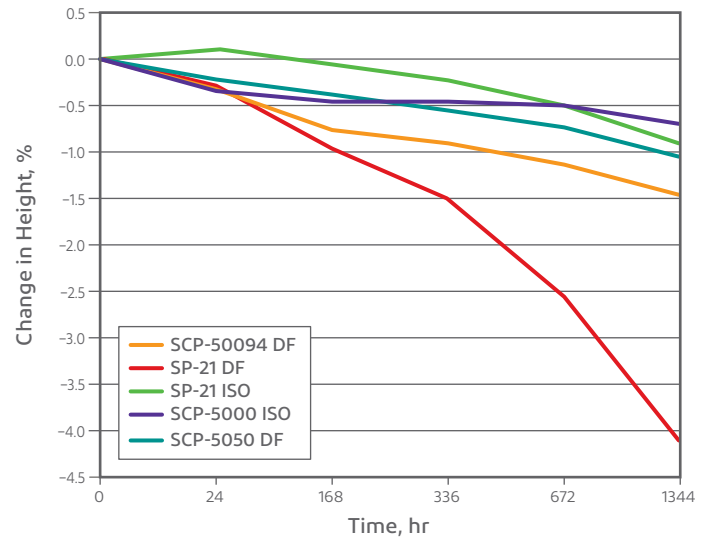
Effect of Moisture Absorption

Figures 22 through 24 illustrate typical rates of dimensional change caused by moisture absorption for machined and direct-formed parts made of SP polyimide.

Time to reach equilibrium moisture content from the dry state in a controlled environment is very long, involving thousands of hours. Since the absorption of moisture is diffusion controlled, the rate is inversely affected by the minimum dimension of the part.

Figures 25 and 26 show typical effects of relative humidity (RH) changes at 23 °C (73 °F) on the dimensions of machined and direct-formed parts. A part attains its full dimensional change at a given humidity level only after it has reached equilibrium in the particular environment. Allowing a completely dry part to reach equilibrium at 100% RH at 23 °C (73 °F) will result in a maximum change of about 0.5% or 0.005 mm/mm (1.968 in/in).

Figure 23. Direct-formed SP-1 polyimide. Typical dimensional change with time at 50 and 100% RH, 23 °C (73 °F), 25 mm (0.98 in) dia. discs, 2.5 mm (0.098 in) thick

Figure 22. SP-1 and SP-21 polyimide ISO shapes. Typical dimensional change vs. time at 23 °C (73 °F), 50% RH, 3.2 mm (0.13 in) plates

Figure 24. Direct-formed SP-21 polyimide. Typical dimensional change with time at 50 and 100% RH, 23 °C (73 °F), 25 mm (0.98 in) dia. discs, 2.5 mm (0.098 in) thick
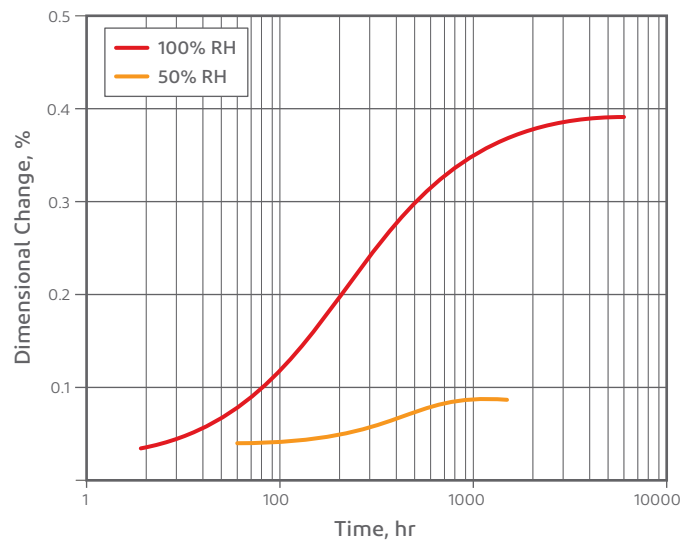
Figure 25. SP-1 and SP-21 polyimide ISO shapes. Typical dimensional change with relative humidity at equilibrium, 23 °C (73 °F)
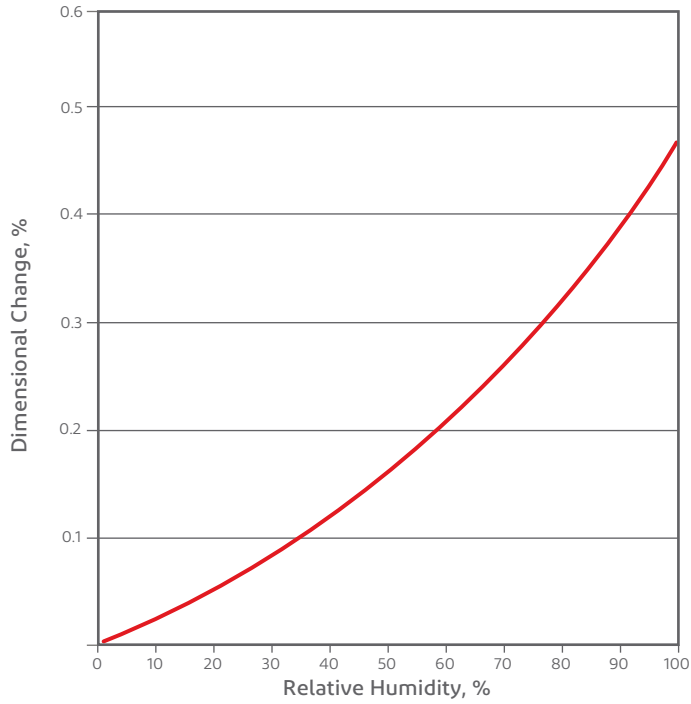
Figure 26. Direct-formed SP polyimide. Typical dimensional change with relative humidity at equilibrium, 23 °C (73 °F)
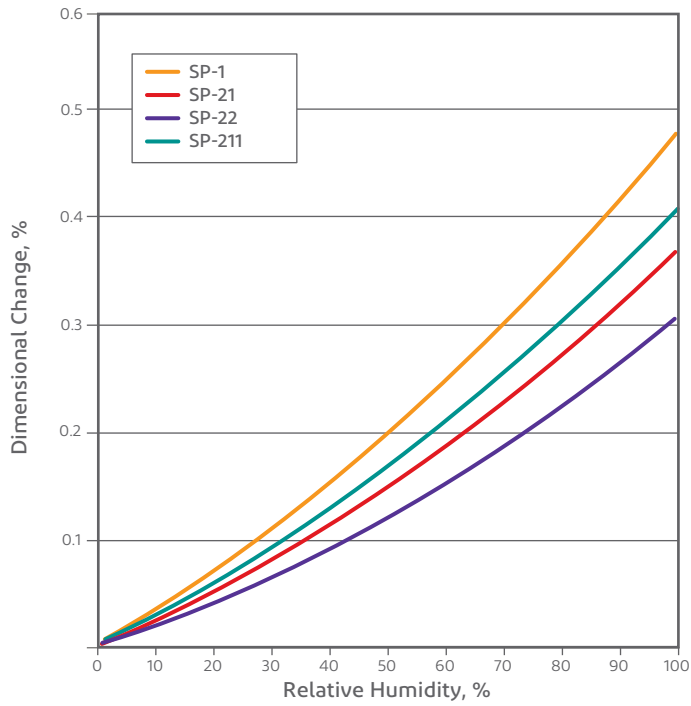
Thermal Expansion

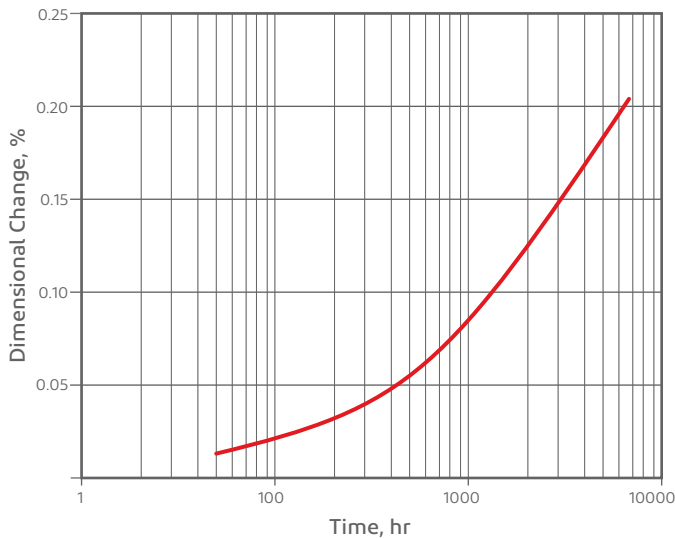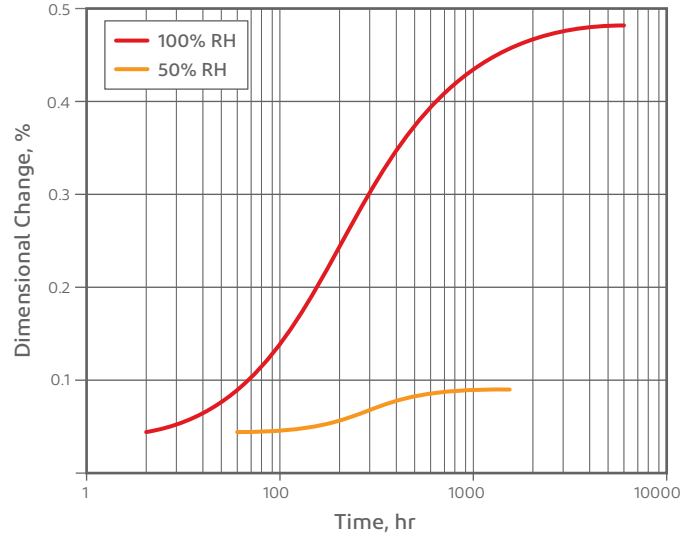Linear dimensional change with temperature is shown in Figure 27 for machined SP polyimide ISO shapes and in Figure 28 for direct-formed polyimide. Each plot contains the average coefficient of thermal expansion over the temperature range 23 to 300 °C (73 to 572 °F). The coefficient over any other range of temperature may be slightly different and can be determined from the curves by dividing the percent dimensional change over the desired range by 100x the temperature differential in degrees (ΔT).

For all compositions, thermal expansion of direct-formed parts is lower than for ISO machined parts — a result of the "directionality" of direct-formed parts, as discussed earlier.

The addition of graphite filler reduces thermal expansion. Thus, SP-21 and SP-22 polyimide offer a lower expansion than unfilled SP-1. The coefficient of thermal expansion of SP-22 approaches that of aluminum. Multiple grades of graphite filled Vespel® SCP are available. The highly graphite filled grade Vespel® SCP-5050 has the lowest CTE of any Vespel® S material.

Figure 28. Direct formed SP polyimide. Linear thermal expansion (⊥ to forming) ASTM D696

Average coefficient of thermal expansion (x 10⁻⁶) Over 23–300 °C (73–572 °F)		
Polyimide	m/m °C	in/in °F
SP-1	50	28
SP-211	41	23
SP-21	41	23
SP-22	27	15

Figure 27. SP polyimide ISO shapes. Linear thermal expansion ASTM D696

Average coefficient of thermal expansion (x 10⁻⁶) Over 23–300 °C (73–572 °F)		
Polyimide	m/m °C	in/in °F
SP-1 and SP-211	54	30
SP-21	49	27
SP-22	38	21
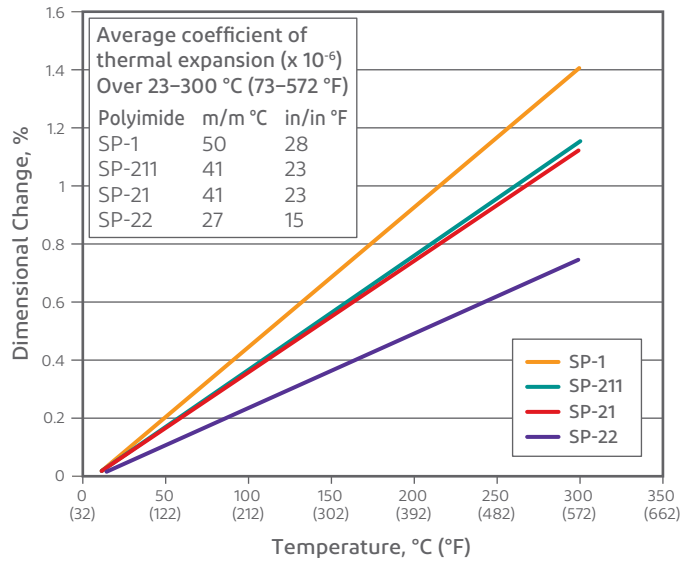
Fatigue and Impact Resistance

Failure of materials at stress levels lower than their ultimate tensile strengths when the applied stress is repeated cyclically is known as fatigue failure. A plot of stress to cause failure at 10^5 to 10^7 cycles vs. temperature to 260 °C (500 °F) is shown in Figure 29 for machined SP-1 and SP-21. Stress was applied by alternating tension and compression at 1800 cycles per minute. At this frequency there is little or no effect of overheating of the specimen which could cause premature failure.

Although fatigue data obtained through testing procedures can be used as a guide in designing parts, they should not be used without considering environment and stress concentrations. While test specimens usually have smooth surfaces, the presence of notches, scratches, holes or sharp corners can cause concentration of stress. No fatigue testing is a substitute for actual or simulated end-use testing of a part.

Impact resistance is difficult to predict since the geometry of the part, stress concentrations and the rate of loading all have an effect. To increase impact resistance, parts should be designed to obtain the maximum area of load application. Designing a part for maximum flexibility will also help by increasing the distance over which impact energy is expended.

Vespel® polyimides, like most other plastics, display notch sensitivity as shown by the values of notched Izod impact strength shown in Tables 1 and 4. As with most materials, avoid designing sharp corners and other stress raisers into the part.

Figure 29. SP polyimide ISO shapes. Typical fatigue resistance vs. temperature reversed tensile and compressive stress, 1800 cycles/min (30 Hz)

15
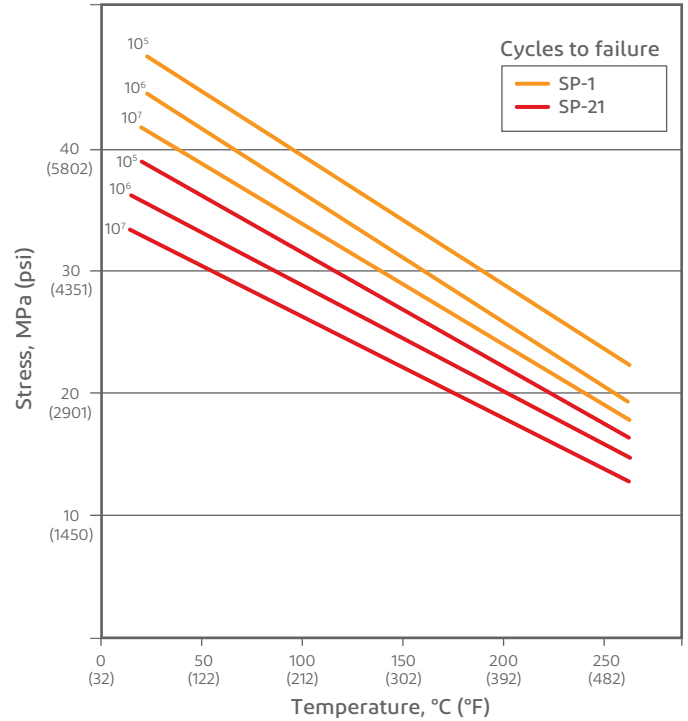
Electrical Properties

The combination of very good electrical properties, high strength and excellent thermal and radiation resistance makes Vespel® parts outstanding candidates for electrical applications in severe environments. More importantly, Vespel® parts retain their dielectric properties at high temperatures.

Dissipation factor (Figure 30) is influenced by both temperature and frequency. Up to about 100 °C (212 °F), dissipation factor increases with increasing frequency. From 100 to 200 °C (212 to 392 °F), frequency has essentially no effect, while above 200 °C (392 °F), dissipation factor decreases with increasing frequency. Additionally, Figure 31 shows the dielectric constant for SCP-5000 and SP-1 as a function of temperature and frequency. While both grades offer very low dielectric constant values, the SCP-5000 exhibits a more stable dielectric constant across a broad temperature and frequency range. Figure 32 shows the dielectric strength of SCP-5000 and SP-1. For a 1.0 mm (0.04 in) thick sample, test results indicate both grades offer exceptional dielectric strength that is stable across a broad temperature range with SCP-5000 exhibiting slightly higher strength than SP-1. Furthermore, surface and volume resistivity are similar for both grades as shown in Table 5.

Table 5. Surface and Volume Resistivity

Surface Resistivity (ohm/square)	
SCP-5000	SP-1
1.4 E+17	4.0 E+16
Volume Resistivity (ohm·cm)	
SCP-5000	SP-1
3.6 E+16	5.5 E+16

Figure 30. Dissipation factor vs. temperature, ASTM D150
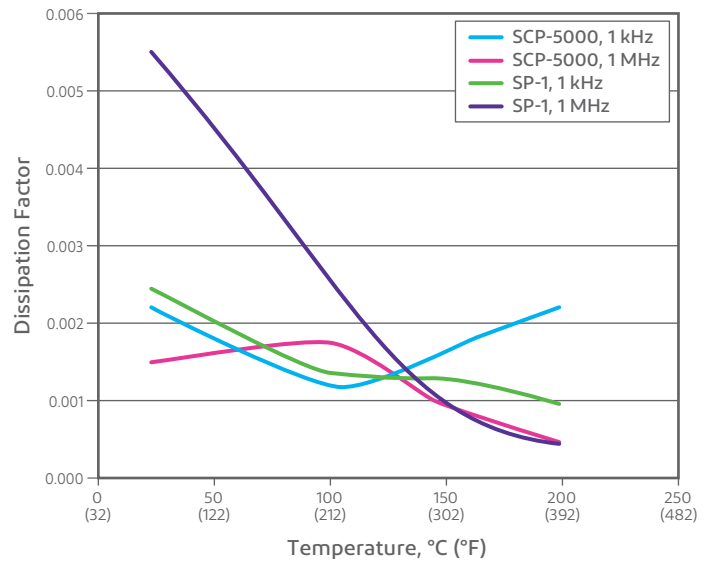
Figure 31. Dielectric constant vs. temperature, ASTM D150
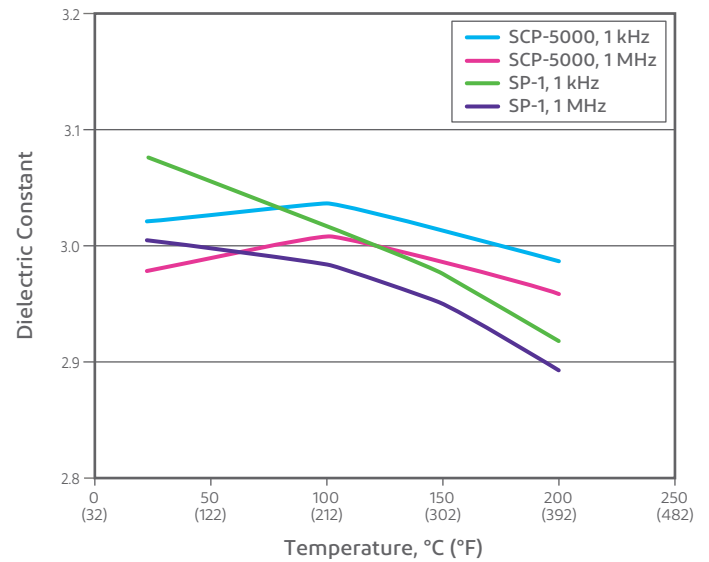
Figure 32. Dielectric strength vs. temperature in air
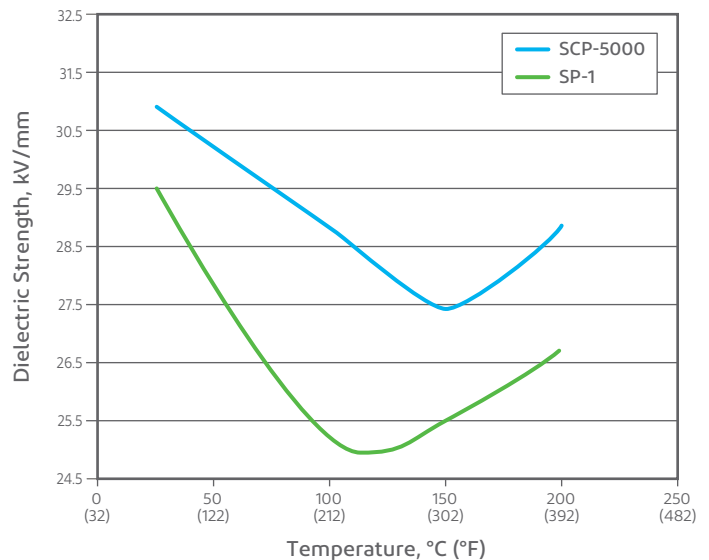
Both dielectric constant and dissipation factor increase with increasing moisture content. For example, at 10^3 Hz and room temperature, the dielectric constant of a dry test bar (fabricated from SP-1 polyimide resin) is 3.1 and the dissipation factor is 0.001. With a moisture content of 2.4% (obtained after 300 hours immersion in water at room temperature), these values are 4.0 and 0.002, respectively. Drying will restore the original values.

The volume resistivity of samples molded from unfilled polyimide is 10^{17} ohm-cm at room temperature (Figure 33). This value decreases linearly to 10^{11} ohm-cm at 300 °C (572 °F). Surface resistivity (Figure 34) is 10^{16} ohm at room temperature, and decreases linearly to 5×10^{10} at 300 °C (572 °F).

The corona resistance of DuPont™ Vespel® parts is superior to that attainable with fluorocarbons and polyethylenes. For example, at 7.8 kV/mm (60 Hz and room temperature), corona life is 2200 hours.

Figure 34. SP-1 polyimide ISO shapes. Surface resistivity vs. temperature, ASTM D257

Figure 33. SP-1 polyimide ISO shapes. Volume resistivity vs. temperature, ASTM D257
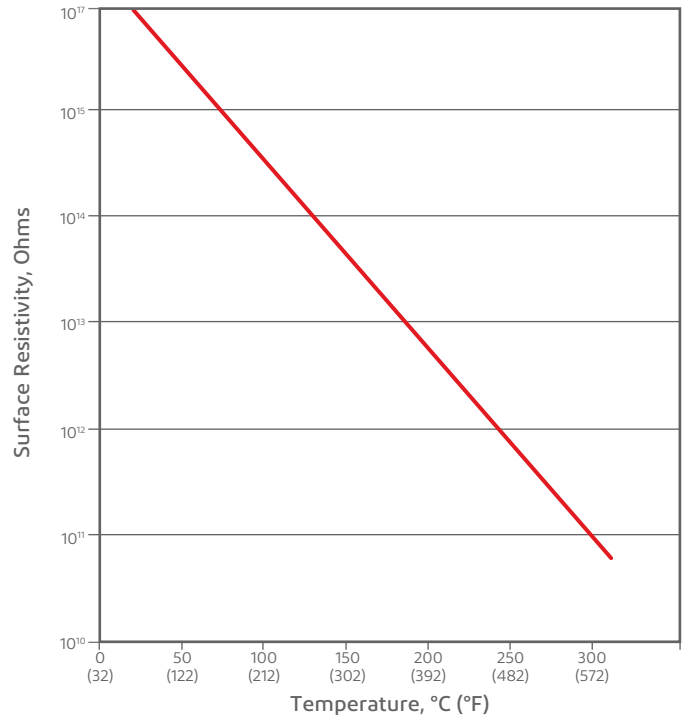
Figure 35. SP-1 polyimide ISO shapes. Dielectric strength vs. thickness, ASTM 149 — IN A-8 oil

9 kV/mm at 6.35 Thickness

17
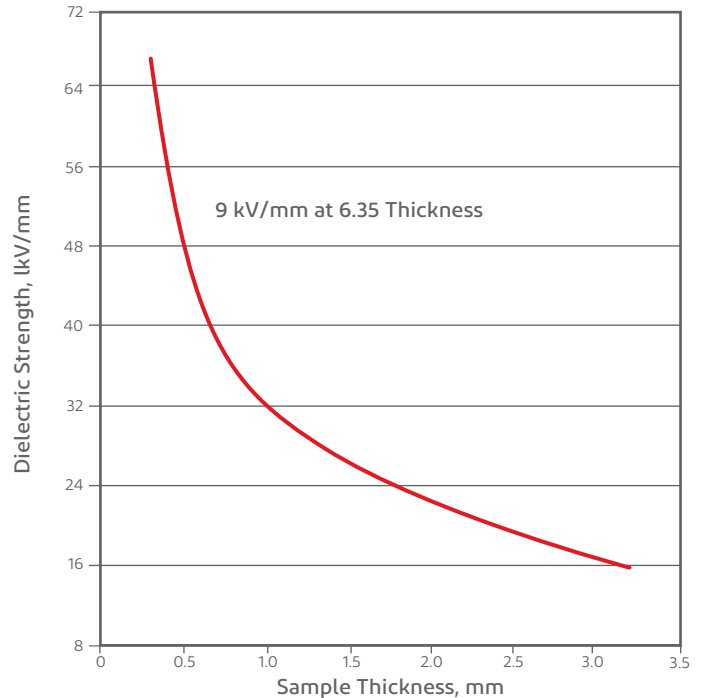
Effect of Chemicals

Vespel® SP/SCP parts perform well in a variety of chemical environments. The tensile strength data shown in Table 6 were determined using exposure tests patterned after ASTM Method D 543-67, "Resistance of plastics to chemical reagents".

A. Solvents

1. Organic solvents in general have little effect on the mechanical and dimensional stability of polyimide parts.

2. Chlorinated and fluorinated solvents such as perchlorethylene, trichlorethylene and Axarel® are recommended for surface cleaning of Vespel® parts.

3. Hydrocarbon solvents such as toluene and kerosene have virtually no effect on the polyimide material.

4. At high temperatures some solvents containing functional groups such as m-cresol and nitrobenzene can cause swelling of SP without substantially reducing its mechanical strength.

5. Below are some solvents which have been tested:

   perchlorethylene   1900 hours at 100 °C (212 °F)
   100% retention tensile strength
   0.4% wt loss

   toluene   1900 hours at 100 °C (212 °F)
   85% retention tensile strength
   0.1% wt loss

   ethanol   1900 hours at 100 °C (212 °F)
   100% retention tensile strength
   0.2% wt gain

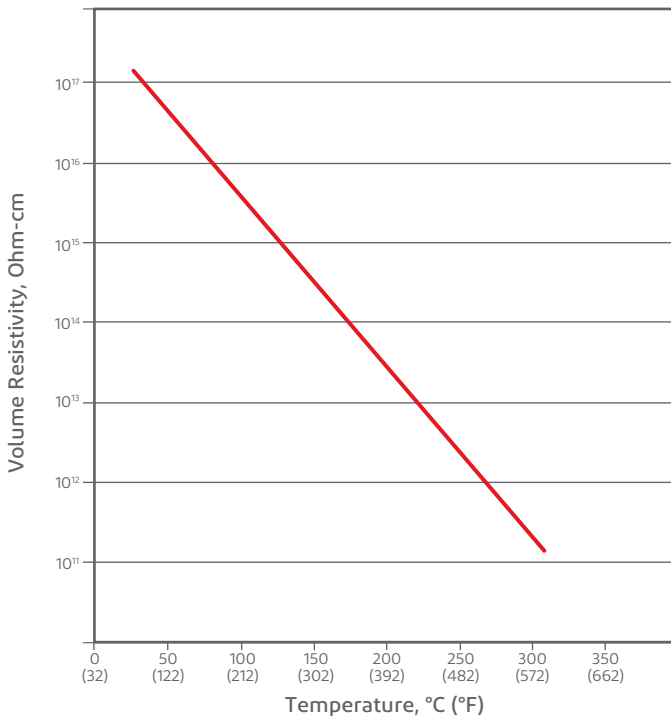   diethyl ketone   1900 hours at 100 °C (212 °F)
   75% retention tensile strength
   0.3% wt gain

   JP-4 jet fuel   1900 hours at 100 °C (212 °F)
   80% retention tensile strength
   0.8% wt loss

   o-dichlorobenzene   1000 hours at 180 °C (356 °F)
   100% retention tensile strength
   2.4% wt gain

   m-cresol   1000 hours at 200 °C (392 °F)
   75% retention tensile strength
   3% dimensional increase

   nitrobenzene   1000 hours at 215 °C (419 °F)
   85% retention tensile strength
   9% wt gain
   2.5% dimensional increase

Table 6. Effects of chemicals

Chemical media	Temperature, °C (°F)	Time, hours	% tensile strength retained by SP-1
Organic solvents			
M-Cresol	200 (392)	1000	75[1]
o-Dichlorobenzene	180 (356)	1000	100
Diethyl ketone	100 (212)	1900	100
Ethanol	100 (212)	1900	100
Nitrobenzene	215 (419)	1000	85[1]
Perchlorethylene	100 (212)	1900	100
Toluene	100 (212)	1900	85
Industrial fluids			
Hydraulic fluid ("Skydrol")			
Polyphosphate ester	120 (248)	1000	100
JP-4 Jet fuel	100 (212)	1900	80
Jet engine oils	260 (500)	600	60 (90)[2]
(MIL L 7808G)	260 (500)	1000	30 (60)[2]
Mineral oil	200 (392)	1000	70 (90)[2]
Silicone fluid	260 (500)	1000	80
Tricresyl phosphate (oil additive)	260 (500)	1000	80
Acids			
Acetic, 15%	100 (212)	1900	20
Hydrochloric, 38%	23 (73)	120	70
Hydrochloric, 5%	100 (212)	1900	15
Nitric, 70%	23 (73)	120	40
Bases			
Sodium hydroxide, 5%	23 (73)	120	55
Oxidizing agents			
Nitrogen tetroxide	23 (73)	120	60

[1]Swelling.
[2]SP-21 polyimide (15% graphite-filled).

B. Oils

1. **Jet engine oils:** Exposures of SP-1 and SP-21 in a MIL L7808 oil and a type 2 jet oil were made at 260 °C (500 °F). In both oils SP-1 retained 60% of its tensile strength and 30% of its elongation after 600 hours, while SP-21 retained 90% and 70% of the same properties, respectively. After 1000 hours the retention of tensile strength was 30% for SP-1 and 60% for SP-21. Retention of elongation was 10% for SP-1 and 30% for SP-21. Both compositions gained about 0.2% weight in the MIL L7808 oil and 0.5% in the type 2 oil in 1000 hours. Dimensions in the parallel direction increased up to 0.3% while those in the perpendicular direction decreased up to 0.1%.

2. **Silicone fluid:** At 260 °C (500 °F), SP-1 retained 70% of its tensile strength and 35% of its elongation after 1000 hours. SP-21 retained 85% of its tensile strength and 50% of its elongation under the same conditions. Both compositions gained 0.3% in weight. Dimensional increases in the parallel direction were 0.2% while decreases in the perpendicular direction were less than 0.1%.

3. **Refined mineral oil:** At 200 °C (392 °F) retention of tensile strength after 1000 hours was 70% for SP-1 and 90% for SP-21. Retention of elongation was 40% for SP-1 and 65% for SP-21. Weight gains were about 0.3%. Dimensional increases were about 0.1% in the parallel direction while decreases in the perpendicular direction were less than 0.1%.

4. **Polyphosphate ester hydraulic fluid:** No changes in properties were noted after 1000 hours at 120 °C (248 °F).

5. **Tricresyl phosphate (oil additive):** After 1000 hours at 260 °C (500 °F), SP-1 gained 1.5% in weight retaining 80% of its tensile strength. Dimensions increased about 0.25%.

C. Water

1. At 100 °C (212 °F) the tensile strength and elongation of SP are reduced to 45% and 30% of the original values respectively, in about 500 hours, at which point they level out.

2. Most of the reduced tensile values from 100 °C (212 °F) water exposure can be restored by drying, indicating that the reduced properties are not due to chemical changes.

3. Vespel® parts can be used in applications where they are exposed to water up to 100 °C (212 °F), providing the stresses are low enough to take into account the reduced mechanical properties.

4. As with all polyimides, SP is subject to hydrolysis. Severe cracking may occur in water or steam at temperatures exceeding 100 °C (212 °F).

D. Acids

1. Concentrated mineral acids cause severe embrittlement of polyimide parts in a relatively short time.

2. Concentrated (38%) hydrochloric acid caused a 30% reduction in tensile strength and a 40% reduction in elongation after 120 hours exposure at room temperature.

3. Concentrated (70%) nitric acid caused a 60% reduction in tensile strength and a 75% reduction in elongation after 120 hours exposure at room temperature. These large decreases are probably due, in part, to the oxidizing action of the acid.

4. Five per cent (5%) hydrochloric acid reduced the tensile strength of SP by 80% after 1900 hours at 100 °C (212 °F).

5. Fifteen per cent (15%) acetic acid reduced the tensile strength of SP by 80% after 1900 hours at 100 °C (212 °F).

6. Generally, dilute acid solutions and aqueous solutions of inorganic salts having acidic pHs have about the same effect on SP as does water itself.

E. Bases

1. Generally, polyimide resins are susceptible to alkaline attack. Aqueous bases attack Vespel® parts chemically, causing rapid deterioration of properties.

2. A 5% solution of sodium hydroxide reduced the tensile strength of SP by 45% upon exposure for 120 hours at room temperature. The normally brown color of the SP surfaces became black and the weight increased by 27%.

3. All basic solutions with a pH of 10 or greater, including salt solutions, should be avoided.

4. Cleaning agents of a caustic nature are not recommended.

5. Non-aqueous bases such as anhydrous ammonia (liquid or vapor) and the hydrazines readily attack SP chemically.

6. Severe cracking occurred when SP was exposed to liquid anhydrous ammonia for a relatively short period of time.

7. Blistering and other evidence of chemical attack occurred upon exposure to ammonia vapor.

8. Both liquid and gaseous unsym-dimethylhydrazine caused a 55% reduction in tensile strength and a 35% reduction in elongation in a short period of time.

9. Primary and secondary amines can attack SP chemically.

10. All chemicals basic in nature should be avoided in applications of polyimide parts.

F. Oxidizing agents

1. Chemical reagents which act as powerful oxidizing agents can cause oxidation of Vespel® parts even under mild conditions. (See acids for the effect of nitric acid.)

2. Nitrogen tetroxide (N_2O_4) caused a 40% reduction in both tensile strength and elongation after 120 hours at room temperature. A three percent weight gain also occurred.

G. Oxygen compatibility

An important property of SP-21 is its compatibility with liquid and gaseous oxygen systems.

SP-21 by DuPont has been tested by the National Aeronautics and Space Administration and meets MSFC-SPEC-106B, "Testing Compatibility of Materials for Liquid Oxygen Systems."

Similarly, SP-21 was tested by the Naval Air Engineering Center, Department of the Navy, and was found compatible according to MIL-V-5027C, "Non-Metallic Materials Compatible with Oxygen."

It is likely that other filled SP compositions will meet the above specifications but have not been tested. The unfilled resin — SP-1 — does not meet these standards.

Other Properties

Weathering

SP/SCP polyimide parts undergo some loss of tensile strength and elongation after prolonged outdoor exposure and should be considered for such applications only after suitable testing. Vespel® parts are completely resistant to fungus attack and test specimens have met the requirements of MIL-E 5272 and of Federal Specification CCC-T-191 b, Methods 5762 and 5751, for resistance to mildew and rot.

Toxicological aspects

Application has not been made for approval by the Food and Drug Administration for use of Vespel® parts in contact with food products.

SP/SCP polymer is extremely heat-stable compared to most organic materials but can yield carbon monoxide (CO) as a product of combustion. To make sure the CO concentrations remain below the acceptable safe level, care should be taken to provide adequate ventilation where Vespel® parts are exposed to elevated temperatures in confined locations. For additional information, reference available Safety Data Sheets (SDS) on the DuPont website.

Outgassing

Once absorbed moisture has been removed from Vespel® parts, weight loss in vacuum at high temperatures is low. In tests run by NASA at the Lewis Research Center, samples first dried at 93 °C (199 °F) gave a weight loss rate of less than 10^{-10} g/cm^2/s at temperatures below 260 °C (500 °F). At 350 °C (662 °F) the weight loss rate was 10^{-7} g/cm^2/s.

Flammability classification, UL 94

Many Vespel® S/SCP grades are classified UL 94-5VA and 94 V-0.

Review published UL Yellow Cards for Vespel® grade specific values.

Storage

To ensure maximum performance when needed, Vespel® parts and shapes are best stored under normal, indoor, ambient conditions. Temperature should not exceed 40 °C (104 °F). No exposure to sunlight, UV-light or other form of radiation and no direct contact to water and chemicals is recommended.

Limited Oxygen Index (LOI)

ASTM D2863

Definition:
LOI is the minimum concentration of oxygen in a flowing mixture of oxygen and nitrogen that will just support flaming combustion.

Vespel® SP-1 — 53% O_2
Vespel® SP-21 — 49% O_2

Hot wire ignition, UL 746 A

Vespel® S/SCP grades are rated PLC 0.

Review published UL Yellow Cards for Vespel® grade specific values.

Direct Forming

Production quantities of Vespel® precision parts can be more economically fabricated by the DuPont-developed direct-forming process. Direct-forming utilizes powder metallurgy techniques to produce precision parts or blanks which are nearly identical to those machined from solid stock with the advantage that material wastes are either eliminated completely or minimized. In most cases, the forming process is so precise that the parts require no secondary machining.

While there are no rules concerning minimum order size since each job is considered individually, economics are usually realized with 1000 or more units per order.

The precision dies used to form the parts are bought and owned by DuPont. However, the customer is charged initially for the engineering and development work required to design and test the tooling.

Direct-formed parts do have limitations. Not all shapes and sizes can be formed, although many parts once considered impractical are now routinely made.

One-level parts such as bushings and discs, with or without holes, or any contour that can be pressed with identical single upper and lower punches are made routinely. Core pins are used to form holes of any radial contour that can be machined into the pin and mating tool surfaces. Flats, splines and gear shapes can be formed as readily as round holes. In some cases, blind holes (such as a cap part) can be provided. A small step or indentation can be formed into flat part subject to limitations described in "Design Consideration."

Multilevel parts require multiple pressing motions since powder does not readily flow from one level to another. Two-level parts such as a flanged bushing can be produced. Such parts would require two lower and one upper pressing motion. Parts which have more than two levels usually require secondary machining.

Part geometry must permit ejection from the die. Undercuts, holes at right angles to the pressing direction, reverse tapers, reentrant angles and threads cannot be pressed. But, often features that cannot be formed into the part can be machined without losing all of the economic advantage offered by direct-forming.

Wall thicknesses are a function of the part height. A higher part requires a thicker wall because the powder must flow into the die cavity and fill it equally.

Chamfers, when required, should be angled no more than 30° from the horizontal, i.e., right angle to pressing direction. Chamfers of 45° are produced, but tool life is shortened. Chamfers require that punches have a 0–0.3 mm (0–0.01 in) flat (skirt) to avoid a feather edge.

Parts can be direct formed as thick as approximately 58 mm (2.28 in).
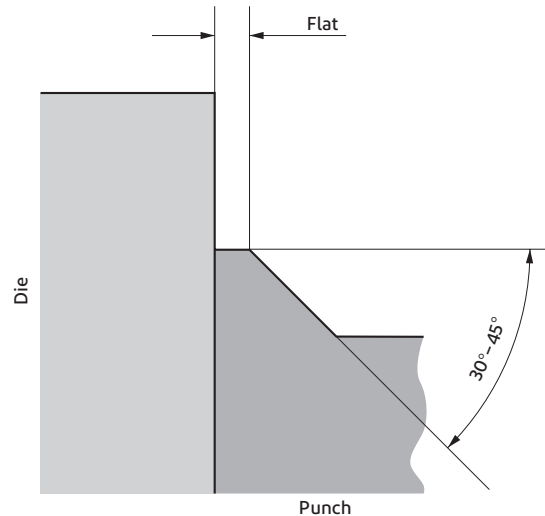
The physical properties of direct-formed Vespel® precision parts will differ slightly from the properties of Vespel® parts machined from a basic shape.

For most applications, the designer need not be concerned about this slight difference in property values. However, when critical applications are involved, we suggest you test with the actual direct-formed part.

Direct-Formed Parts

The direct-formed process developed by DuPont is carried out in two steps.

Fast running vertical toggle-joint presses equipped with pressing dies produce die-formed parts from polyimide powder. This is very similar to the operation of ceramic powder pressing. Due to much tighter tolerances the pressing process must be strictly controlled and kept within narrow parameters. Powder flow and elastic behavior are also considered to ensure homogenous density and stable dimensions.

The product out of this process is a solid part, made from polyimide powder, with specific ingredients, determined by the requested properties under the conditions of the end-use.

These green parts can be handled in large lots in crates or containers without suffering any damage before forwarding to the following sintering process.

From storage in metal containers the parts are placed In large sintering ovens. Sintering takes place at high temperatures, with measures being taken to keep the oxygen away at the elevated temperatures. After a few hours the sintering is completed and the parts obtain their final properties.
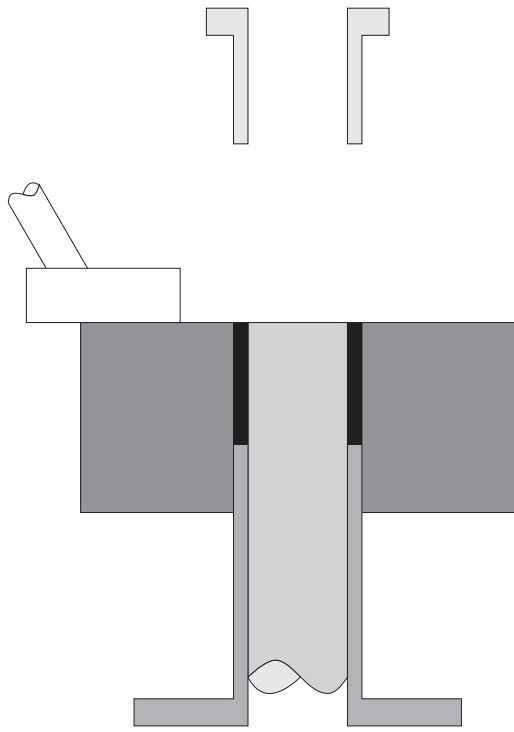
1. The filling shoe is moving back after the powder has been filled into the die. The upper and the lower punches are moved to their top and bottom position.

2. Upper punch and lower punch are moving towards each other to compact the powder and press the part.

3. The upper punch is moving up while the lower punch is punching the pressed "green part" out of the die.
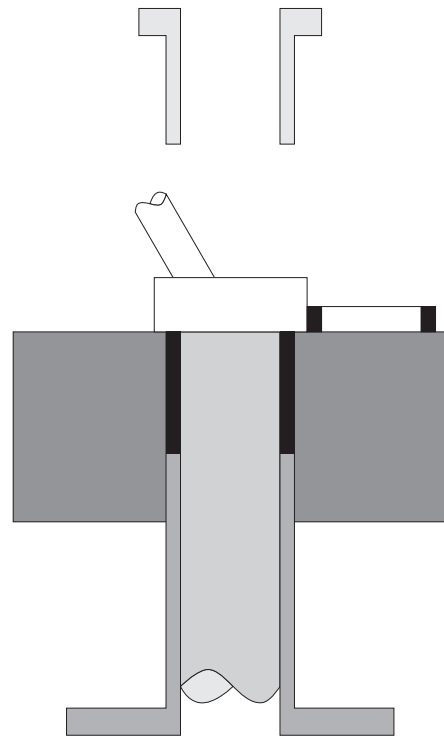
4. The lower punch is moving down while the filling shoe moves over the die to fill it with powder. Simultaneously the lifted part is pushed away from the tool.

During sintering the parts shrink according to size and shape and pressing direction. This shrinkage must be considered when the die is being designed and made. DuPont is able to apply decades of knowledge and experience in order to account for this additional three-dimensional shrinkage.

During shrinkage more changes take place. The green part necessarily reflects features and toolmarks of die and punches. While sintering all surfaces change slightly to a rolling profile with a roughness of approximately Rz 7 (metric, DIN 4786). A cross section of the roughness profile under a microscope shows a surface which is similar to soft sinus lines. This enables Vespel® to work in contact with metal parts in sliding bearings without additional machining of the bearing surfaces.

All sharp edges of the green part get rounded to a shape similar to a radius of 0.05 mm (0.002 in). This feature is very useful as it is not necessary to design parts with chamfers like designers would use on metal parts.

According to the customer's specification the parts undergo final inspection and documentation and are ready either for additional machining or packaging and shipment.

Direct forming capabilities

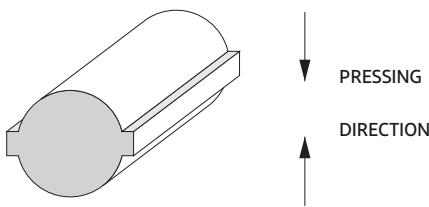|	
Thinnest part	~1 mm (0.04 in)
Thickest part	~58 mm (2.28 in)*
Largest OD	~300 mm (11.81 in)
Minimum ID	~0.5 mm (0.02 in)
Largest surface area	~2800 mm^2 (4.34 in^2)
	can be increased by heated process
	to ~7000 mm^2 (10.85 in^2)
Surface finish	~1 µm (Ra)
Flat on chamfers	0–0.3 mm (0–0.01 in)

PRESSING

DIRECTION

* Cylindrical parts longer than 58 mm (2.28 in) may be pressed horizontally instead of vertically. However, these parts will have 2 flats (see sketch).

Tolerances and General Design Guidelines

Tolerances and design guides for typical direct-formed parts are presented below. However, each part is considered individually, so that variations and exceptions can be made, depending on the function of the part and its operating environment.

Standard level of tolerances

Dimension	Standard tolerance
Diameters, mm (in)	µm (in)
7.5–12.5 (0.30–0.49)	± 40 (0.0016)
12.5–19 (0.49–0.75)	± 50 (0.0020)
>19 (>0.75)	± 65 (0.0026)

Height, mm (in)	µm (in)
0.4–2.5 (0.02–0.10)	± 75 (0.0030)
2.5–6.5 (0.10–0.26)	± 100 (0.0039)
6.5–12.5 (0.26–0.49)	± 125 (0.0049)
12.5–25 (0.49–0.98)	± 150 (0.0059)

Please note: To make optimum use of Vespel® tolerance capabilities do not specify OD and ID, but only the most important diameter and the wall width.
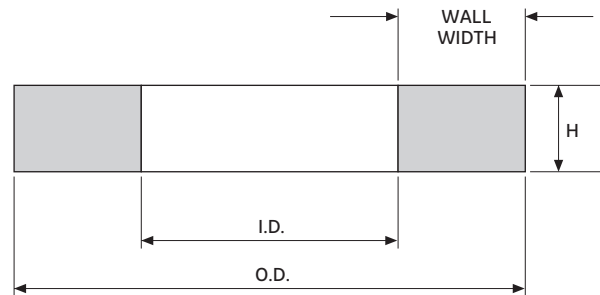
Additional tolerance guidelines, mm (in)

	⊙	→	//	�
Diameter	Concentricity	Roundness	Parallelity	Flatness*
< 25.4 (< 1.0)	0.040 (0.0016)	0.050 (0.0020)	0.040 (0.0016)	0.050 (0.0020)
25.4–50.8 (1.0–2.0)	0.050 (0.0020)	0.125 (0.005)	0.075 (0.003)	0.125 (0.005)
> 50.8 (> 2.0)	0.050 +[1] (0.0020)	0.125 +[2] (0.005)	0.075 +[3] (0.003)	0.125 +[2] (0.005)

1 = 0.0005* (d-50.8) mm * For simple parts
2 = 0.005* (d-50.8) mm
3 = 0.001* (d-50.8) mm

Design Considerations

A

0–0.3
Flats on Chamfers

ø (30°± 2° Recommended)

D max = 0.15 H

D max = 0.3 H

B

Simple parts such as bushings or washers which can be formed with flat punches are more reliable.

C

45° Min.

AVOID

Preferred 60°

0–0.3

PREFERRED

a. Chamfers with angles 45° or less from the vertical should be avoided.

b. Flats (0-0.3 mm [0.012 in]) are required at the base of all chamfers with angles from 45°–60°.

c. Depth "D" of a chamfer or the total depth of chamfers on both ends of a part is limited to a maximum of 30% of the part height "H".

D

1.25 Min.

15° Max.

An acute angle (15° maximum) for a lead-in can be formed in the compacting die in most cases. A small parallel portion (1.25 mm [0.049 in] minimum) is required above the acute angle to prevent jamming of the top punch.

E

AVOID

a. Undercuts cannot be formed into a part.

b.

PREFERRED

b. A radius (0 to 0.5 mm [0.02 in]) is required between the flange and the hub of the part.

AVOID   **PREFERRED**

F

See Detail

0.3 H Max.

H

Detail

R

r   r   Typical

Curved or semicircular grooves can be formed to a maximum depth of 30% of the total part height.

G

a.

AVOID

b.

PREFERRED

a. Parts with reentrant angles cannot be formed.

b. The part must be formed parallel and machined to shape.

I

1
2

AVOID

1
2

PREFERRED

a. Avoid sharp edges which weaken the die (1) and sharp corners which weaken parts (2).

b. Radiused edges (1) and radiused corners (2) add strength to tools and parts.

H

a.

AVOID

b.

PREFERRED

Rad.

c.

a. Parts with a minimum wall thickness of 1 mm (0.039 in) are recommended, although parts with wall thicknesses of 0.65 mm (0.026 in) can be produced. Minimum wall thickness is a function of part height.

b. The size of the square has been decreased to increase the wall thickness. The OD of the circle could have been increased to achieve the same effect.

c. Alternate ways to increase wall thickness.

J

a.

AVOID

2 mm

PREFERRED

a. Profiles requiring feather edges on punches should be avoided. Holes should not be less than 2 mm (0.08 in) diameter.

b. Part re-designed for stronger punches and hole large enough for forming.

Direct-Formed Secondary Machined Parts

As direct-formed parts are pressed on vertical presses the design of those parts is limited by the one-dimensional stroke of the press.

Because of this there are some limitations to the shape of the die-pressings. The parts cannot have undercuts perpendicular to the pressing direction. These would not allow the part to be ejected after the pressing stroke.

Differently to many polymers Vespel® is easy to machine with all usual machine tools. Any cutting operation can be carried out easily and will yield very smooth surfaces.

Machining can be done on customer's request either by DuPont or by any machine shop determined by the customer.

Machined Parts from Shapes

Vespel® shapes are made by DuPont from high-performance SP and SCP polyimide resins, and are available as rods, tubes, plaques, rings, discs and bars. (See Appendix A).

Parts machined from Vespel® shapes are ideal for prototype, low volume or complex geometry parts. Keep in mind that if you need more than 1000 parts at a time, they can often be manufactured more cost effectively by DuPont using our "direct-forming" process.

It is very important when testing Vespel® in an application, to use the material (either shape or direct formed) that will be used commercially. For this reason DuPont offers direct formed material (slugs) for prototyping.

General Machining Procedures

Vespel® shapes are relatively easy to machine because of their inherent mechanical strength, stiffness and dimensional stability at machining temperatures. In addition, they can be machined with standard metal-working equipment to produce parts to tolerances once considered too close for plastic materials. For additional information reference the Vespel® S Family Machining Guide.

Bonding

A variety of adhesives can be used to join Vespel® parts to themselves or to other plastics, metals and elastomers. The choice of an adhesive depends on the particular application, especially on end-use temperature. Cleanliness of the surfaces to be adhered and strict observation of the adhesive manufacturer's recommendations are essential for good results. Surfaces to be adhered should have reasonably matching contours since optimum adhesion requires a thin, uniform thickness of adhesive.

Types of adhesives

Epoxy, phenolic and polyimide adhesives have been used successfully with Vespel® parts. Contact your Vespel® Technical Service Engineer for specific recommendations

Surface preparation of Vespel® parts

Surface preparation is critical. Chemical etching is not recommended. Only mechanical etching by abrasive blasts should be used in preparing Vespel® parts surfaces for adhesion. Surface contaminants such as dirt and oils should be removed with solvents. Cleaning in refluxing perchloroethylene is recommended.

Application and curing

The adhesive should be mixed strictly according to the manufacturer's recommendations. Procedures for curing should follow adhesive manufacturer's recommendations. Cure cycles should not exceed the temperature limits of the Vespel® parts. The adhesive manufacturer's recommendations for safe handling of a adhesive product should be scrupulously observed.

Overmolding and Coating

As Vespel® does not melt it may be beneficial for complex or big parts to overmold a Vespel® insert by another injection moldable engineering polymers (e.g., PA66, UHMWPE, etc.) or by an elastomer (e.g., Nitrile or Silicon types for vibration dampening).

Using the superior Vespel® properties in the area where it is needed — while the rest of the surrounding part is of an injection molded material — may offer the most cost effective solution to your technical requirement. The high performance Vespel® parts may also be coated, for example with Teflon®, to provide additional specific properties.

Radiation Resistance

This brief overview shows that Vespel® parts can perform well in different radioactive environments, even at relatively high dosage rates. The small losses in weight, tensile strength and elongation properties, at doses up to 1×10^8 rads, suggest that the superior properties of Vespel® parts may be used even in environments containing gamma or electron beam radiation.

Working with radiation

Radiation from various sources may be present in the environments of a number of technical and industrial applications. At high radiation levels, it is often necessary to use remote handling or automatic equipment to avoid injury to personnel. Materials used in the construction of such equipment must be able to withstand exposure to radiation.

While metals perform well in static structures, the necessity for lubrication, with the consequent possibility of contamination from the lubricant, reduces their usefulness in bearings, bushings and sliding surfaces. For applications requiring moving parts, as in the handling systems for the production of radio chemicals, or the handling of nuclear fuel rods, self-lubricating high performance polymers such as Vespel® SP polyimide parts can overcome some of the limitations of metals.

The performance of Vespel® SP polyimide parts when subjected to different kinds and levels of radiation is described below.

Testing

To determine how well direct-formed Vespel® bars (SP-1, SP-21 and SP-22) performed after radiation exposure, three parameters were evaluated:

1. weight loss;

2. change in tensile strength; and

3. change in elongation, compared to randomly selected control bars which received no radiation exposure.

Gamma radiation was provided at a dosage of 3.8×10^6 rads/hour from a cobalt 60 source. Exposure times of 16 minutes, 2.6 hours and 26.3 hours resulted in total dosages of 10^6, 10^7 and 10^8 rads.

Weight Loss	Tensile Strength	Tensile Elongation
Less than 1.0% loss	Less than 6.5% loss	19.2% loss at the maximum

Electron beam radiation from a 2,0 MV Van de Graaf generator provided a dosage rate of 4.0×10^6 rads/hour. Exposure times of 1.6 minutes, 80 minutes and 2.7 hours resulted in total dosages of 10^6, 5×10^7 and 10^8 rads.

Weight Loss	Tensile Strength	Tensile Elongation
Less than 2.0% loss	Less than 4.5% loss	Less than 15.0%

Vespel® parts and neutron beam radiation

Neutron beam radiation was provided by a neutron flux of $5 \times 10^{13}/cm^2/second$. Tensile bars were subjected to this exposure level for 100 and 150 hours respectively. Co-incident gamma radiation, at an average dosage rate of 1.2×10^8 rads/hour, accompanied the neutron beam exposures.

Although none of the test bars swelled or were noticeably distorted, tensile strength was substantially reduced after the exposure to high levels of neutron beam irradiation. Therefore, we suggest that you discuss applications involving neutron radiation with a Vespel® Technical Service Engineer and that you perform specific exposure tests.

Bushings and Bearings

The earlier you "think Vespel®," the more cost-effective your total design can be

The engineers and sales staff at the Division of DuPont™ Vespel® are ready to help you make the best use of the superior performance of Vespel® parts. Visit www.Vespel.com to view additional Vespel® literature or contact a Vespel® Technical Service Engineer.

Putting Vespel® to work in your system

DuPont™ Vespel® SP polyimide bearings have been hard at work for more than fifty years, keeping equipment running longer and with less maintenance than conventional bearing materials.

Vespel® bearings are the cost-effective choice in thousands of applications, because they are tough, lightweight and resist wear and creep — even at extremes of temperature. They can outperform metals and other engineering plastics under a wide range of conditions.

This design chapter is provided to help you choose the Vespel® bearing that is best suited to your application.

Inside you will find:

- general information about bearing design;
- a method for determining pressure-velocity (PV) loading in your application;
- guidelines for selecting the correct SP polyimide for PV loadings found in practice;
- considerations for use in the design of Vespel® bearings, and
- a sample bearing design problem.

Vespel® Bearings vs. Other Materials

The ability of a bearing to perform in a given application depends, in general, on:

- the operating environment, including temperature and lubrication;
- load or pressure on the bearing surface;
- sliding velocity of the mating surfaces relative to the bearing;
- hardness and finish of the mating surface;
- friction behavior of the bearing material;
- thickness of the bearing material combined with the material's ability to dissipate heat of friction.

Vespel® parts, made from DuPont polyimide resins, perform well with or without lubrication under conditions that destroy most other plastics and cause severe wear in most metals. Vespel® bearings reduce or eliminate problems with abrasion, corrosion, adhesion, fatigue and wear that plague conventional bearing materials, especially when used without lubricants.

Vespel® bearings can accommodate higher pressure-velocity (PV) loading than most high-performance engineering plastics. In addition, Vespel® bearings excel over a wide range of temperatures and stresses because they retain their outstanding creep resistance, abrasion resistance and strength. They have performed successfully in the following adverse environments:

- air and inert gases at 370 °C (698 °F);
- gamma and electron beam radiation;
- high vacuum (10^{-10} torr);
- hydraulic fluids and jet fuels;
- liquid hydrogen.

Unlike ordinary ball, needle and roller bearings, Vespel® bearings:

- need no external lubrication;
- perform at temperatures where lubricants break down;
- perfom well in dirty environments;
- can reduce noise, weight and costs.

Compared with bronze, brass and porous metal bearings, Vespel® bearings:

- extend the life of other components by eliminating metal-to-metal wear;
- withstand combinations of temperature, pressure and surface velocity beyond the reach of unlubricated metals;
- resist creep and poundout:
- eliminate problems of lubricant loss in the presence of paper dust or lint.

Compared with other polymer bearings, Vespel® bearings:

- perform at temperatures, pressures and surface velocities that other plastics cannot survive;
- increase creep and poundout resistance;
- machine like brass and hold tighter tolerances.

How to Choose a Bearing Material

PV loading — a prime factor in material selection

PV is the product of load or pressure (P) and sliding velocity (V).

A plastic bearing subjected to increasing PV loading will eventually reach a point of failure known as the PV limit. The failure point is usually manifested by an abrupt increase in the wear rate of the bearing material.

As long as the mechanical strength of the bearing material is not exceeded, the temperature of the bearing surface is generally the most important factor in determining PV limit. Therefore, anything that affects surface temperature — coefficient of

friction, thermal conductivity, lubrication, ambient temperature, running clearance, hardness and surface finish of mating materials — will also affect the PV limit of the bearing.

The first step in evaluating a bearing material consists of determining whether the PV limit of that material will be exceeded in your application. It is usually prudent to allow a generous safety margin in determining PV limits, because real operating conditions often are more rigorous than experimental conditions.

**Determining your PV requirements**

1. First determine the static loading per unit area (P) that the bearing must withstand in operation.

   P = pressure, MPa

   W = static load, N

   d = bearing surface ID, mm

   B = bearing length, mm

   N = rotation speed, rpm

   D = bearing surface OD, mm

For journal bearing configurations: P = W/(d x b)

Projected area,
A = bd
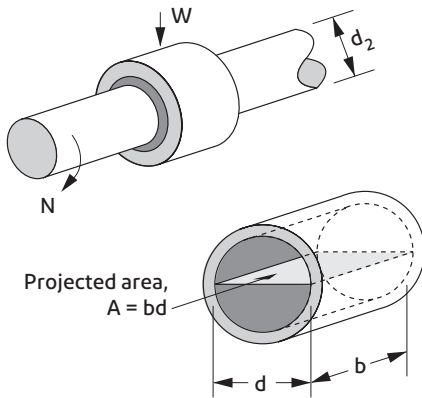
For thrust bearing configurations: P = 4W/π(D^2– d^2)

Runner

Bearing surface area,
A = $\frac{\pi}{4}$ (D^2– d^2)
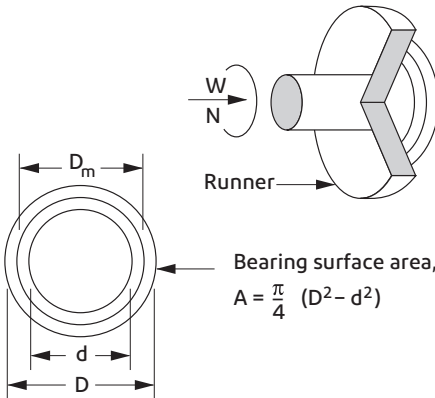
For either bearing configuration, pressure (P) should not exceed the values shown here at room temperature:

Allowable static bearing pressure

Composition	SP-1		SP-21		SP-22	
Fabrication process	Mach.	Direct Formed	Mach.	Direct Formed	Mach.	Direct Formed
MPa	51	33	46	34	41	26

Composition	SP-211		SCP-50094		SCP-5050	
Fabrication process	Mach.	Direct Formed	Mach.	Direct Formed	Mach.	Direct Formed
MPa	37	28	99	78	62	53

2. Next, calculate the velocity (V) of the bearing relative to the mating surface:

	Journal bearing	Thrust bearing
Continuous rotation	V = π(dN)/60	V = π(D$_m$N)/60
Oscillatory motion	V = π(dN) (θ/180)/60	V = π(D$_m$N) (θ/180)/60

where:

   N = speed of rotation, rpm or cycles/min

   D$_m$ = (D + d)/2, m

   θ = angle between limits of oscillation, degrees

   V = surface velocity, m/s

3. Finally, calculate PV:

   PV (MPa·m/s) = P (MPa) x V (m/s)

PV limits of unlubricated bearing materials

Table 7 shows the maximum PV limits for unlubricated Vespel® parts and several other unlubricated materials under conditions of continuous motion. Properly lubricated Vespel® SP and SCP parts can withstand approximately 40 MPa·m/s at mx speed of 1.7 M/sec (1,142 ksi fpm at 335 fpm).

Figure 36 illustrates the maximum unlubricated operating PV limits of plastics, metals and ceramics. Vespel® SCP-50094 offers excellent PV resistance and compressive strength above 17 MPa·m/s (485 ksi fpm), closely followed by Vespel® SCP-5050 ISO and SP-21 ISO. The worst ratings are exhibited by materials that perform poorly in unlubricated PV environments such as unfilled PEEK and PTFE, aluminum, stainless steel and cubic zirconia.

Table 7. PV limit guidelines, unlubricated**

Material	Filler	MPa·m/s (ksi fpm)	Maximum contact temperature, °C (°F)
SP-21	graphite	12 (343)	395 (743)
SP-22	graphite	12 (343)	395 (743)
SP-211	graphite and fluoropolymer	3.6 (103)	260 (500)
SCP-50094	graphite	24 (685)	<300 (<572)
SCP-5050	graphite	24 (685)	<300 (<572)
PEEK	30% carbon fiber	5.2 (148)	<300 (<572)
PAI	graphite, PTFE	1.8 (51.4)	<300 (<572)
PTFE*	Unfilled	0.064 (1.8)	260 (500)
PTFE*	15–25% glass	0.45 (12.8)	260 (500)
PTFE*	25% carbon	0.71 (20.3)	260 (500)
PTFE*	60% bronze	0.66 (18.8)	260 (500)
Nylon	Unfilled	0.14 (4)	150 (302)
Acetal	PTFE	0.27 (7.7)	120 (248)
Acetal	Unfilled	0.12 (3.4)	120 (248)

* At 0.5 m/s.

** These guideline values are supplied for reference only. PV limits for any material vary with different combinations of pressure and velocity as well as with other test conditions. Consult manufacturer's literature for detailed information.

Figure 36. PV limit guidelines, unlubricated

Unlubricated Limiting PV, MPa·m/s (ksi fpm)
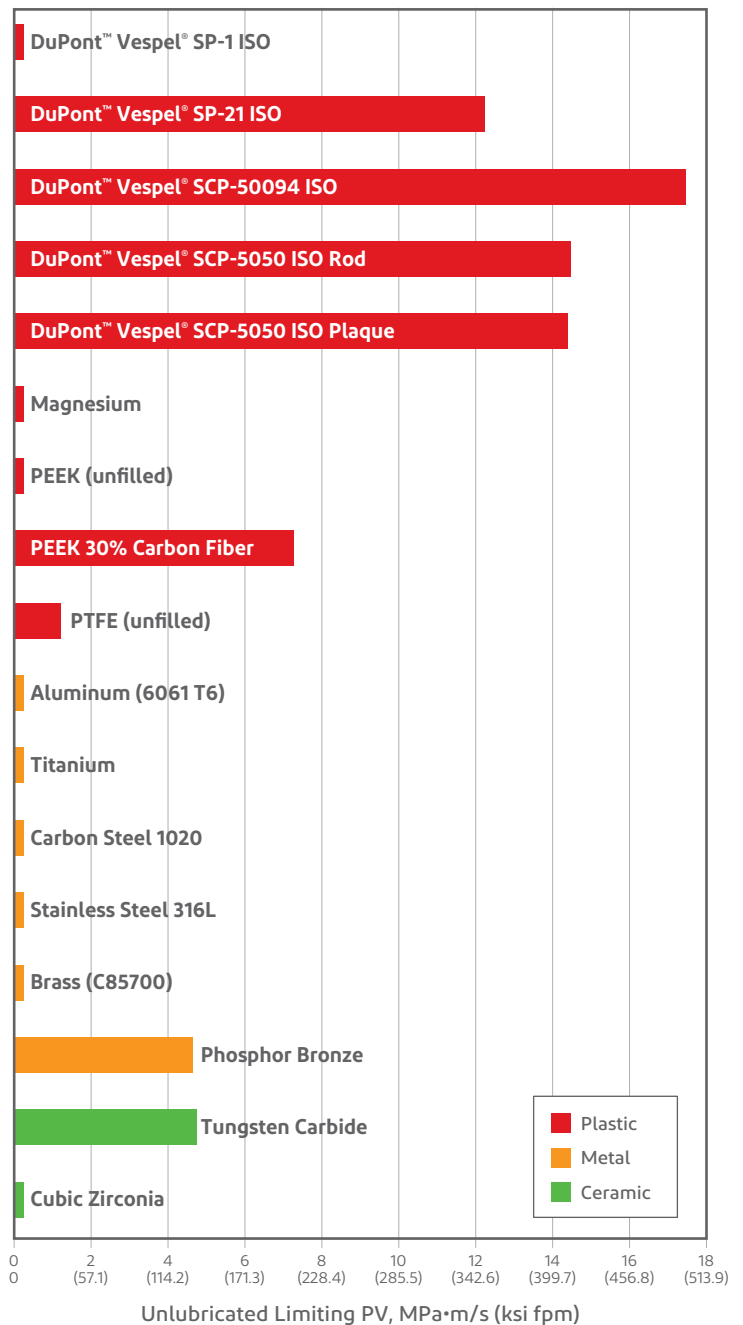
Designing DuPont™ Vespel® Bearings

Effect of surface temperature on wear characteristics

PV is a very useful measure in determining the suitability of a material for a bearing application. However, contact pressure and sliding velocity alone do not adequately characterize bearing materials. Temperature, system geometry and mating surface material also play significant roles in wear of bearings.

Of the factors just named, temperature is generally the most important, because it not only affects the coefficient of friction but also determines the usable combinations of pressure and sliding velocity, or PV. Wear characteristics of Vespel® bearings will be moderate even at high PVs if sufficient cooling is provided. Wear can be severe at any PV if the ambient temperature is too high. The wear resistance, which is a system property (tribological system) and not only a material property of a Vespel® bearing operating at a temperature below its limit can be predicted from an experimentally determined wear factor. The wear factor is derived from an equation relating the volume of material removed by wear in a given time per unit of load and surface velocity.

v = f (KFVT)

where:

   v = wear volume, mm^3

   K = wear factor, mm^3/Nm
      function of mating material roughness and hardness, temperature and environment

   F = supported load, N

   T = time, s

   V = velocity, m/s

For flat surfaces the equation is modified so that:

X = f (KPVT)

where:

   X = wear depth, mm

   P = pressure, MPa

Operating limits

The wear rate of unlubricated SP-21 operating in air is directly proportional to pressure and velocity if the surface temperature does not exceed 395 °C (743 °F) (see Figure 37). The proportionality factor (which we call the wear factor) is unaffected by large changes in operating conditions as long as the temperature does not exceed this critical value, called the wear transition temperature. Below the transition temperature, wear will be mild. However, the wear factor increases as soon as the temperature exceeds 395 °C (743 °F) and becomes very large at about 540 °C (1004 °F). Above 540 °C (1004 °F), the SP will no longer support a load without yielding. However, if this high temperature excursion is short, the SP component will function normally after the temperature is reduced to a compatible level. This decrease in wear resistance occurring at elevated temperatures is related to the thermal stability of the polyimide,

so we expect the wear transition temperature will increase to 540 °C (1004 °F) in an inert or vacuum environment.

Figure 38 shows the pressure-velocity curve for a 395 °C (743 °F) surface temperature for a SP-21 thrust bearing operating in air at 23 °C (73 °F) against mild steel. Note that the PV limit varies from 1 MPa·m/s at 0.07 MPa to 12 MPa·m/s at 7 MPa.

Figure 37. Wear rate vs. Pressure x Velocity for SP-21 vs. carbon steel. Thrust bearing tester — no lubrication
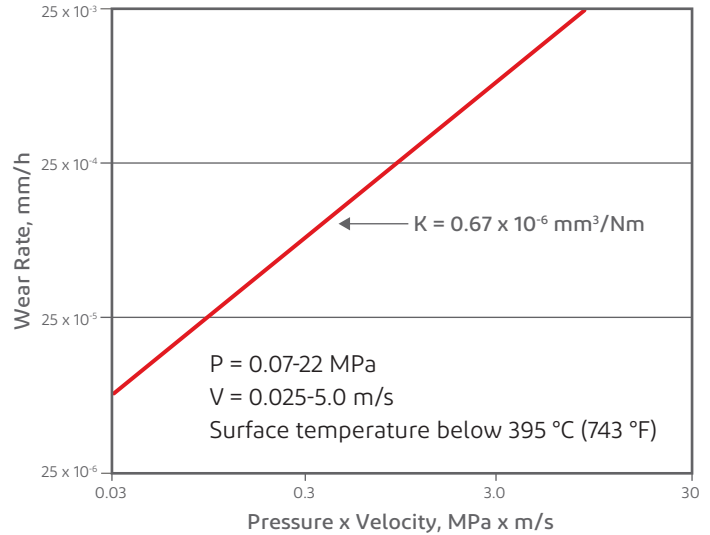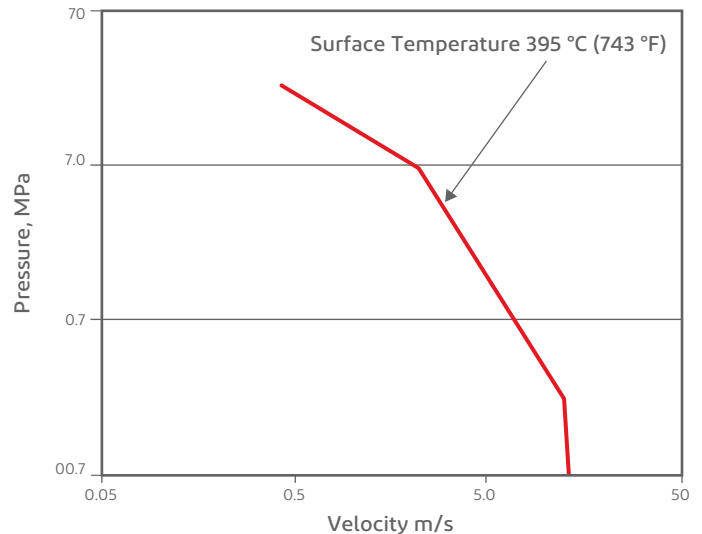

Figure 38. PV-limit of SP-21 on thrust bearing tester vs. carbon steel — no lubrication

Frictional behavior

Temperature, pressure and velocity all affect the dynamic coefficient of friction. Typical coefficients of friction for various polyimide compositions are shown in Table 8 below.

The coefficients of friction for filled compositions undergo a transition at about 150 °C (302 °F), as shown in Figure 39. Below this temperature the frictional behavior is similar to that of 66 nylon, but above 150 °C (302 °F) the frictional forces drop

sharply, and in the range of 200–540 °C (392–1004 °F), the friction characteristics of compositions remain independent of temperature. The friction transition is not associated with wear transition. The magnitude of the transition, and the wear rate below 150 °C (302 °F), are greatly reduced in SP-211 (Figure 40).

The designer must allow for the higher frictional forces, resulting from two separate phenomena, which may be present during start-up. One is the transfer of a layer of polyimide resin/filler composition to the mating surface and the second is the temperature transition for polyimide resins. During restart, it may not be necessary under service conditions to break in a new layer, but the temperature effect is reversible and will continue to operate at each restart.

Figure 39. Coefficient of friction of SP-21 and SP-211 for unlubricated operation against mild carbon steel
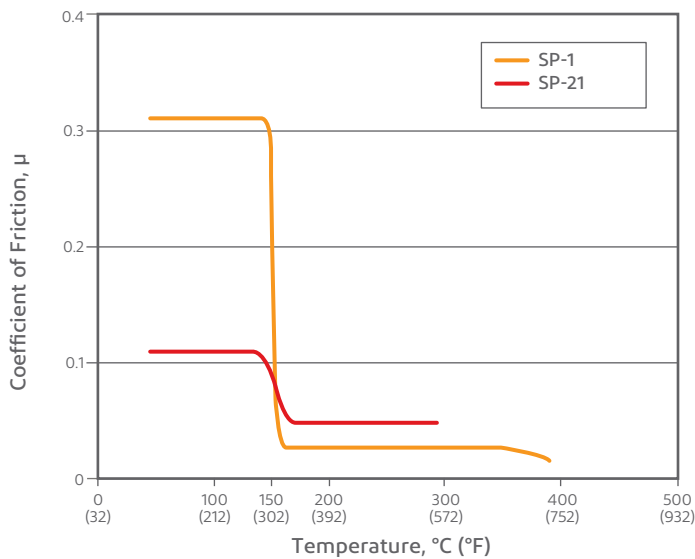

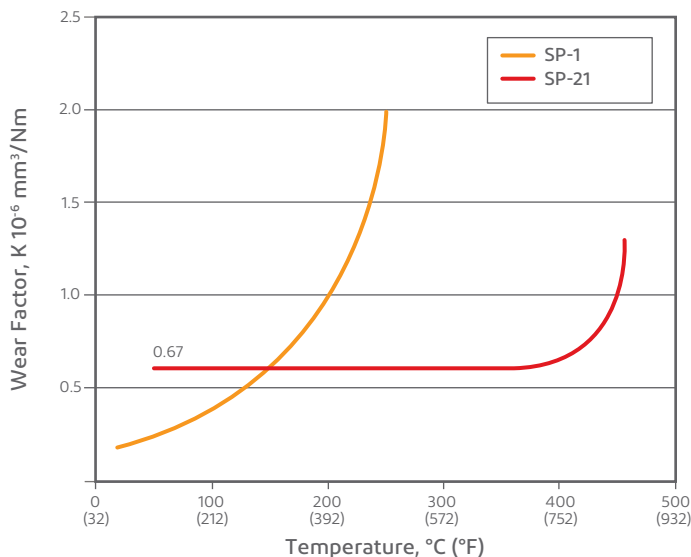**Figure 40. Wear factor of SP-21 and SP-211 for unlubricated operation against mild carbon steel**

**Table 8. Typical coefficients of friction — Unlubricated thrust bearing test**

Measurement		Composition		
Conditions	PV (MPa·m/s)	SP-21	SP-22	SP-211
Static		0.30	0.27	0.20
P = 0.34 MPa V = 2.54 m/s	0.86	0.24	0.20	0.12
P = 0.69 MPa V = 0.51 m/s	0.35	0.35	—	0.24
P = 0.69 MPa V = 1.52 m/s	1.05	0.17	0.21	—
P = 0.69 MPa V = 5.08 m/s	3,5	0.07	0.09	0.08
P = 6.90 MPa V = 1.6 m/s	11	0.04	—	—

SCP wear and friction

Vespel® SP is widely used for its superior wear and friction properties, an area further improved on by Vespel® SCP. While Vespel® SP already compares favorably to other high performance polymers like PEEK and PAI, parts made from Vespel® SCP have improved wear rates and the highest pressure-velocity limits. For the most challenging wear applications with the highest loads, Vespel® SCP should be considered when Vespel® SP or other engineering plastics have failed.

PV Condition		Composition	
	SCP-5050 DF	SCP-5050 ISO	SCP-50094 ISO
0.87 MPa·m/s (24.8 ksi fpm)	0.20	0.23	0.25
3.5 MPa·m/s (100 ksi fpm)	0.08	0.16	0.06

Figure 41. Limit of acceptable wear*
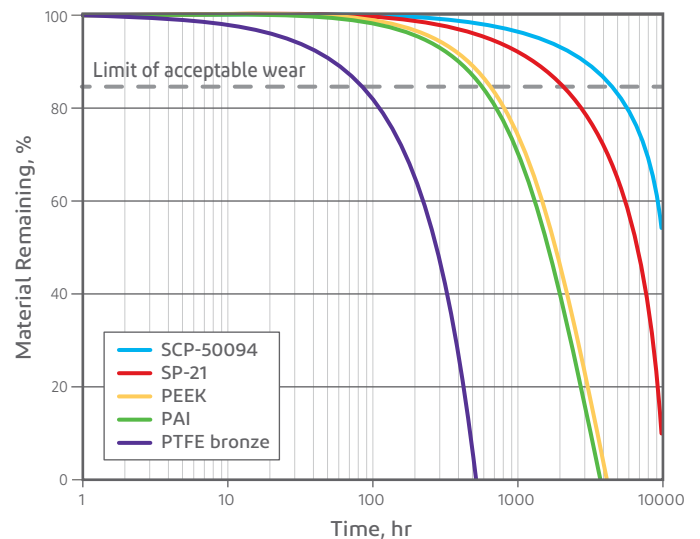
* DuPont dry wear behavior test of PEEK, PAI, PTFE w/bronze, Vespel® SP-21 and Vespel® SCP-50094 indicates the percentage of material remaining under pressure of 14 MPa.m/s (0.7 m/s) at 60 °C in dry friction running conditions against a PH 17-4 steel Ra 0.4 disk for up to 10000 hours. (Source: DuPont)

Mating material and surface finish

The wear performance of Vespel® parts can be substantially affected by the hardness of the mating material and its surface finish. Unlubricated bearing wear rates can be reduced by increasing the hardness and decreasing the roughness of the mating surface. In general, a ground surface finish on the mating material is preferable to a turned surface. A fine polishing operation is often beneficial. The finishing operation should be in the same direction as the bearing motion relative to the mating surface. DuPont recommends a surface finish of 0,4 µm (Ra) and a hardness of Rc = 55.

Steel and cast iron are generally very good mating materials for all Vespel® grades.

Very good behavior has been seen with 100 Cr-6 and 20 Mn Cr-5 materials in bearings and transmission applications.

Aluminum and zinc are not good mating surfaces for plastic bearings because the softness of these materials can lead to rapid wear. If used, aluminum should be hardened or, preferably, anodized.

Die-cast aluminum with high silica content is very abrasive to Vespel®.

Figures 42 and 43 illustrate the effects of mating material hardness and finish on wear performance.

Plastic is not a good material for Vespel® bearings and, if used, should be limited to low PV conditions. The softness of a plastic mating surface can lead to high wear. In addition, since plastics are relatively poor thermal conductors, plastic-to-plastic bearing interfaces run hotter than plastic-to-metal interfaces, so metal-plastic bearing systems have higher PV limits than plastic-plastic bearing systems.
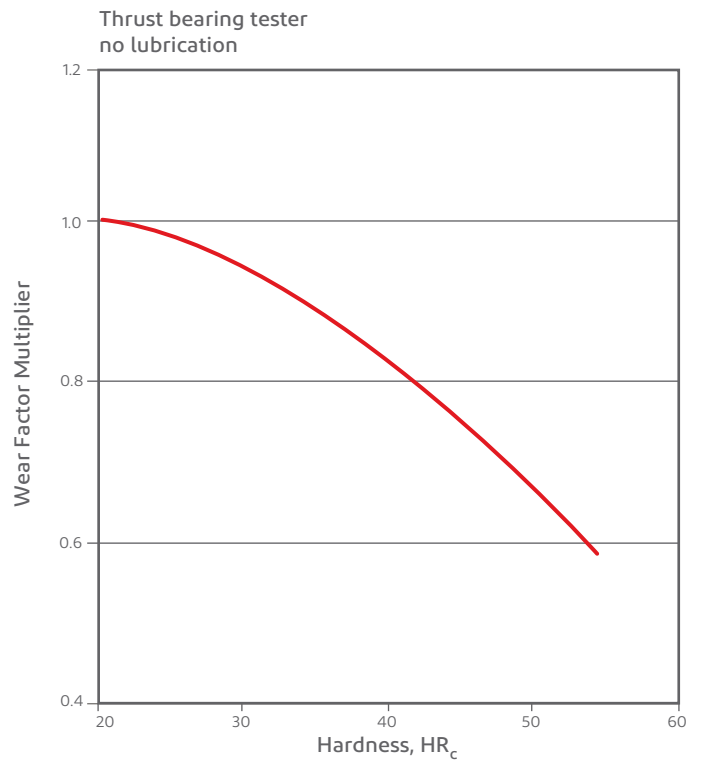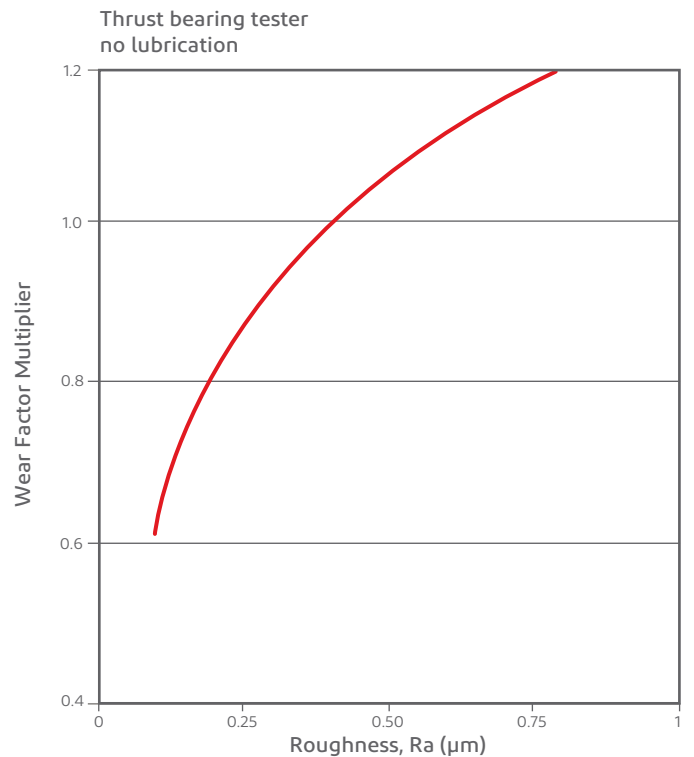
Figure 42. Effect of mating material hardness on wear

Figure 43. Effect of mating material surface finish on wear

## Lubrication and Other Bearing Design Considerations

When determining whether bearings need to be lubricated, the following points should be considered:

- A one-time lubrication, consisting of an initial greasing or use of dry lubricant, generally reduces break-in wear and improves overall wear resistance.

- Lubrication of bearings can increase the PV limit by reducing coefficient of friction and helping to remove wear debris. Circulation of the lubricant can further increase the PV limit by cooling the bearing.

- Lubrication with a chemically compatible fluid to wet Vespel® bearings will reduce both friction and wear rates. The amount of reduction increases with increasing fluid film thickness, which in turn increases with fluid viscosity and surface velocity, and decreases with increasing bearing pressure. Application geometry will also affect the reduction of friction. Even thin film lubricants can reduce dry wear rates by a factor of 10 or more. Thick films, which cause complete separation of the solid mating surfaces, can theoretically reduce wear to negligible proportions.

- The frictional behavior of a bearing system using thin film lubrication is determined by the properties of the bearing material as well as by the properties of the lubricant. Frictional behavior is determined exclusively by the lubricant properties with thick film lubrication.

- Unlubricated bearings should have surface grooves to carry wear debris out of the interface. In lubricated systems the grooves can help increase the supply of lubricant. The effect of grooving on bearing pressure should be considered.

- Because it does not wet SP/SCP resin, water is not an effective thin film or boundary lubricant for Vespel® bearings. In fact, water can adversely affect the wear rate of dry Vespel® bearings. However, periodic contamination by casual water should not cause any problems.

- Purging an unlubricated Vespel® bearing with nitrogen gas can reduce wear rates to less than 20% of the corresponding rate in air. In addition, operation in nitrogen can increase the wear transition temperature by at least 50 °C (122 °F) above the value in air.

- For applications in dirty environments, sealing or purging should be considered for prevention of bearing surface contamination.

Proportions

Journal bearings: For optimum performance of Vespel® journal bearings, l/d (length/diameter) ratios in the order of 1/2 to 3/2 are suggested. If a long bearing is required, consider using two bearings with a gap between them.

Smaller values of l/d will result in:
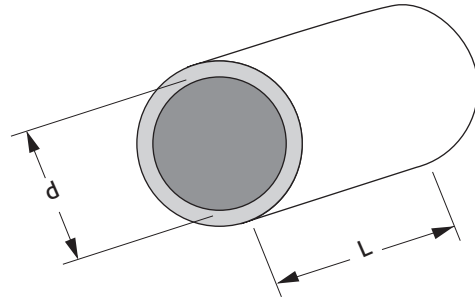
- more efficient debris removal;
- less sensitivity to shaft deflection and misalignment;
- better heat dissipation;
- cost advantages due to lower fabrication costs.

Thrust bearings: For optimum performance of Vespel® thrust bearings, it is best not to exceed a ratio of outside to inside diameter (D/d) of 2. Ratios greater than 2 can cause overheating at the outside edge, and problems may arise from lack of flatness and from trapped wear debris.
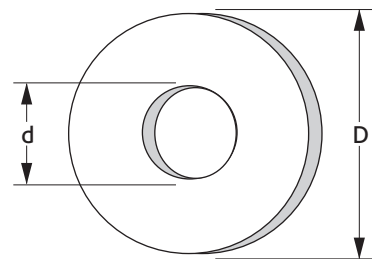
Running clearances for journal bearings

Although Vespel® bearings have much lower coefficients of thermal expansion than most plastics, minimal running clearances are required. Normal operating clearances for Vespel® journal bearings are from 0.3% to 0.5% of shaft diameter, depending on the application. In general, heavier loads require larger clearances. Closer running clearances can be engineered by slotting the bearing to allow for circumferential thermal expansion.

Table 9. Coefficient of thermal expansion αSP

Composition	SP-1		SP-21		SP-22		SP-211		SP-2515	SCP-50094		SCP-5050	
Fabrication process	Mach.	Direct Formed	Mach.	Direct Formed	Mach.	Direct Formed	Mach.	Direct Formed	Direct Formed	Mach.	Direct Formed	Mach.	Direct Formed
αSP 10^{-6} m/m/°C (10^{-6} in/in/°F)	54 (30)	50 (28)	49 (27)	41 (23)	38 (21)	27 (15)	54 (30)	41 (23)	23 (13)	43 (24)	34 (19)	29 (16)	16 (9)

*Measured perpendicular to pressing direction

To calculate the Vespel® bearing design inside diameter it is important to estimate the actual temperature on the shaft and the Vespel® bearing surface. The heat created by friction must be added to the ambient temperature. In a broad range of applications the thermal expansion of the housing is negligible, but can be considered for high ambient temperatures.

The following formula to determine the Vespel® bearing design inside diameter should be used as a guideline. For more information contact DuPont Vespel® by going to www.Vespel.com

Bearing design ID = shaft diameter at room temperature + change in shaft diameter due to temperature change + operating clearance of shaft + change in the bearing wall thickness due to temperature.

$$ID = D\,(1 + \alpha S_\Delta T_1 + C) + 2t\alpha SP_\Delta T_2$$

where:

D = shaft diameter at ambient temperature

C = shaft operating clearance, percent of shaft diameter

αS = coefficient of expansion of shaft material

αSP = coefficient of thermal expansion of Vespel® bearing

t = Vespel® bearing wall thickness

$_\Delta T_1$ = temperature rise for the shaft

$_\Delta T_2$ = temperature rise for the bearing

Running clearances for Vespel® bearings usually do not have to be adjusted for moisture, because polyimides absorb very little moisture. See Figures 23 to 25 for moisture absorption curves.

Of course, PV limits and maximum use temperatures of any material will vary from application to application depending upon a number of different factors. Thorough application testing should be performed to determine how Vespel® parts will perform in your application.

Wall thickness for journal bearings

Vespel® journal bearing walls should be as thin as possible, because thin walls:

- improve dissipation of frictional heat;

- reduce running clearance variations resulting from thermal- and moisture-related dimensional changes;

- reduce distortion under high loading.

For most applications, the typical wall thickness for Vespel® bearings ranges from 1 to 2.5 mm (0.04–0.1 in).

Installation of journal bearings

Vespel® journal bearings can be installed either mechanically or with adhesive.

To press-fit Vespel® bearings into metal, the suggested practice is to use a low-interference fit. After it is pressed into place, the bore of the bearing will be reduced by 90 to 110% (depending on wall thickness, diameter and interference) of the calculated diametrical interference, which will result in a small compressive load in the bearing wall. A typical interference fit is 0.5%, but press-fit interference should be adjusted to the needs of the application. For more accurate calculations contact a DuPont engineer by visiting www.Vespel.com.

Vespel® SP and SCP parts can be used with most commercial adhesives. The "Bonding Chapter" discusses selection of adhesives, surface preparation and other considerations. With any adhesive, it is important to follow the manufacturer's recommendations for best results.

Sample design problem

Vespel® bearings are being considered for a blender dryer with the following requirements:

- Two bearings on a 38 mm (1.5 in) shaft must support 17800 N, at temperatures ranging from 21 to 274 °C (70 to 525 °F).

- Maximum bearing length is 38 mm (1.5 in) and maximum allowable running clearance hot or cold is 0.40 mm (0.02 in).

- To prevent product contamination, the bearings cannot be lubricated and they must operate without service 40 hours per week for 3 years.

- The blender-dryer shaft rotates intermittently, 5% on, 95% off, at 20 rpm.

To check that Vespel® bearings meet these requirements, refer to Table 7, "PV limit guidelines."

Solution

1. Check temperature limit

Limiting surface temperature of SP-21 polyimide in air is 393 °C (739 °F), so unless PV is very high, the surface temperature should rise less than the 119 °C difference between 274 and 393 °C (214 °F difference between 525 and 739 °F).

2. Check PV

Calculate bearing pressure:

$$P = \frac{F}{LD} = \frac{8900 \text{ N (per bearing)}}{38 \text{ mm x } 38 \text{ mm}} = 6.163 \text{ MPa}$$

Calculate shaft speed:

$$V = \pi \cdot DN = \frac{\pi \text{ x } 0.038 \text{ m x } 20 \text{ rpm}}{60} = 0.04 \text{ m/s}$$

Calculate PV:

PV = 6.163 MPa x 0.04 m/s = 0.245 MPa·m/s

At this low PV, SP-21 polyimide will operate in its mild wear regime, so PV will not limit, especially considering the intermittent operation.

3. Check wear resistance

Calculate running time:

$$T = 0.05 \text{ x } \frac{40 \text{ hours}}{\text{week}} \text{ x } \frac{52 \text{ weeks}}{\text{year}} \text{ x 3 years} = 312 \text{ hours}$$

Radial wear = wear factor* x PV x running time =
0.67 x 10^{-6} mm^3/Nm x 0.245 MPa·m/s x 1123200 s = 0.183 mm

*assumed to be 0.67·10^{-6} mm^3/Nm in that case.

This wear is less than the maximum allowable operating clearance. If the difference is enough to accommodate thermal expansion, then Vespel® parts will meet the requirements.

4. Design-determine room temperature clearance

At this point, experience and judgment play a big role, and one can only approximate a solution. Experience dictates that the shaft, bearing surface, bearing OD and housing will all reach different operating temperatures.

Assume that:

· the contact surface reaches 56 °C (133 °F) higher than the dryer temperature, but:

· the bearing body average temperature is only 28 °C (82 °F) higher than the dryer, while:

· the housing remains at room temperature and restrains the bearing securely, so:

· the bearing will expand inward when the temperature rises, and

· the shaft will expand outward.

With these assumptions, initial room temperature clearance, Cd, can be determined with the following equation:

$$Cd = D\,(\alpha S \Delta T_1 + C) + 2\,t\alpha SP \Delta T_2$$

where:

    D   = shaft diameter

    αS = coefficient of thermal expansion for shaft
           = 11 x 10^{-6} m/m/°C

    C   = operating clearance, here 0.1%

    t   = bearing wall thickness

    αSP = coefficient of thermal expansion for SP-21 bearing
           = 41 x 10^{-6} m/m/°C

    ΔT_1 = temperature rise for shaft

    ΔT_2 = temperature rise for bearing

If one picks a wall thickness of 1.59 mm

Cd = 38 [11 x 10^{-6}·(330 − 21) + 0.001] + (2 x 1.59 x 41 x 10^{-6}) x (302 − 21)
    = 0.167 mm + 0.037 mm
    = 0.204 mm

5. Check maximum clearance

Initial clearance plus wear after 3 years will then be

            0.204 + 0.183 = 0.387 mm

which is below the stated requirements.

Thus, Vespel® bearings do meet the requirements to operate without lubrication in this elevated temperature situation.

If you encounter expansion problems, slot the bearing.

Lubricated Bearings

Vespel® parts also perform well lubricated. With full hydrodynamic lubrication (thick film), normal mechanical wear is absent and Vespel® parts will perform as well as any conventional bearing material. With boundary layer (thin film) lubrication the wear (and friction) characteristics of SP are modified by the lubricant. The combination of partial separation and chemical modification of the surfaces influences the performance.

Lubricant film thickness, defined as:

- Lubricant dynamic viscosity (Z)
- Revolutions (N)
- Contact Surface Pressure (P)

The wear factor of an SP-21 plane thrust bearing operating with thin film lubrication drops rapidly with increasing ZN/P (the non-dimensional parameter controlling film thickness). See Figure 44 to compare lubricated performance of SP-21, bronze and babbitt. The SP-21 wear factor for all but the thinnest films is 0.2–0.4 x 10⁻⁷, which is substantially better than the bronze and approximately equivalent to the babbitt for most film thicknesses.

Figure 44. Lubricated wear test results. Wear factor vs. ZN/P — Mating surface (AISI 1080, HRc = 55, Ra = 0.4). Segmented plane thrust bearing. "Sunvis" 31 Oil
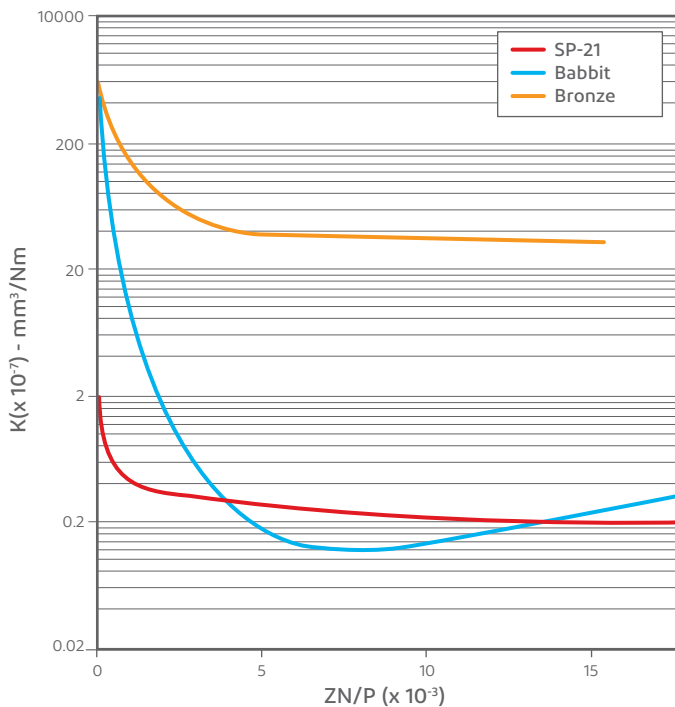
However, SP outperforms both of these conventional materials when films are thin (ZN/P <3). Unfortunately, we do not understand enough about solid-liquid interactions to predict reliably the wear under all thin film conditions.

The coefficient of friction vs. ZN/P for all three materials is plotted in Figures 45, 466 and 47. Again SP shows its superiority; thinner films are required to reduce the friction forces. These results (as were the wear factors) were determined for a three segment plane thrust bearing lubricated with a non-additive petroleum oil with contact pressure ranging up to 13.8 MPa and sliding velocities ranging from 0.015 m/s to 15 m/s. The transition from thin film to thick film lubrication occurs at about the same film thickness for all materials and the hydrodynamic friction coefficients are the same.

Lubrication failure

An important factor to consider if lubricant starvation can occur in one of your systems is the unlubricated performance of the bearing. While neither bronze nor babbitt will operate without lubrication, Vespel® parts will perform without galling or failing as long as the temperature limit is not exceeded. Thus, if the lubricant supply is shut off, the wear and friction characteristics will merely shift from the boundary layer regime to the unlubricated regime. The superiority of polyimide material in this situation is clearly shown in Figure 48. As the lubricant benefits are lost, the friction forces for all three systems quickly rise. However, both of the conventional bearing materials fail while the Vespel® bearing operates without interruption.

SP-21 thrust bearings have performed well in type "A" transmission fluid and F-50 silicone fluid. However, thin film of some fluids, such as water, do not lubricate well. The fluid must wet the sliding surfaces to be effective. For instance, a water film thick enough to provide sufficient surface separation actually increases the wear rate of polyimide parts. This effect is not unusual; it has occurred with other plastics. The general solution is to add a surfactant to reduce the fluid surface tension.

Stick-slip effect

This term describes a splutter movement at start-up when changing from adhesion to sliding. It appears predominantly at extreme small velocities and increased sliding rate. Frequently it is a result of a surface smoothing of the metal counterpart.

Through decrease of the surface load, utilization of a rougher metal surface, or hardening of it, as well as lubricating, this effect may often be overcome.

Figure 45. Lubricated friction test results. SP-21 vs. steel (AISI 1080, HRc = 55, Ra = 0.4). Segmented plane thrust bearing. "Sunvis" 31 Oil
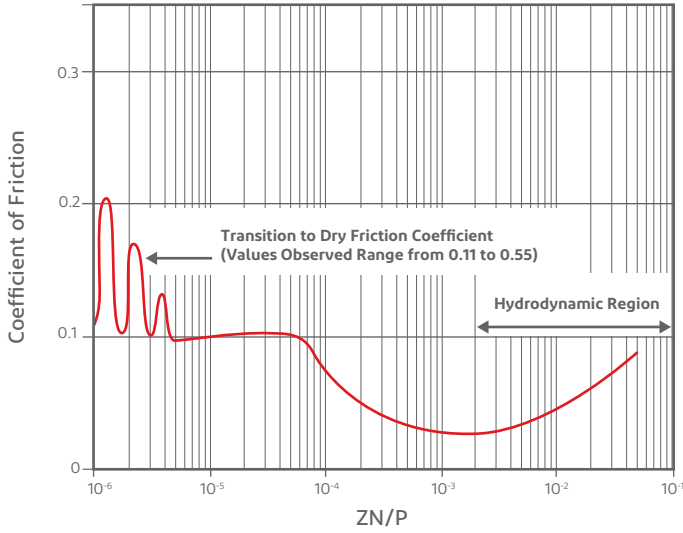

Figure 46. Lubricated friction test results. Bronze vs. steel (AISI 1080, HRc = 55, Ra = 0.4). Segmented plane thrust bearing. "Sunvis" 31 Oil

Figure 47. Lubricated friction test results. Babbitt vs. steel (AISI 1080, HRc = 23, Ra = 0.4). Segmented plane thrust bearing. "Sunvis" 31 Oil
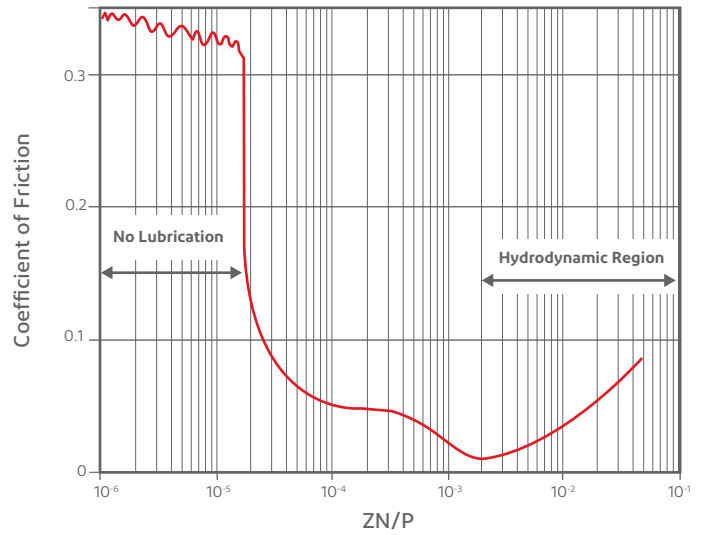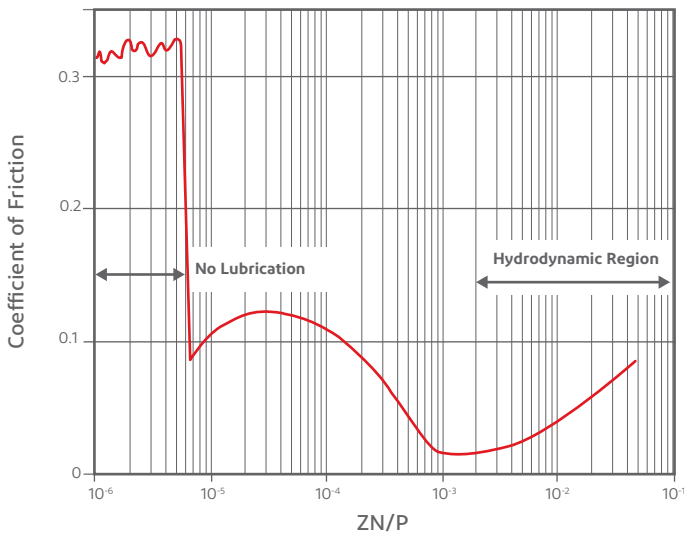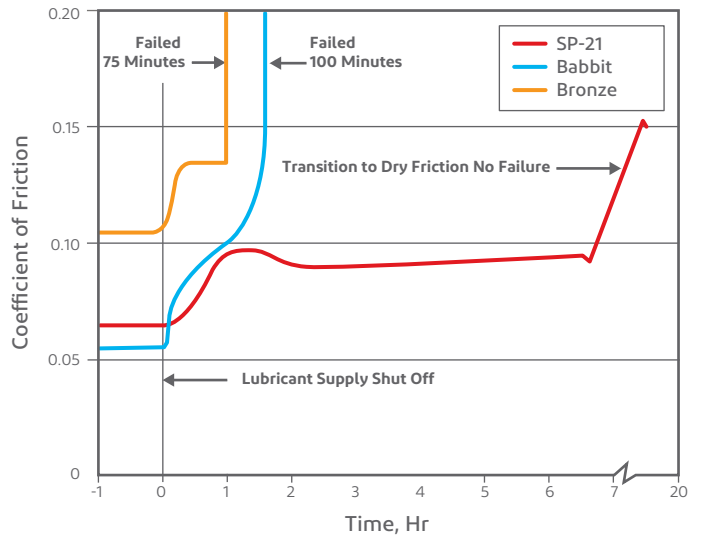

Figure 48. Lubricated starvation test. Segmented plane thrust bearing. Mating surface: AISI 1080.

Surface finish: HRc = 55, Ra = 0.4.
P = 3.5 MPa - V = 0.1 m/s
"Sunvis" 31 Oil — ZN/P ~ 1.4 x 10^{-4} at T = 0

Seal Ring

Why Polyimides?

For high temperature applications requiring flexibility and superior sealing compliance, polyimide plastics boost seal ring performance. Polyimides operate continuously from cryogenic temperatures to 300 °C (572 °F), with short-term use to 500 °C (932 °F), and can carry loads at temperatures beyond the reach of other plastics. They are far more compliant than metals, but because of their resiliency resist permanent deformation.

Polyimides offer the best structural features of cast iron — a common seal ring material — and engineering plastics, including low wear and low friction characteristics, coupled with greater stability than most other plastics. An important difference between polyimides and other seal ring materials is performance in unlubricated environments, such as gas sealing applications. Because of their inherent lubricity, polyimides provide outstanding wear resistance in unlubricated environments, with dry pressure velocity limits up to 12 MPa m/s.

Polyimides stand up to most industrial fluids, solvents, hydrocarbons and synthetic lubricants (hydraulic oil, transmission fluid), inert gases (such as nitrogen and argon) and certain fuels. Because of this, polyimide seal rings are well suited for transmissions, pneumatic and hydraulic cylinders, off-road vehicles, military equipment and valve applications.

Using Vespel® parts in your application can result in reduced warranty costs, less machine down time, and lower manufacturing cost.

This chapter helps you to use Vespel® seal rings in the most economical and efficient way. Inside you will find:

- A guide to parameters important in seal ring design;
- Methods for designing Vespel® seal rings;
- Proposals on getting the maximum performance from Vespel®;
- Recommended tolerances for Vespel® seal rings.

More detailed information about Vespel® seal rings can be found in the "Automotive Vespel®" brochure reference H-11198 and in the SAE paper 980734 "Improving Automatic Transmission Quality with High Performance Polyimide Rotary Seal Rings."

Glossary of Design Parameters

All seal ring applications share certain geometric parameters, as shown in these two illustrations.

- **Bore** – the inner diameter of the cylindrical space within which the seal ring is constrained to move.
- **Nominal diameter** – outer diameter of the seal ring. Usually equals the bore.
- **Gauge diameter** – Diameter of the measuring device, usually ~0.2 mm (0.01 in) above nominal diameter.
- **Radial thickness** – the difference between inner and outer diameters of the seal ring, sometimes referred to as "wall thickness."
- **Axial thickness** – thickness of the seal ring from top to bottom (ring height).
- **Gap** – distance between the open ends of the seal ring when constrained at the gauge diameter.
- **Nominal gap** – distance between the open ends of the seal ring when constrained at the nominal diameter.
- **Groove root** – the diameter of the groove which will face the inner surface of the seal ring.
- **Groove width** – axial dimension of the seal ring groove.

Design Parameters
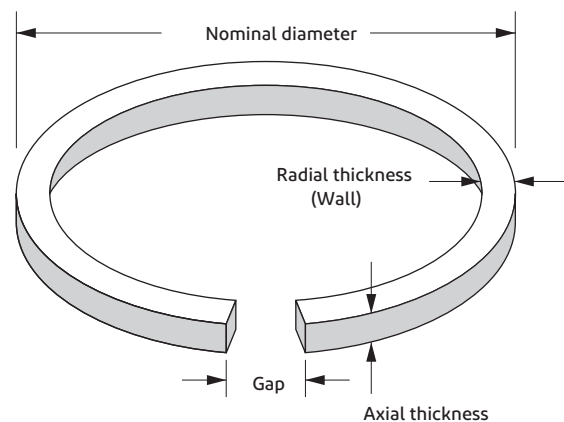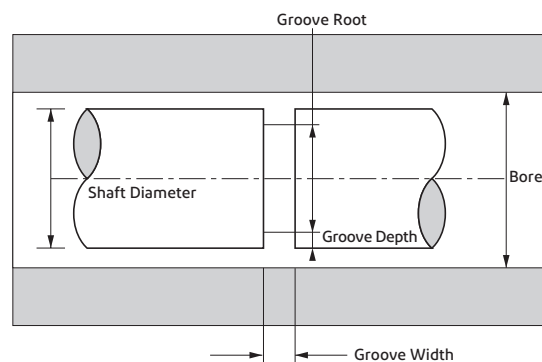
Standard Design Direct Formed Butt Joint Seal Rings

If you have an existing application which uses a seal ring made from metals or from other engineering plastics, several factors should be considered when specifying new Vespel® seal rings. The following guidelines specify the relationships between dimensions of the existing system and the size of the replacement ring. All dimensions are given in mm.

1. **Nominal Diameter**
   The outer diameter of the expanded seal ring should be equal to the bore diameter in the system.

2. **(Axial thickness)$_{max}$ = (GROOVE WIDTH)$_{min}$ − 0.1 mm**
   Allow a total of 0.1 mm (0.04 in) lateral clearance for the seal ring in the ring groove at maximum temperature.

3. **(RADIAL THICKNESS)$_{max}$ = 0.5 [(BORE)$_{min}$ − (GROOVE ROOT DIAMETER)$_{max}$] − 0.1 mm**
   Allow a total of 0.1 mm (0.04 in) radial clearance between bore and root at maximum temperature.

1.1 × radial thk. = axial thk.

Radial thk.

Chamfer reduces contact area with groove wall

Chamfer allows fit with reduced machining in groove

30° max

Function of groove radius

0.7 × axial thk. min. allowable

(0−0.3)

4. **(GAP)$_{min}$ = π × (GAGE DIAMETER) (T$_{max}$ − 20) (αSP − αB)**
   where

 | | | |
   |---|---|---|
   | T | = | temperature, °C |
   | αB | = | thermal coefficient of expansion of bore material, 10^{-6} 1/ °C |
   | αSP | = | thermal coefficient of expansion of Vespel® part, 10^{-6} 1/ °C (see Table 9, page 35). |

   This equation calculates the minimum gap required accounting for thermal expansion of the seal ring at operating temperature. Ring will just close at calculated temperature.

5. **(AXIAL THICKNESS) ≥ 1.1 (RADIAL THICKNESS)**
   Vespel® seal rings may be chamfered at the inside diameter to reduce contact between the ring and groove faces if the geometry of the assembly results in an axial thickness less than 1.1 times the radial thickness. Radial thickness is reduced by the chamfer length, creating a better pressure balance to hold the ring against the bore. Another advantage of the chamfer is that it allows clearance with any groove root radii present from the groove machining operator.

   The chamfer should be tapered no greater than 30° and have a 0−0.3 mm (0−0.01 in) shoulder, below the chamfer. The thickness at the shoulder (i.e., at the thinnest part of the ring) should be no greater than 70% of axial thickness.
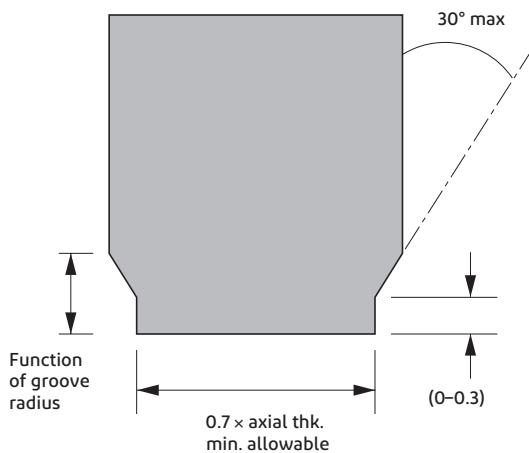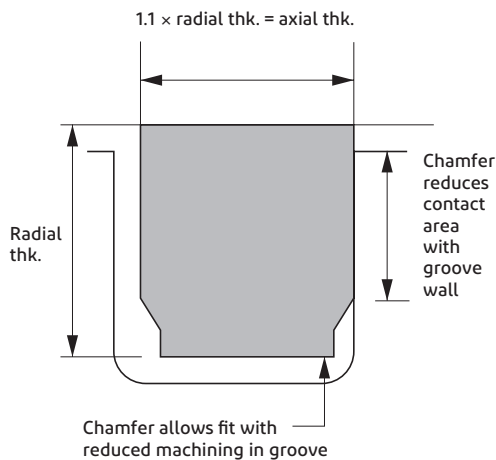
Other Design Considerations

- **Groove surface finish** – Surface finish of the metal is an important factor in the design of seal ring systems, because of the abrasive action between mating materials. Vespel® parts perform extremely well, especially under lubricated conditions. A smooth surface finish of 0.4 μm Ra is recommended. The mating material of the ring groove should be as hard as possible. If cast iron is used, however, surface finish is less crucial. Field tests demonstrate that cast iron mating surfaces with a finish of 2.0 μm Ra wear as well as those ground to 0.8 μm Ra finish.

- **Measuring ring gaps** – Most plastics will absorb moisture to some extent when held in air. Because the moisture content will affect the dimensions of the ring, gaps are measured only after the ring has been dried for 3 hours at 150 °C (302 °F). This simulates the condition of the ring during actual use, and ensures that all moisture has been eliminated. Vespel® rings can only be measured accurately when placed in a gauge and expanded to the outside of the gauge. Optical methods are required.

- **Oil grooves** – Grooves designed to carry lubricant to the face of the ring will improve wear characteristics of the ring. Vespel® seal rings can be optionally supplied with a number of oil groove configurations. The two designs shown here have been tested in a broad variety of applications and have proved successful in numerous cases.
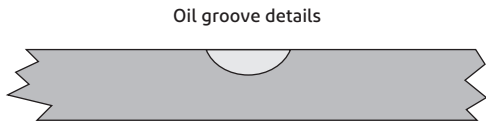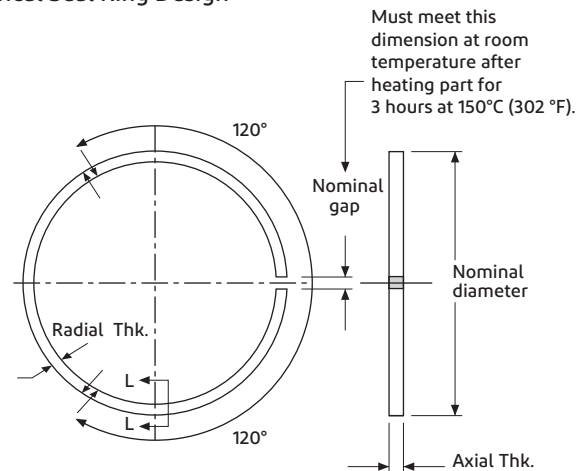
Oil groove details
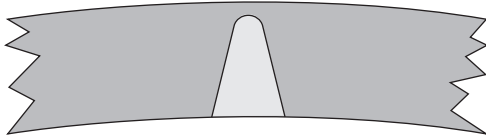
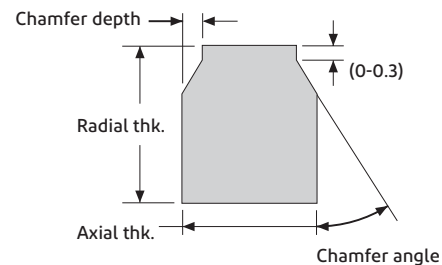
Thumbnail
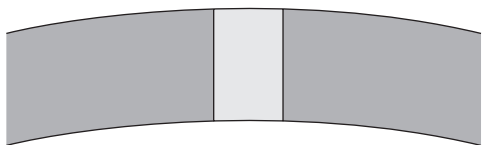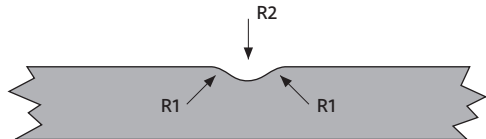
Straight through

Tolerance guidelines, mm (in)

Gauge diameter	Gap	Axial wall	Radial wall
<38 (<1.5)	±0.10 (±0.004)	±0.10 (±0.004)	±0.025 (±0.001)
38 to 64 (1.5 to 2.5)	±0.125 (±0.005)	±0.125 (±0.005)	±0.025 (±0.001)
64 to 89 (2.5 to 3.5)	±0.15 (±0.006)	±0.15 (±0.006)	±0.040 (±0.0016)
89 to 127 (3.5 to 5.0)	±0.175 (±0.007)	±0.175 (±0.007)	±0.040 (±0.0016)
127 to 178 (5.0 to 7.0)	±0.23 (±0.009)	±0.23 (±0.009)	±0.050 (±0.002)

Typical Seal Ring Design

Must meet this dimension at room temperature after heating part for 3 hours at 150°C (302 °F).
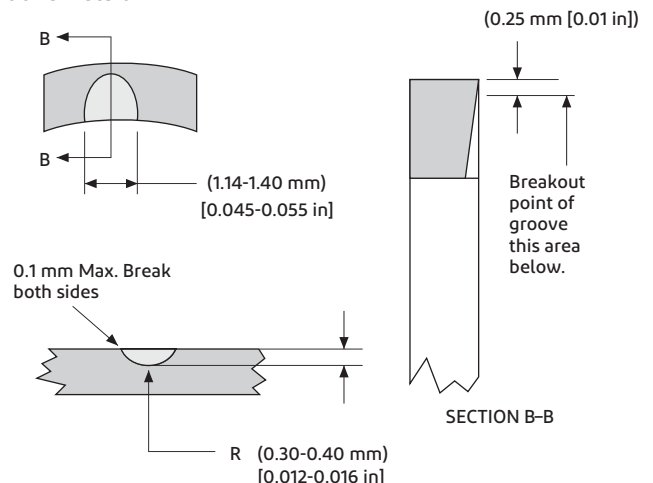
Part must be clean and free from burrs.

Section L–L

Design Tolerances

Designing seal rings with polyimides calls for a new approach to tolerances. Their superior compliance and low-friction surfaces allow designers to create seal rings that do not need the tight tolerances necessary with metals. In fact, polyimide rings provide better sealing compliance than metal-to-metal seals machined to much tighter tolerances.

This helps designers cut costs by reducing expensive surface finishing and machining operations. The Table below gives tolerance guidelines for standard polyimide seal rings.

Another benefit of the material's excellent compliance occurs during system assembly. Because polyimides offer more stability than other engineering plastics but more flexibility than metals, they hold up better during assembly, and are often easier to install.

Cast iron seal rings are hard but brittle, and often break during assembly. Seal rings made from other engineering plastics, because they are softer than polyimides, will often shear or cut during assembly without detection.

Groove Detail

(0.25 mm [0.01 in])

(1.14-1.40 mm) [0.045-0.055 in]

Breakout point of groove this area below.

0.1 mm Max. Break both sides

R (0.30-0.40 mm) [0.012-0.016 in]

SECTION B–B

Vespel® grades for seal rings

SP-21 is the standard material for seal rings chosen because it offers the best combination of mechanical strength and wear resistance.

SP-22 provides approximately the same wear characteristics but is more brittle. The linear thermal expansion, however, is lower than SP-21.

SP-211 is similar to SP-21 but offers a lower coefficient of friction up to 150 °C (302 °F).

SP-2515 offers a low coefficient of thermal expansion (CTE), excellent wear against both aluminum and steel alloys, and a low coefficient of friction in both dry and lubricated conditions.

Due to the influence of the manufacturing process on the coefficient of thermal expansion (see Table 9) customer testing should be done with parts machined out of the material (Direct Formed or Stock Shapes) which will be used later on in the end-use application.

Aluminium mating surface

Contrary to most other seal rings Vespel® may run either against the groove side wall or the bore. When one material is aluminum and the other one steel/cast iron it is beneficial to design the ring in a way that the relative movement takes place between Vespel® and steel/cast iron.

Special Designed Seal Rings

More and more special requirements on seal rings, especially in automotive automatic transmissions, have lead to a variety of different guidelines to design seal rings according to specific needs.
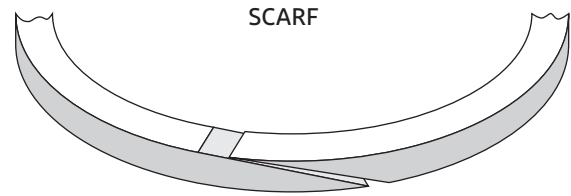
Gap geometry

Butt joint

- Direct formable
- Gap will close over temperature and can take compression without permanent deformation
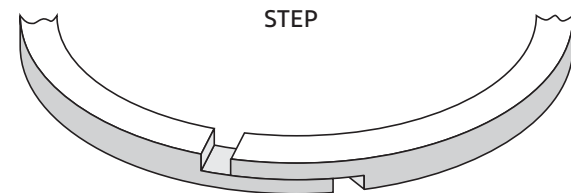- Cost-effective solution
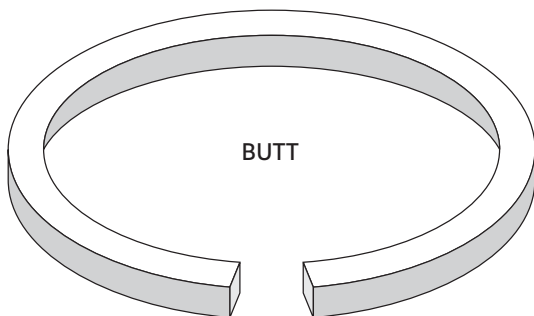
BUTT

Scarf joint

- Not direct formable
- Has to be cut
- Gap closing effect over temperature is much smaller than the butt joint gap.

SCARF

Stepped joint

- Can be direct formed depending on geometry
- Behaves in principle like a butt joint with a slightly reduced clearance

STEP

Very low leak rates with compressed butt joint seal rings

As Vespel® is a tough material it can take some compression without permanent deformation. Therefore a Vespel® butt joint seal ring can be designed to have a closed ("0") gap from 20 °C (68 °F) up to maximum operating temperature. The thermal expansion of the Vespel® ring will be taken by the inherent elastic deformation rate of the material. A minimum oil pressure is needed to press the ring against the sealing surface to overcome the warped shape of the ring in the groove when under thermal compression. The needed minimum oil pres-sure increases with smaller diameters. Therefore, it is very important to know the minimum pressure of this sealing system.

For these very low constant leak rate rings, the axial thickness should be as large as groove and design guidelines permit. It is recommended that the relative movement of the seal ring should take place between itself and the shaft groove, i.e., the seal ring is almost stationary relative to the housing.

Scarf joint seal rings

Scarf joint seal rings with a cut of usually 20° are very widely used and well known. These rings cannot be produced in one step; the cut has to be machined after the full ring has been pressed.

The leak rate for scarf joint seal rings is somewhat higher than that for compressed butt joint rings. However, scarf joint rings are not as sensitive to the minimum pressure of the transmission.

Assembly

Vespel® rings can be produced to have a memory that forces the rings to the groove root. These rings will be delivered closed or overlapped at the gap. Once these rings are assembled on to the shaft, they tend to stay to the inside of the groove root. This effect allows easy and safe assembly into the housing, without using grease.

It is recommended nevertheless to keep the rings packed till the final assembly and to use conical tools to smoothly guide the seal rings in their respective grooves. Contact your local Vespel® Technical Service Engineer for more details and advice.

Vespel® rings have a higher flexural modulus than, for example, PTFE rings and can therefore be used in automated assembly production lines.

The maximum wall thickness for compressed rings has to be:

$$0.5 \times (\text{DIAM. SHAFT}_{min} - \text{GROOVE ROOT DIAM}_{max}) - 0.05 \text{ mm}$$

In order to avoid breakage of the seal ring during shaft assembly into the housing, the tolerance on the wall thickness has to be as small as possible.

Selection

The grade selection should take into account the difference in thermal expansion and wear rates of the various proposed grades. The seal ring gap type and gap tolerances are specified on the basis of the operating conditions, leakage requirements and minimum pressure of the transmission. Figures 49 to 52 show the influence of seal ring gap type and material grade on leak rates.

Figure 50. SP-21 Seal ring. Butt joint gap compressed (negative)

Seal ring leak test Vespel® SP-21
30 mm diameter butt-joint, gap= +0.068 mm
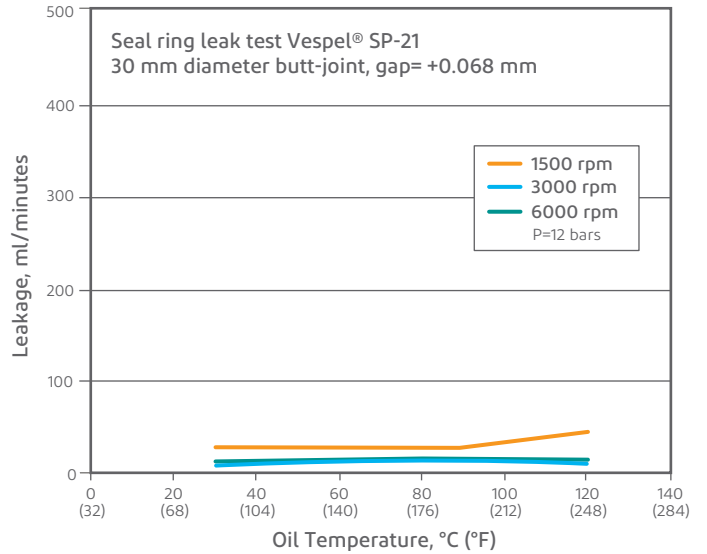
Figure 51. SP-21 Seal ring. Scarf joint gap

Seal ring leak test Vespel® SP-21
30 mm diameter scarf joint, gap = +0.050 mm

Figure 49. SP-21 Seal ring. Butt joint gap (positive)

Seal ring leak test Vespel® SP-21
30 mm diameter butt-joint, gap = +0.057 mm
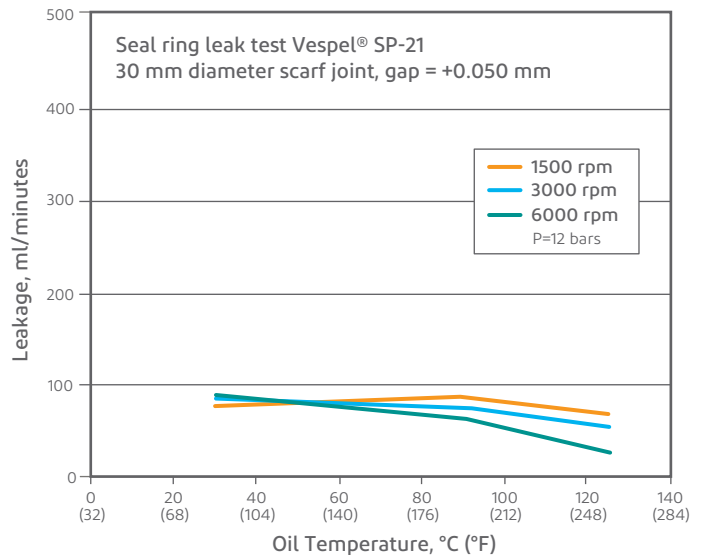
Figure 52. SP-22 Seal ring. Scarf joint gap

Seal ring leak test Vespel® SP-22
30 mm diameter scarf joint, gap = +0.018 mm
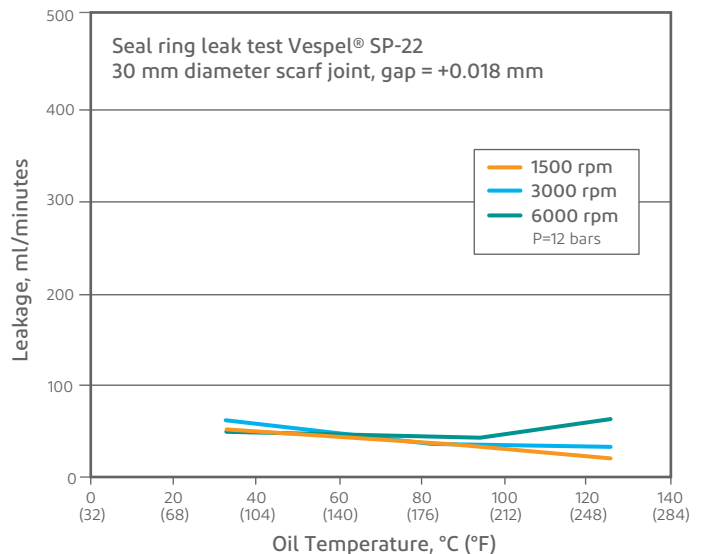
Appendix A   Vespel® Stock Shapes and Sizes

Vespel® S Family Sizes

Shape	Grade	Size Range*
Rod**	SP-1, SP-21, SP-22, SP-211 and SP-3	OD: 3.1-82.5 mm (0.125-3.25 in) Max. Length: 965.2 mm (38 in)
	SCP-5009, SCP-50094 and SCP-5050	SCP-5009: OD: 6.3-38.1 mm (0.25-1.5 in) SCP-50094: OD: 6.3-50.8 mm (0.25-2 in) SCP-5050: OD: 6.3-82.5 mm (0.25-3.25 in) Max. Length: 914.4 mm (36 in)
	SCP-5000	OD: 6.3-69.8 mm (0.25-2.75 in) Max. Length: 482.6 mm (19 in)
Tube	SP-1, SP-21, SP-22, SP-211 and SP-3	OD: 40.6-317.5 mm (1.6-12.5 in) ID: 27.9-266.7 mm (1.1-10.5 in) Max. Length: 838.2 mm (33in)
Plaque Square**	SP-1, SP-21, SP-22, SP-211, SP-3 and SP-202	Max. Size: 254 x 254 mm (10 x 10 in) Max. Thickness: 50.8 mm (2 in)
Plaque Disk	SP-1	OD: 165.1-469.9 mm (6.5-18.5 in) Thickness: 22-59.8 mm (0.87-2.35 in)
	SCP-5000	OD: 215.9-414 mm(8.5-16.3 in) Thickness: 25-46 mm (.98-1.8 in)
Plaque Ring	SP-1, SP-21 and SCP-5000	OD: 125-545 mm (4.9-21.5 in) ID: 55.9-419.1 mm (2.2-16.5 in) Thickness: 1.2-63 mm (0.05-2.5 in)
Balls	SP-1	OD: 3.2-12.7 mm (0.125-0.5 in)

*There are some special sizes available not included on this list. Not all sizes listed are available in all grades.

**Rods and square plaque are available through distribution.

Appendix B Property Tables

Table 1. Summary of Typical Properties of Standard SP Polyimide Resins

	Property	Temperature, °C (°F)	ASTM Method	Units	SP-1		SP-21		SP-22		SP-3
					ISO	DF	ISO	DF	ISO	DF	ISO
MECHANICAL	Tensile strength, ultimate	23 (73) 260 (500)	D1708 or E8†	MPa (kpsi)	86.2 (12.5) 41.4 (6)	72.4 (10.5) 36.5 (5.3)	65.5 (9.5) 37.9 (5.5)	62.0 (9) 30.3 (4.4)	51.7 (7.5) 23.4 (3.4)	48.3 (6.5) 26.2 (3.8)	58.5 (8.5)
	Elongation, ultimate	23 (73) 260 (500)	D1708 or E8†	%	7.5 6.0	7.5 7.0	4.5 3.0	5.5 5.2	3.0 2.0	2.5 2.0	4.0
	Flexural strength, ultimate	23 (73) 260 (500)	D790	MPa (kpsi)	110.3 (16) 62.1 (9)	82.7 (12) 44.8 (6.5)	110.3 (16) 62.0 (9)	82.7 (12) 48.3 (7)	89.6 (13) 44.8 (6.5)	62.1 (9) 37.9 (5.5)	75.8 (11) 39.9 (5.8)
	Flexural modulus	23 (73) 260 (500)	D790	MPa (kpsi)	3102 (450) 1724 (250)	2482 (360) 1448 (210)	3792 (550) 2551 (370)	3171 (460) 1792 (260)	4826 (700) 2758 (400)	4826 (700) 2758 (400)	3275 (475) 1862 (270)
	Compressive stress at 1% strain at 10% strain at 0.1% offset	23 (73)	D695	MPa (kpsi)	24.8 (3.6) 133.1 (19.3) 51.0 (7.4)	24.1 (3.6)* 112.4 (16.3)* 33.1 (4.8)*	29.0 (4.2) 133.1 (19.3) 45.5 (6.6)	22.8 (3.3)* 104.8 (15.2)* 33.8 (4.9)*	31.7 (4.6) 112.4 (16.3) 41.4 (6)	24.1 (3.5) 93.8 (140* 25.5 (3.7)*	34.5 (5) 127.6 (18.5)
	Compressive modulus	23 (73)	D695	MPa (kpsi)	2413 (350)	2413 (350)*	2895 (420)	2275 (330)*	3275 (475)	2654 (385)*	2413 (350)
	Axial fatigue, Endurance limit at 10³ cycles at 10⁷ cycles	23 (73) 260 (500) 23 (73) 260 (500)		MPa (kpsi)	55.8 (8.1) 26.2 (3.8) 42.1 (6.1) 16.5 (2.4)		46.2 (6.7) 22.8 (3.3) 32.4 (4.7) 16.5 (2.4)	– – – –	– – – –	– – – –	– – – –
	Flexural fatigue, Endurance limit at 10³ cycles at 10⁷ cycles	23 (73) 23 (73)		MPa (kpsi)	65.5 (9.5) 44.8 (6.5)		65.5 (9.5) 44.8 (6.5)	– –	– –	– –	– –
	Shear strength	23 (73)	D732	MPa (kpsi)	89.6 (13)		77.2 (11.2)				
	Impact strength. Izod. notched	23 (73)	D256	J/m	42.7		42.7				21.3
	Impact strength. Izod. unnotched	23 (73)	D256	J/m	747		320				112
	Poisson's ratio	23 (73)			0.41		0.41				
WEAR AND FRICTION	Coefficient of friction** PV = 0.875 MPa·m/s				0.29	0.29	0.24	0.24	0.30	0.30	0.25
	PV = 3.5 MPa·m/s				–	–	0.12	0.12	0.09	0.09	0.17
	In vacuum				–	–	–	–	–	–	0.30
	Static in air				0.35	–	0.30	–	0.27	–	–
THERMAL	Coefficient of linear thermal expansion	23 to 260 (73 to 500) −62 to +23 (−143 to +73)	D696	μm/m/°C	54	50 45	49	41 34	38	27	52
	Thermal conductivity	40 (104)		W/m · °C	0.35	0.29*	0.87	0.46*	1.73	0.89*	0.47
	Specific heat			J/kg/°C	1130						
	Deformation under 14 MPa load	50 (122)	D621	%	0.14	0.20	0.10	0.17	0.08	0.14	0.12
	Deflection temperature at 2 MPa		D648	°C (°F)	~360 (~680)		~360 (~680)				

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(continued)

Appendix B   Property Tables (continued)

Table 1. Summary of Typical Properties of Standard SP Polyimide Resins (continued)

	Property	Temperature	ASTM Method	Units	SP-1 ISO	SP-1 DF	SP-21 ISO	SP-21 DF	SP-22 ISO	SP-22 DF	SP-3 M
ELECTRICAL	Dielectric constant at 10^2 Hz at 10^4 Hz at 10^6 Hz	23 °C (73 °F)	D150	MPa	3.62 3.64 3.55	– – –	13.53 13.28 13.41	– – –	– – –	– – –	– – –
	Dissipation factor at 10^2 Hz at 10^4 Hz at 10^6 Hz	23 °C (73 °F)	D150	MPa	0.0018 0.0036 0.0034	– – –	0.0053 0.0067 0.0106	– – –	– – –	– – –	– – –
	Dielectric strength short time 2 mm (0.08 in) thick		D149	MV/m	22	–	9.84	–	–	–	–
	Volume resistivity	23 °C (73 °F)	D257	$\Omega \cdot m$	10^{14}–10^{15}	–	10^{12}–10^{13}	–	–	–	–
	Surface resistivity	23 °C (73 °F)	D257	Ω	10^{15}–10^{16}	–					
OTHER	Water absorption 24 h 48 h equilibrium, 50% RH		D570	%	0.24 0.72 1.0–1.3	– – 1.0–1.3	0.19 0.57 0.8–1.1	– – 0.8–1.1	0.14 0.42 –	– – –	0.23 0.63 –
	Specific gravity		D792		1.43	1.34	1.51	1.42	1.65	1.56	1.60
	Oxygen index		D2863	%	53	–	49	–	–	–	–

† Machined tensile specimens made per D1708 and direct-formed specimens made per figure 19 of E-8 (standard bar for powdered metallurgy products); specimens tested by D638.

* Direct-formed (DF) properties marked with asterisk were measured parallel to the forming direction.
  All other direct-formed properties were measured perpendicular to the forming direction.

††Unlubricated in air (PV 0.875 MPa·m/s).

**Steady state, unlubricated in air.

ISO: Parts machined out of isostatic shapes material. Properties are non-directional.

DF: Parts obtained by «Direct Forming» process.

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Appendix B Property Tables (continued)

Table 2. Preliminary Properties of SP Polyimide Resins

	Property	Temperature	Test Method	Units	SP-211		SP-2515
					ISO	DF	DF
MECHANICAL	Tensile Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D638	MPa (kpsi)	44.8 (6.5) 24.1 (3.5)	51.7 (7.8) 24.1 (3.5)	39 (5.7) 25 (3.6)
	Tensile Elongation	23 °C (73 °F) 260 °C (500 °F)	ASTM D638	%	3.5 3	5.5 5.3	1.9 2.1
	Young's Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D638	MPa (kpsi)	– 	– 	6340 (920) 2260 (328)
	Flexural Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	68.9 (10.0) 34.5 (5.0)	68.9 (10.0) 34.5 (5.0)	61 (8.8) 39 (5.5)
	Flexural Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	3102 (450) 1379 (200)	2758 (400) 1379 (200)	5560 (807) 3820 (554)
	Compressive Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	– 	– 	105 (15.3) 71 (10.3)
	Compressive Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	– 	– 	2090 (302) 1840 (266)
	Compressive Stress 　at 1% strain 　at 10% strain 　at 0.1% offset	23 °C (73 °F) 23 °C (73 °F) 23 °C (73 °F)	ASTM D695	MPa (kpsi)	20.7 (3.0) 102.0 (14.8) 37.2 (5.4)	14.5 (2.10)* 75.8 (11.0)* 27.6 (4.0)*	–
	Compressive Modulus	23 °C (73 °F)	ASTM D695	MPa (kpsi)	2068 (300)	1379 (200)*	–
WEAR	Wear Rate †	23 °C (73 °F)	–	m/s x 10⁻¹⁰	4.90	4.90	
	Wear Factor 　PV = 0.875 MPa·m/s 　PV = 3.5 MPa·m/s	23 °C (73 °F)	–	mm-sec/MPa-m-hr (in³-min/ft-lb-hr)	–	–	5.4 x 10⁻³ (74 x 10⁻¹⁰) 20.4 x 10⁻³ (282 x 10⁻¹⁰)
	Friction Coeffiecient 　PV = 0.875 MPa·m/s 　PV = 3.5 MPa·m/s	23 °C (73 °F)	–	–	0.12 0.08	0.12 0.08	0.21 0.33
	Static in Air	23 °C (73 °F)	–	–	0.20	–	–
THERMAL	Coefficient of Linear Expansion	23 °C–260 °C (73°F–500°F) 50–150 °C (122–302°F)	ASTM D696	μm/m/°C (10⁻⁶ in/in/°F)	54 (30)	41 (23)	23 (13), 54 (30)*
	Thermal Conductivity	40 °C (104°F) 50 °C (122°F) 100 °C (212°F)	–	W/m·°C	0.76	0.42*	2.05 2.04
	Specific Heat	60 °C (140°F)	E-1269	J/kg·°C (Btu/lb·°F)	–	–	895 (0.214)
	Deformation Under 14 MPa Load	50 °C (122 °F)	D-621	%	0.13	0.29	–
OTHER	Water Absorption, 24 hrs Water Absorption, 48 hrs	23 °C (73 °F) 50 °C (122 °F)	ASTM D570	% weight change	0.21 0.49	–	0.3
	Specific Gravity	–	ASTM D792	–	1.55	1.46	1.73

* Measured parallel to the forming direction. All other direct-formed properties were measured perpendicular to the forming direction.
† Unlubricated in air (PV 0.875 MPa·m/s).

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Table 3. Typical Properties of DuPont™ Vespel® SP-202 Plaque

Property		Temperature	Test Method	Units	SP-202, Plaque	
					Perpendicular	Parallel
MECHANICAL	Tensile Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D638*	MPa (kpsi)	92 (13.3) 53 (7.7)	56 (8.1) 28 (4.1)
	Tensile Elongation	23 °C (73 °F) 260 °C (500 °F)	ASTM D638*	%	4.5 5.2	2.6 2.6
	Young's Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D638*	MPa (kpsi)	3,700 (530) 2,600 (378)	2,800 (402) 1,800 (256)
	Flexural Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	159 (23) 89 (13)	164 (24) 91 (13)
	Flexural Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	6,300 (911) 4,600 (671)	6,500 (947) 4,600 (674)
	Compressive Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	206 (29.9) 105 (15.2)	230 (33.4) 114 (16.5)
	Compressive Strain at Break	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	30 27	26 21
THERMAL	CLTE	35–300 °C (95–572 °F)	ASTM E 831	E-6/C (E-6F)	28 (16)	86 (47)
ELECTRICAL	Surface Resistivity	23 °C (73 °F)	ASTM D991	ohm	10	0.1
	Volume Resistivity	23 °C (73 °F)	ASTM D991	ohm·cm	0.1	10
OTHER	Specific Gravity	–	ASTM D792	–	1.49	1.49
	Hardness, Rockwell, Scale E	23 °C (73 °F)	ASTM D785	–	66	51
	Water absorption, Immersion, 24 hr	23 °C (73 °F)	ASTM D570	%	0.23	0.23

*Machined tensile specimens made per D1708 and direct-formed specimens made per figure 19 of E-8 (standard bar for powdered metallurgy products); specimens tested by D638.

ISO: Parts machined out of isostatic shapes material. Properties are non-directional.

DF: Plaque parts obtained by Direct Forming process.

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Table 4. Typical Properties of DuPont™ Vespel® SCP

Property	Temperature	Test Method	Units	SCP-5000 ISO	SCP-5009 ISO	SCP-50094 ISO	SCP-50094 DF	SCP-5050 ISO	SCP-5050 DF
Tensile Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D638 D1708 Specimen*	MPa (kpsi)	163 (23.6) 62 (9.0)	116 (16.8) 57 (8.3)	124 (18.0) 55 (8.0)	88 (12.8) 45 (6.6)	72 (10.5) 38 (5.6)	79 (11.5) 41 (6.0)
Tensile Elongation	23 °C (73 °F) 260 °C (500 °F)	ASTM D638 D1708 Specimen*	%	7.5 49	3 9.7	4.3 13	2.1 4.6	2.5 5.3	2.3 3.1
Young's Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D638 D1708 Specimen*	MPa (kpsi)	3,990 (580) 2,370 (340)	6003 (871) 2612 (379)	4,140 (600) 2,350 (340)	6490 (941) 3720 (539)	8,928 (1,295) 2,931 (425)	9590 (1390) 3860 (561)
Flexural Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	254 (36.8) 96.5 (14.0)	195 (28.3) 99 (14.4)	200 (29) 96 (14)	109 (15.8) 69 (10.0)	130 (19) 73 (11)	120 (17) 73 (11)
Flexural Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D790	MPa (kpsi)	5,760 (836) 3,007 (436)	6231 (904) 3560 (516)	6,370 (923) 3,540 (514)	5170 (750) 2700 (392)	7,800 (1,130) 5,080 (740)	7820 (1130) 5270 (764)
Compressive Strength	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	640 (92.9) 549 (79.6)	481 (69.8) 414 (60)	385 (56) 450 (65)	170 (24.7) 77 (11.2)	219 (32) 240 (35)	154 (22) 106 (15)
Compressive Strain, Ultimate	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	%	–	–	41 63	18 31	–	13 27
Compressive Modulus	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	9,060 (1,314) 3,698 (536)	2594 (376) 1663 (241)	–	–	2,997 (435) 3,138 (455)	–
Compressive Stress at 10% Strain	23 °C (73 °F) 260 °C (500 °F)	ASTM D695	MPa (kpsi)	230 (33.4) 73.6 (10.7)	222 (32.2) 96 (13.9)	220 (31.9) 81 (11.7)	168 (24.4) 64 (9.3)	172 (25.0) 184 (26.7)	156 (23) 73 (11)
Deformation Under, 14 MPa (2 kpsi)	23 °C (73 °F)	ASTM D621, 24 hr ASTM D621, 10 minutes Permanent Deformation	% deformation	0.05	0.03	0.05	0.03 0.04	0.03	0.04 0
Compressive Creep, 10 hr 100 hr 1000 hr	23 °C (73 °F)	ASTM D2990 10 MPa (1.5 kpsi)	%	–	–	0.02 0.02 0.05	0.02 0.03 0.05	–	0.02 0.03 0.05
Compressive Creep, 10 hr 100 hr 1000 hr	23 °C (73 °F)	ASTM D2990 14 MPa (2.5 kpsi)	%	–	–	0.03 0.05 0.07	0.04 0.06 0.09	–	0.05 0.07 0.09
Rockwell — "E" Hardness	–	ASTM D785	–	95	91	91	70.4	63	12
Poisson's Ratio	23 °C (73 °F) 260 °C (500 °F)	ASTM D638	–	–	–	0.34 0.34	0.25 0.32	–	0.22 0.23
Coefficient of Thermal Expansion	23–300 °C (73–572 °F)	ASTM E-831	m/m·°C or m/m·K (in/in·°F)	45 x 10⁻⁶ (26 x 10⁻⁶)	44 x 10⁻⁶ (25 x 10⁻⁶)	–	60.1 x 10⁻⁶ (33.4 x 10⁻⁶)[a] 34.1 x 10⁻⁶ (18.9 x 10⁻⁶)[b]	29 x 10⁻⁶ (16 x 10⁻⁶)	51 x 10⁻⁶ (29 x 10⁻⁶)[a] 16 x 10⁻⁶ (9 x 10⁻⁶)[b]
Coefficient of Thermal Expansion	50–150 °C (122–302 °F)	ASTM E-831	m/m·°C or m/m·K (in/in·°F)	–	–	42.7 x 10⁻⁶ (23.7 x 10⁻⁶)	–	–	–
Specific Heat	60 °C (140 °F)	ASTM E-1269	J/kg·°C (Btu/lb·°F)	9.2 x 10⁵ (0.22)	–	9.2 x 10⁵ (0.22)	8.96 x 10⁻⁵ (0.214)	920 (0.22)	887 (0.212)
Heat Deflection Temp in Tin Bismuth, Parallel	–	ASTM D648, 1.8 MPa (0.26 psi)	°C (°F)	–	–	–	334 (634)	–	–
Heat Deflection Temp in Tin Bismuth, Perpendicular	–	ASTM D648, 1.8 MPa (0.26 psi)	°C (°F)	–	–	–	336 (637)	–	–
Thermal Conductivity	50 °C (122 °F) 100 °C (212 °F) 150 °C (302 °F) 200 °C (392 °F) 250 °C (482 °F) 300 °C (572 °F)	ASTM F-433	W/mK (Btu/hr in °F)	–	–	–	0.39 (0.02) 0.40 (0.02) 0.41 (0.02) 0.41 (0.02) 0.41 (0.02)	–	1.65 (0.08) 1.78 (0.09) 1.38 (0.07)

Note: The leftmost vertical labels read "MECHANICAL" (spanning the mechanical property rows) and "THERMAL" (spanning the thermal property rows).

Table 4. Typical Properties of DuPont™ Vespel® SCP (continued)

Property	Temperature	Test Method	Units	SCP-5000 ISO	SCP-5009 ISO	SCP-50094 ISO	SCP-50094 DF	SCP-5050 ISO	SCP-5050 DF
ELECTRICAL Dielectric Constant, 10^2 Hz	23 °C (73 °F)	ASTM D150	–	–	–	–	5.5	–	21.1
Dielectric Constant, 10^4 Hz	23 °C (73 °F)	ASTM D150	–	3.3	–	–	5.4	–	20.6
Dielectric Constant, 10^6 Hz	23 °C (73 °F)	ASTM D150	–	3.3	–	–	5.4	–	19.1
Dielectric Factor, 10^2 Hz	23 °C (73 °F)	ASTM D150	–	–	–	–	0.002	–	0.0075
Dielectric Factor, 10^4 Hz	23 °C (73 °F)	ASTM D150	–	0.001	–	–	0.005	–	0.0112
Dielectric Factor, 10^6 Hz	23 °C (73 °F)	ASTM D150	–	0.001	–	–	0.002	–	0.0165
Dielectric Strength	23 °C (73 °F)	ASTM D149	Volts/mil	–	–	–	413	–	Conductive
Volume Resistivity	23 °C (73 °F)	ASTM D257	Ohm-m	1014	–	–	2.18×10^{16} (8.57×10^{15})	–	9.4×10^7 (3.7×10^7)
Surface Resistivity	23 °C (73 °F)	ASTM D257	Ohm-m	1015	–	–	1.56×10^{17} (6.15×10^{16})	–	4.1×10^5
WEAR Coefficient of Friction, unlubricated, Air	–	0.88 (25 K) PV † 3.50 (100 K) PV** 10.50 (300 K) PV***	Falex	0.26 0.15	0.22 0.14	0.25 0.07 0.11	0.253 0.064 0.084	–	0.2 0.08
Wear Factor, unlubricated, air	–	0.88 (25 K) PV* 3.50 (100 K) PV** 10.50 (300 K) PV***	mm-sec/ MPa-m-hr (in³-min/ft-lb-hr)	–	–	1.7×10^{-3} (24×10^{-10}) 0.8×10^{-3} (11×10^{-10}) 1.2×10^{-3} (17×10^{-10})	1.0×10^{-3} (13×10^{-10}) 0.6×10^{-3} (8×10^{-10}) 1.2×10^{-3} (17×10^{-10})	–	4.0×10^{-3} (55×10^{-10}) 1.9×10^{-3} (26×10^{-10})
OTHER Specific Gravity	–	ASTM D792	–	1.46	1.5	1.5	1.44	1.76	1.68
Water Absorption after 24 hr Water Absorption, total	23 °C (73 °F)	ASTM D570	% weight change	0.08	0.06	0.06	0.96	0.04	0.07

† 0.7 m/s, 1.3 MPa
** 2.0 m/s, 1.7 MPa
*** 3.0 m/s, 3.5 MPa
a Parallel
b Perpendicular

*Machined tensile specimens made per D1708 and direct-formed specimens made per figure 19 of E-8 (standard bar for powdered metallurgy products); specimens tested by D638.
ISO: Parts machined out of isostatic shapes material. Properties are non-directional.
DF: Parts obtained by Direct Forming process.

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Appendix C Safety Data

Consult the Vespel® Safety Data Sheet (SDS) or Article Information Sheet (AIS) for applicable safety information. To obtain an SDS or AIS, contact your Technical Service Engineer or use the regional contact information provided below. Your Technical Service Engineer should also be consulted on the use of Vespel® parts and shapes for other applications not described in this Design Guide.

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