

Engineered for Extreme Service: Understanding High-Performance Polyimides

Webinar Presented by Curbell Plastics



Today's Presenter:

Keith Hechtel, DBA, Vice President of Business Development & Marketing

With 35+ years in plastics, Keith helps companies identify plastic materials that can be used to replace metal components to achieve cost savings, quality improvements, and design innovation.

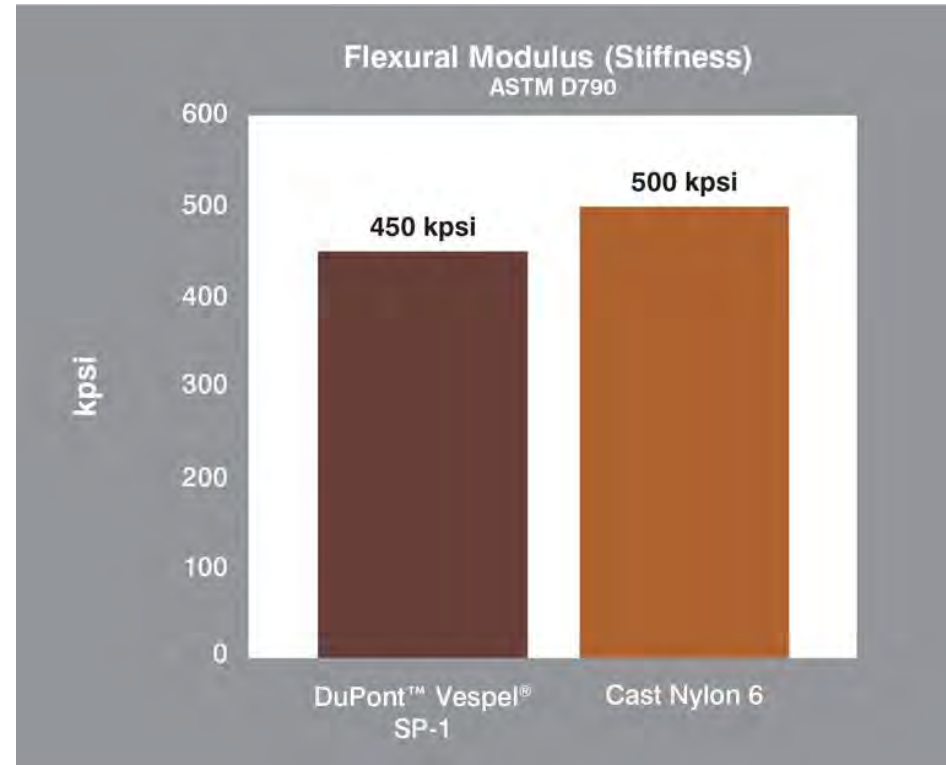
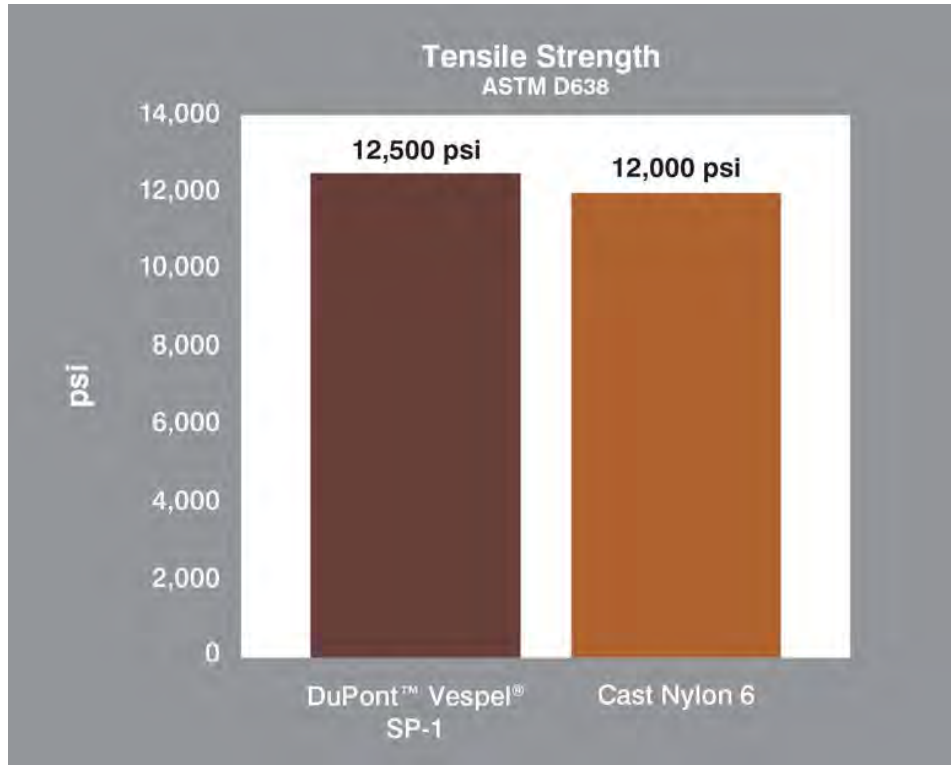


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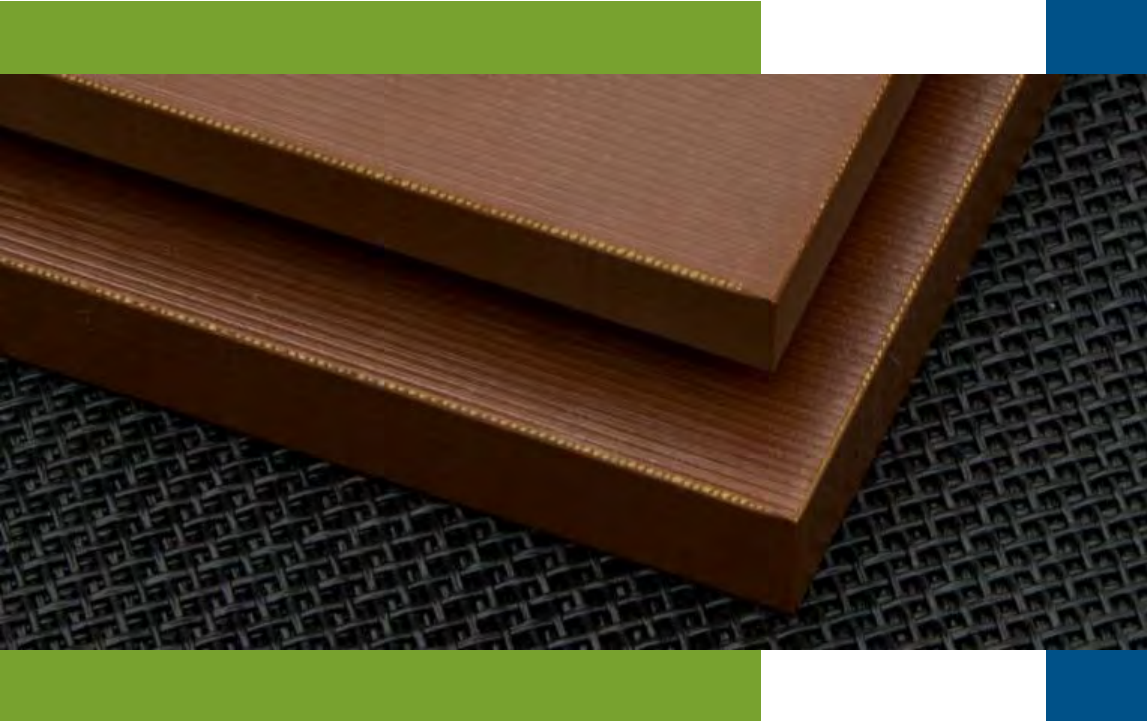


Mechanical Properties of DuPont™ Vespel® and Cast Nylon 6



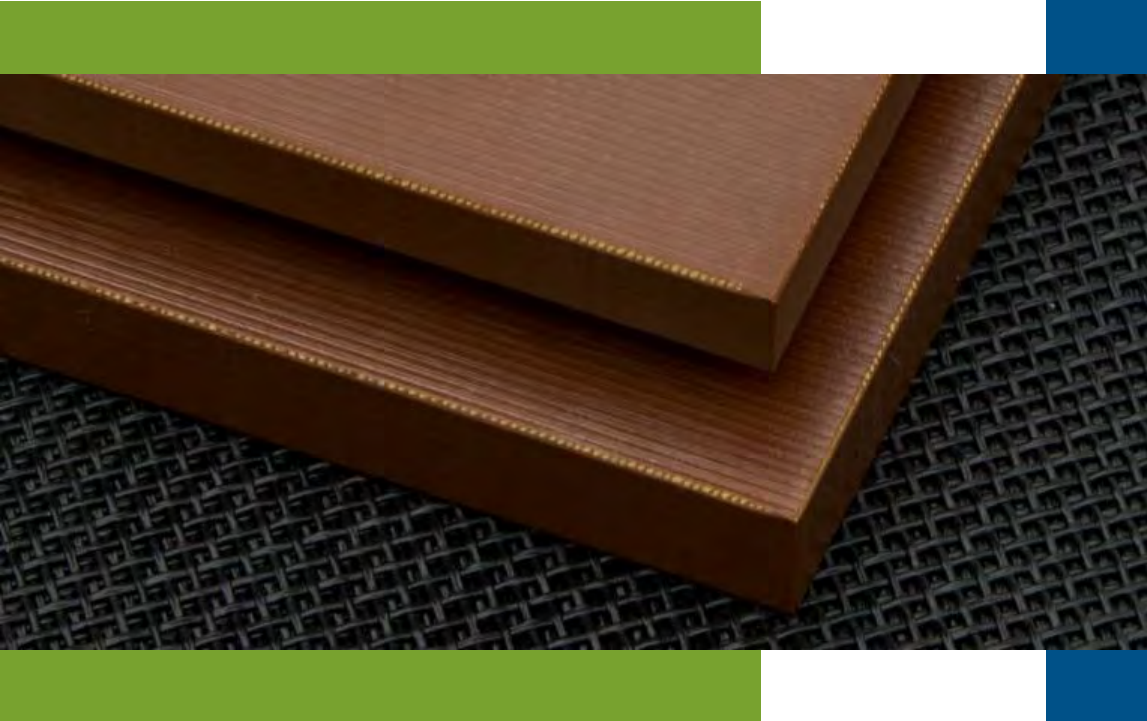
The price of Vespel® is approximately 200 times the price of nylon 6.

Sources of Technical Information on Vespel®



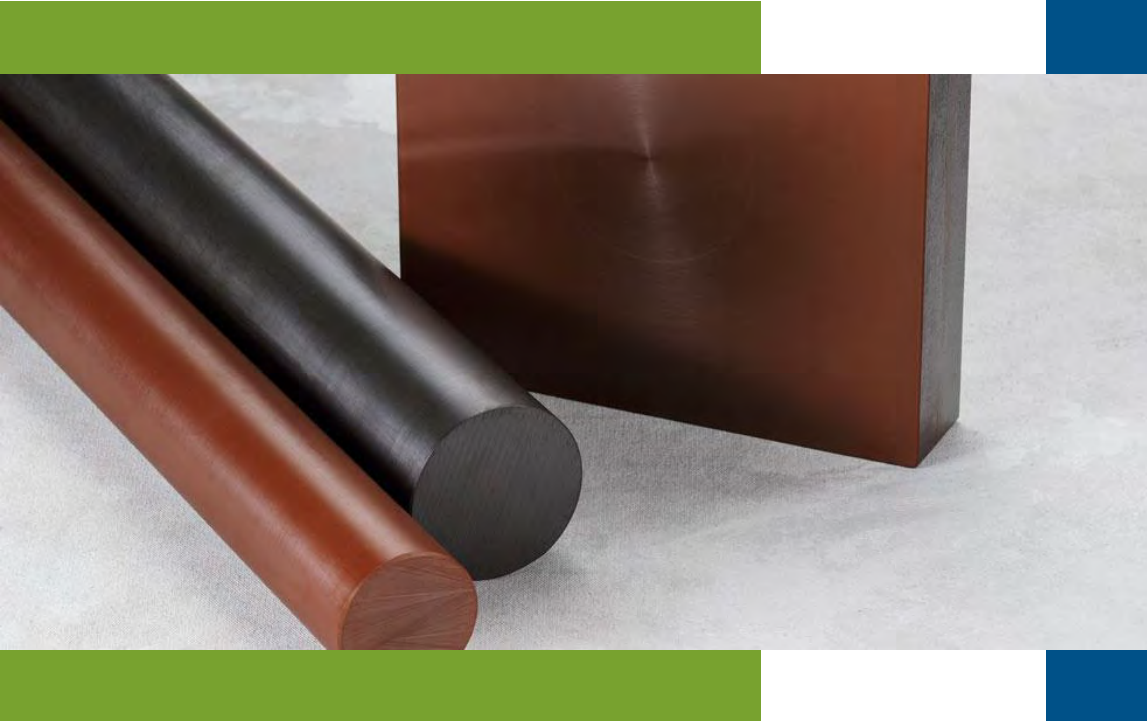
- NASA
- European Space Agency
- U. S. Department of Energy Labs
- CERN
- Naval Air Test Center, Dept. of the Navy
- Army Research Laboratory
- Jet Propulsion Laboratory
- National Bureau of Standards
- Academic Conference Proceedings
- Academic Journals

Primary Benefits of DuPont™ Vespel® for our Customers



- Consistent, moderate modulus across a broad temperature range
- Stress relaxation and creep characteristics
- High temperature performance (modulus, thermal stability, creep)
- Low temperature performance (ductility, low thermal conductivity)
- Radiation resistance

Primary Benefits of DuPont™ Vespel® for our Customers



- Vacuum capability (sealing, low outgassing, and friction and wear)
- Friction and wear properties (high PV, vacuum, etc.)
- Consistent CTE
- Dimensional stability in humid environments
- Flammability characteristics / some degree of oxygen compatibility



**Consistent, Moderate
Modulus Across a Wide
Temperature Range**

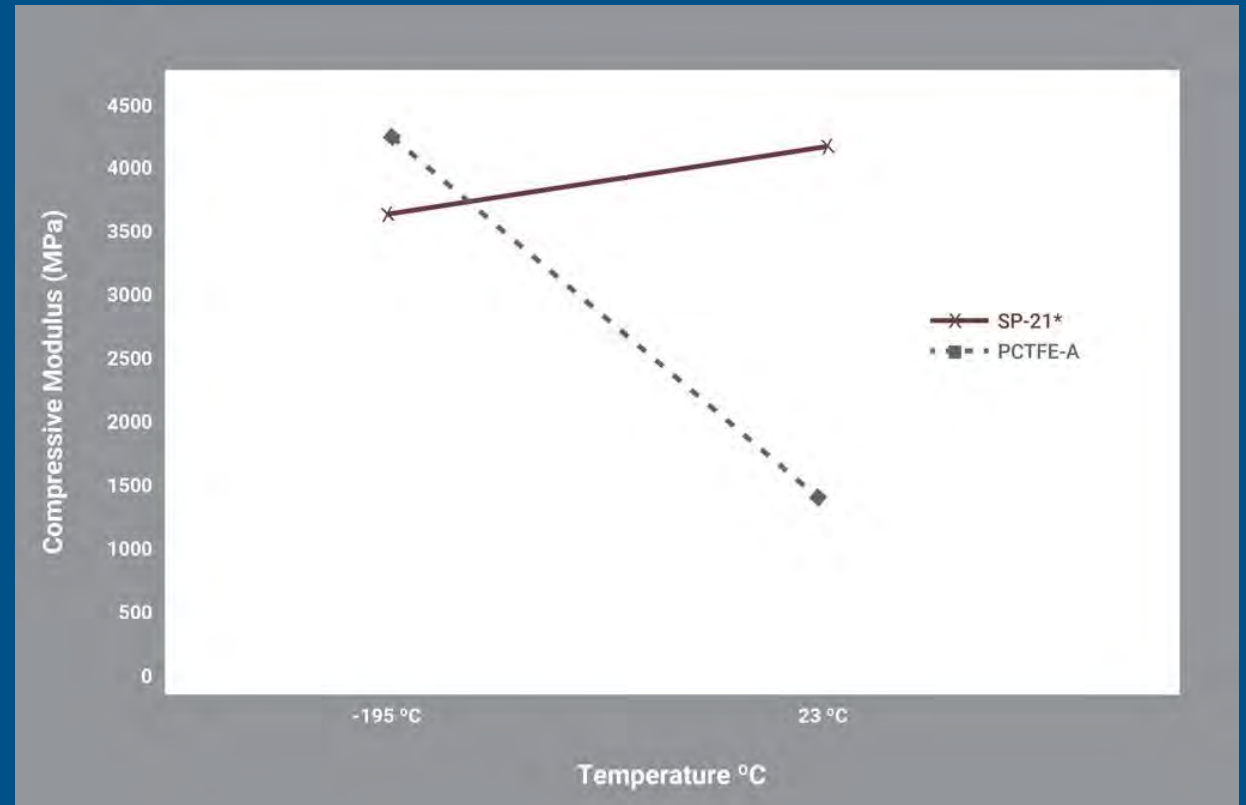
The Power of Moderate Modulus and Conformability



The Power of Moderate Modulus and Conformability

	SP-21 ISO	PCTFE
Compressive Modulus at -195°C	3654	4275
Compressive Modulus at RT	4200	1370

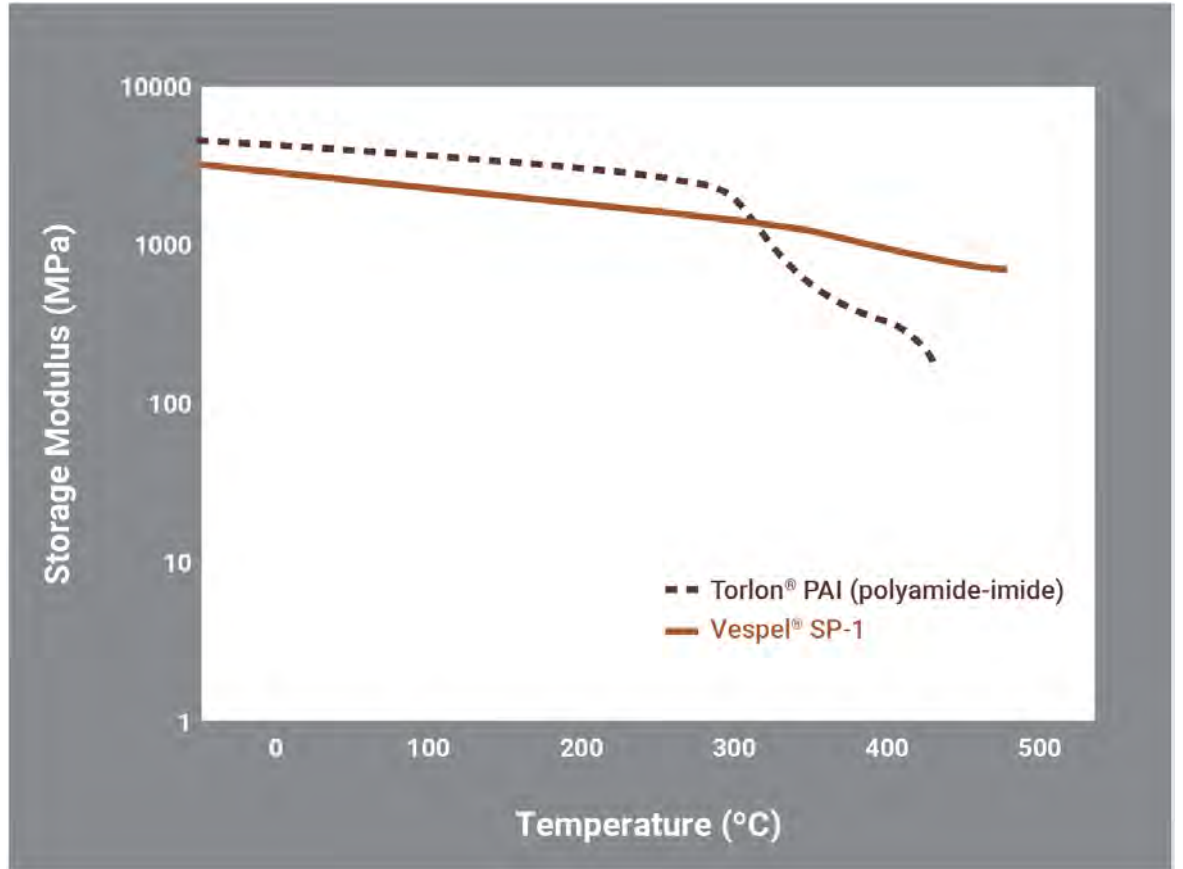
Compressive Modulus (ASTM D695) vs. Temperature



Source: Adapted from Geoff Lewis (2015)

Consistent, Moderate Modulus Across a Broad Temperature Range

Storage Modulus of Vespel® SP-1 Compared with Torlon® PAI

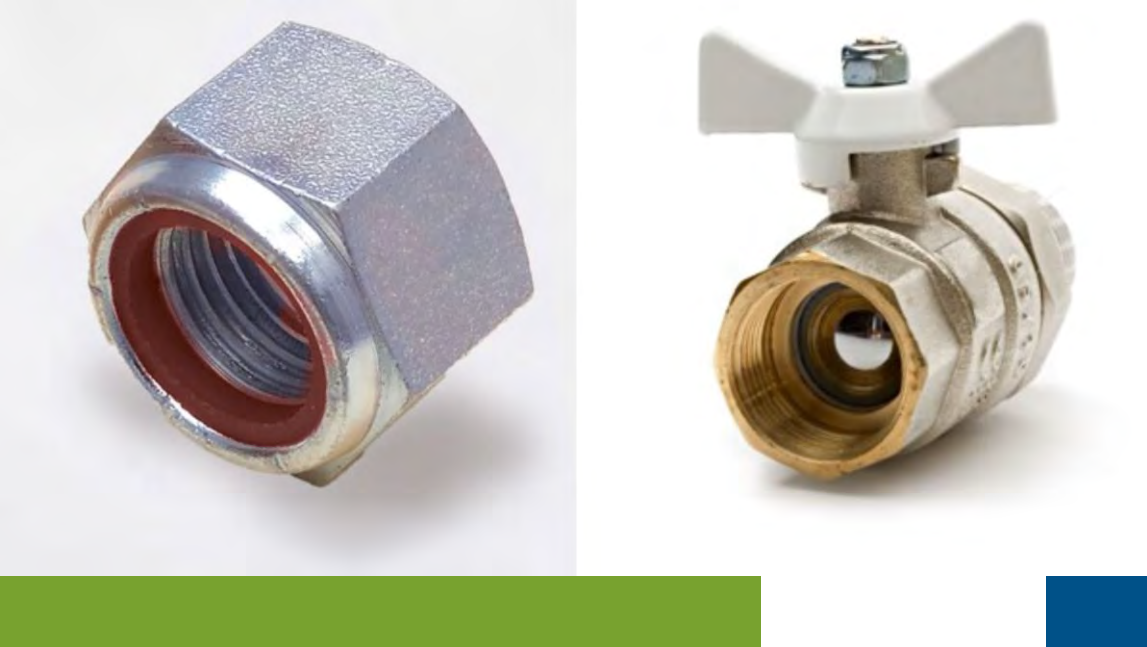


Source: Adapted from Paul Kane (2004). Provided courtesy of DuPont™.

The Power of Moderate Modulus, Dimensional Stability, Low Friction, and Resistance to Stress Relaxation



Modulus, Dimensional Stability, Friction, Stress Relaxation



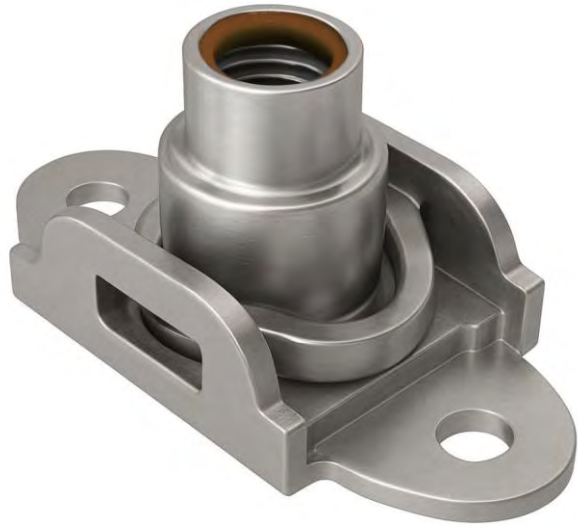
- Consider the following properties for the valve seat and the plastic locking element at cold, room temp, and elevated temperatures?
 - COF
 - Wear
 - CTE
 - Stress relaxation
 - Compressive modulus
 - Tensile elongation
 - Permeation
- What could the effect of fillers be on each property?

Modulus, Dimensional Stability, Friction, Stress Relaxation



- What could happen if the plastic parts were replaced with metal, ceramic, or very soft rubber?
- How could the presence of the following influence functionality?
 - Vacuum
 - Radiation
 - Moisture
 - Chemicals
- What if the valve controlled a critical flight system? An oxygen system for a spacecraft?
- What if the fastener held an engine system on an aircraft?

Modulus, Dimensional Stability, Friction, Stress Relaxation



NASA testing supported the use of reusable Vespel® SP-1 locking elements in threaded fasteners as an alternative to crimped nuts at temperatures up to 450°F.

Artist's representation of a threaded nut containing a DuPont™ Vespel® SP-1 polyimide locking element, similar to the NASA-tested design.

Source: Adapted from Carl Wood (1984) - NASA

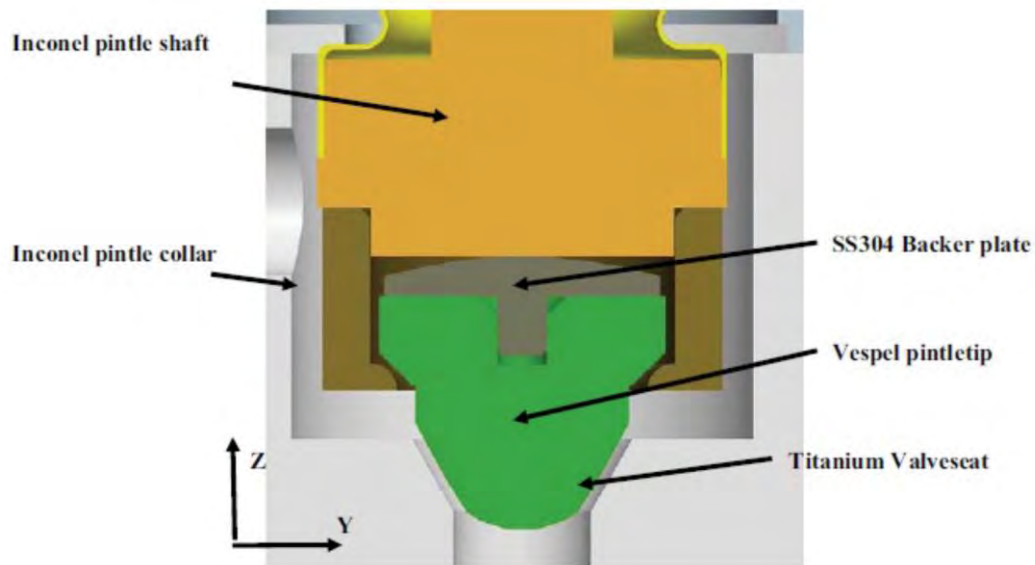
Consistent, Moderate Modulus / Low Outgassing

Optomechanical Design of Nine Cameras for the Earth Observing Systems
Multi-Angle Imaging Spectral Radiometer, TERRA Platform



Source: Adapted from Virginia Ford (1999) - JPL

Consistent, Moderate Modulus / High Temperature



DuPont™ VespeI® SP-22 Pintle Tip for a Miniaturized Solenoid Valve in the Sample Analysis at Mars Instrument Suite

- VespeI® SP-22 pintle tip self-seats when pressed into the conical valve seat
- The design uses DuPont™ VespeI® SP-22 for its inertness and high-temperature capability

Artist's representation pintle tips.

Source: Adapted from James Smith (2008) - NASA



Consistent, Moderate, Low Outgassing, Low Contamination



Source: Adapted from David Gibbon (2000)
Surrey Space Center

Propulsion System for the SNAP-1 Nanosatellite

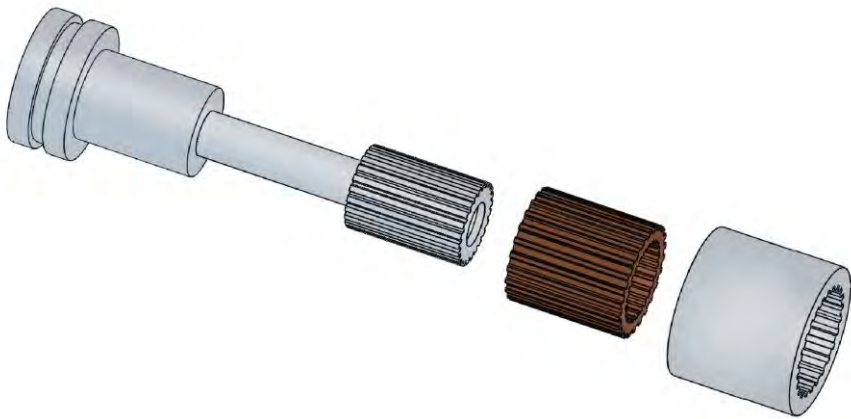
- SNAP-1 used a fill valve with a spring-loaded DuPont™ Vespel® seal
- Compatible with space requirements for cleanliness and leakage



SNAP-1 in flight configuration

Spline Couplings for Military Aircraft

- Spline misalignment and surface slip are unavoidable
- A DuPont™ Vespel® polyimide adapter reduces contact pressure between the metal components



Source: Adapted from Aleck Loker (1976) (1978) (1979)
Naval Air Test Center

Spline Couplings for Military Aircraft



- The adapter deforms to prevent tooth jamming and distribute loads more evenly
- Reduced fretting keeps wear negligible, even near the adapter's torsional limit

Source: Adapted from Aleck Loker (1976) (1978) (1979)
Naval Air Test Center

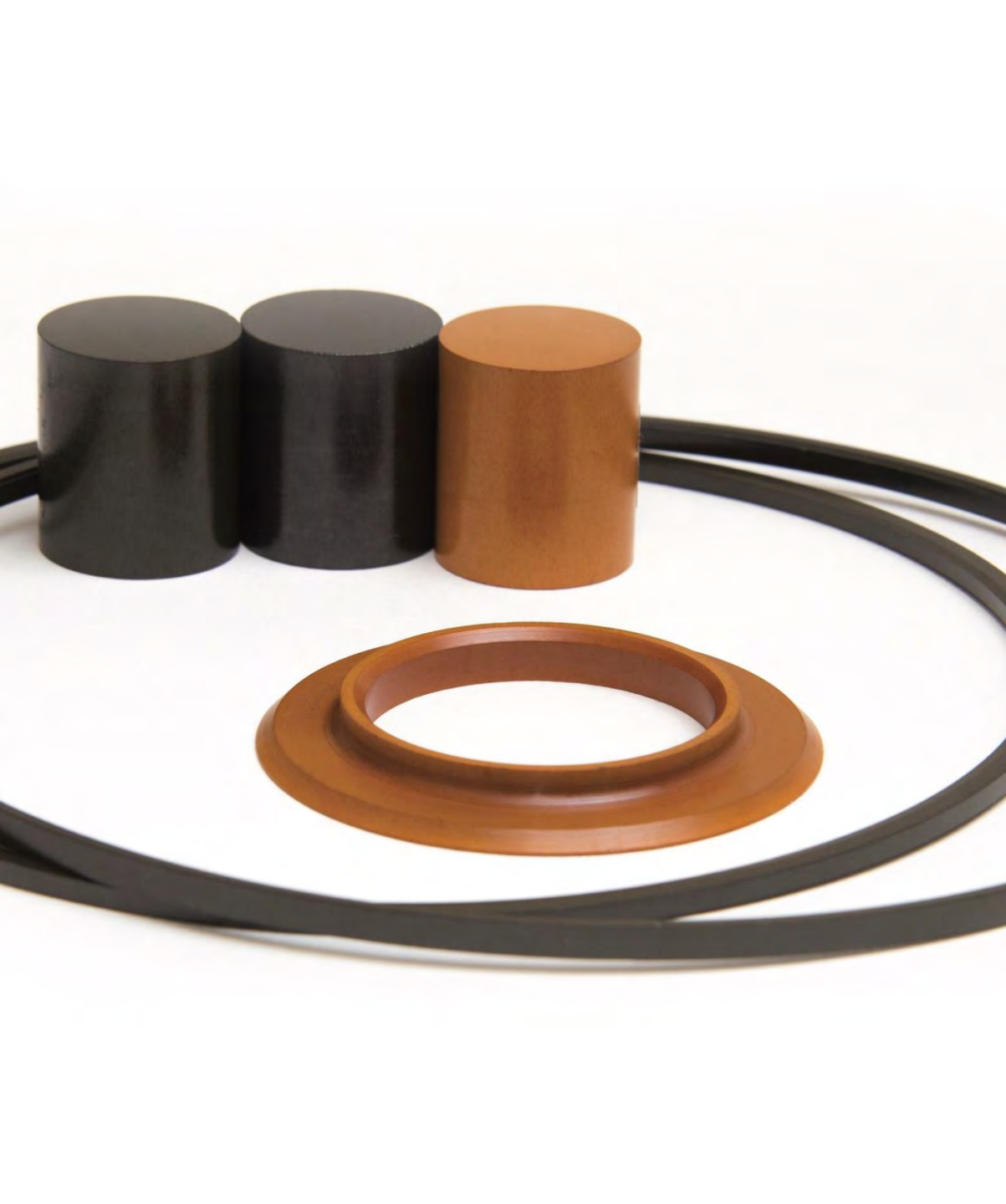
Vespel® SP-1 Spline Couplings for Military Systems



In military aircraft and ground vehicle applications, Vespel® SP-1 spline couplings can provide several operational and maintenance advantages:

- Reduce noise and vibration
- Reduce recurring maintenance costs
- Reduces axial forces on spline support bearings
- Does not require lubrication

Source: Harold Brown (1979)
Journal of Engineering for Industry



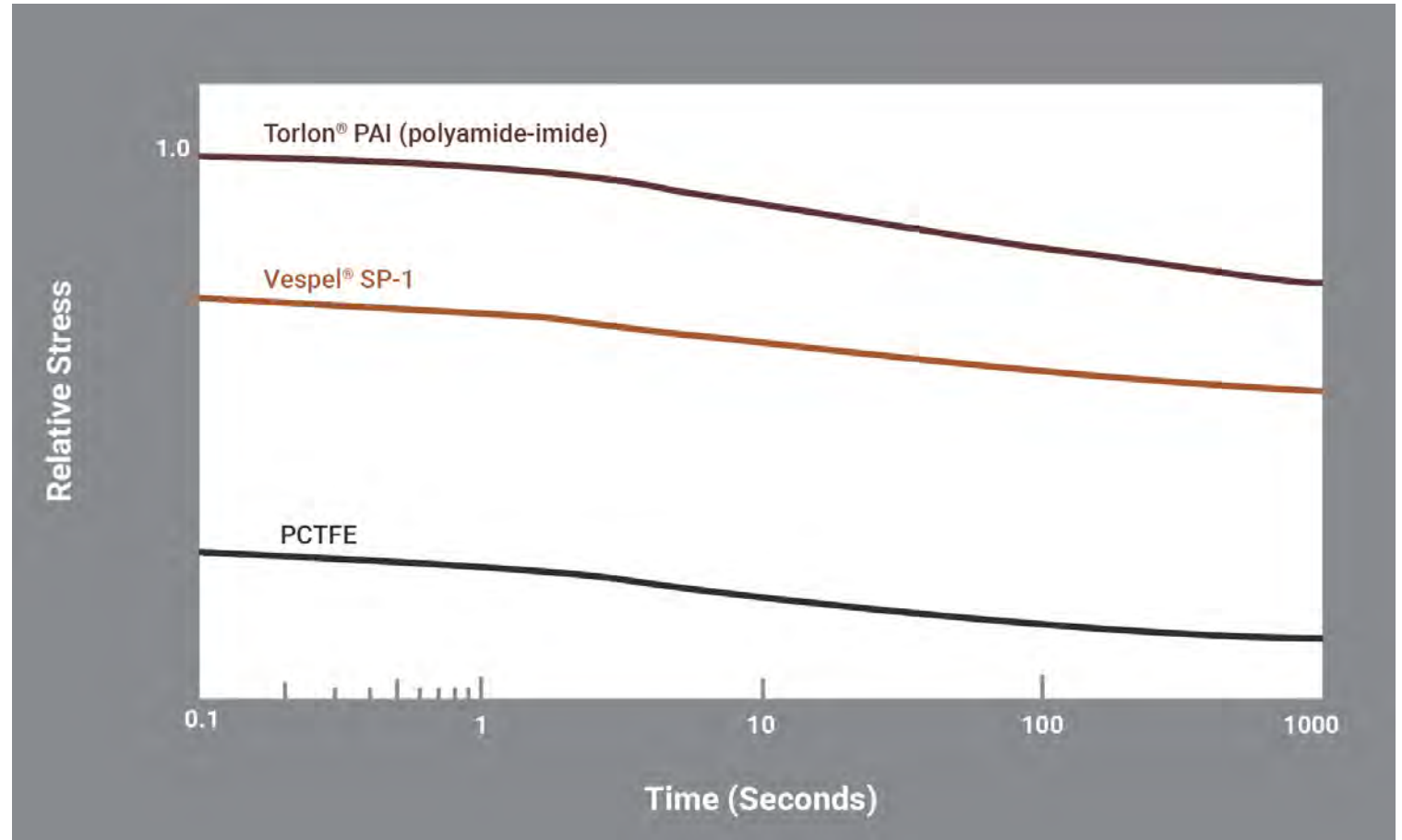
Outstanding Stress Relaxation and Creep Characteristics

Stress Relaxation Characteristics



Stress Relaxation Characteristics

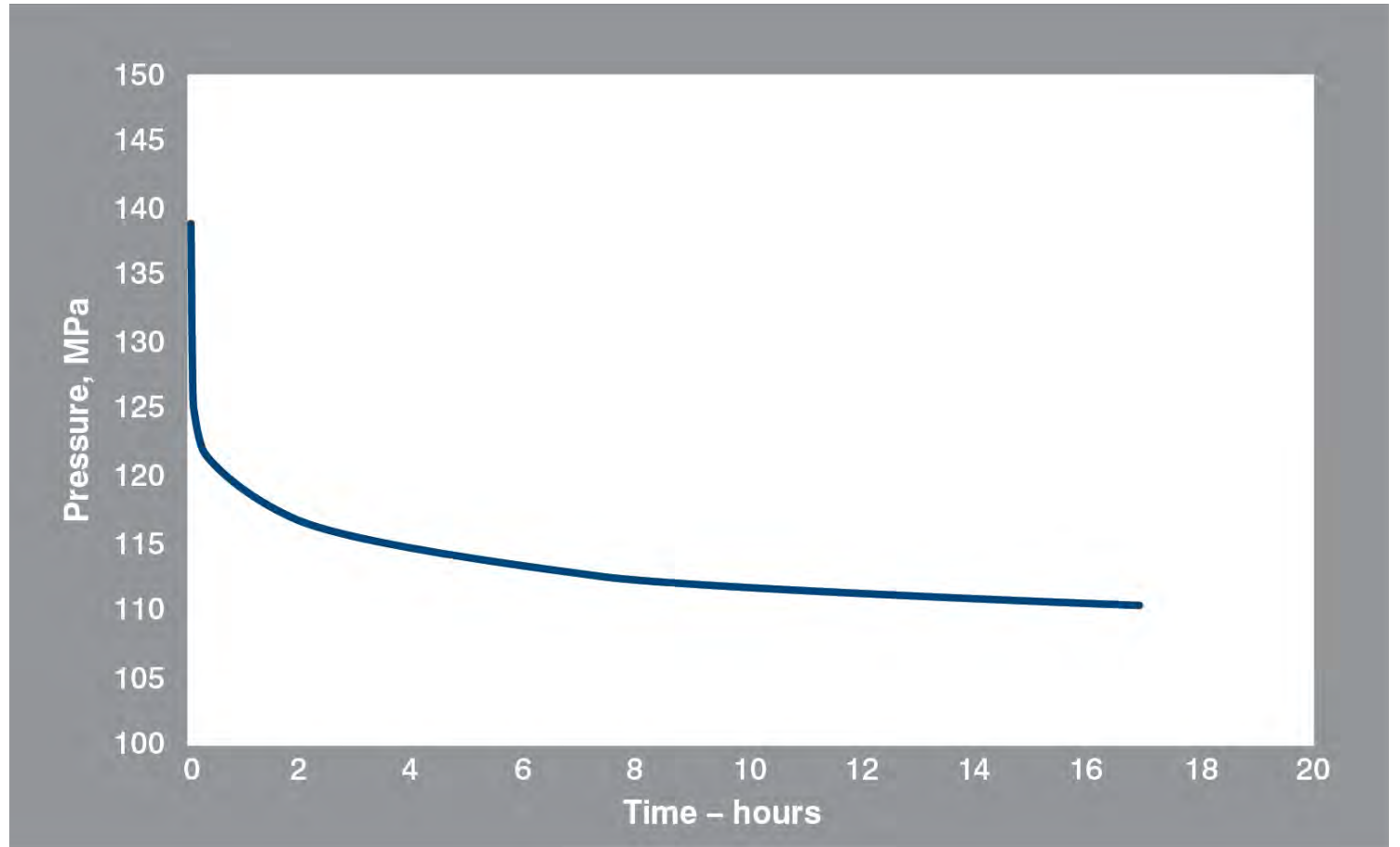
Stress Relaxation of Vespel® SP-1, Torlon® PAI, and PCTFE in Compression at 10% Engineering Strain at 299 K



Source: Adapted from Kenneth Wylie (1981)
Los Alamos National Lab

Stress Relaxation Characteristics

Stress Relaxation of DuPont™ Vespel® SP-1 at 68° F Pressure vs. Time at 15% Constant Compression

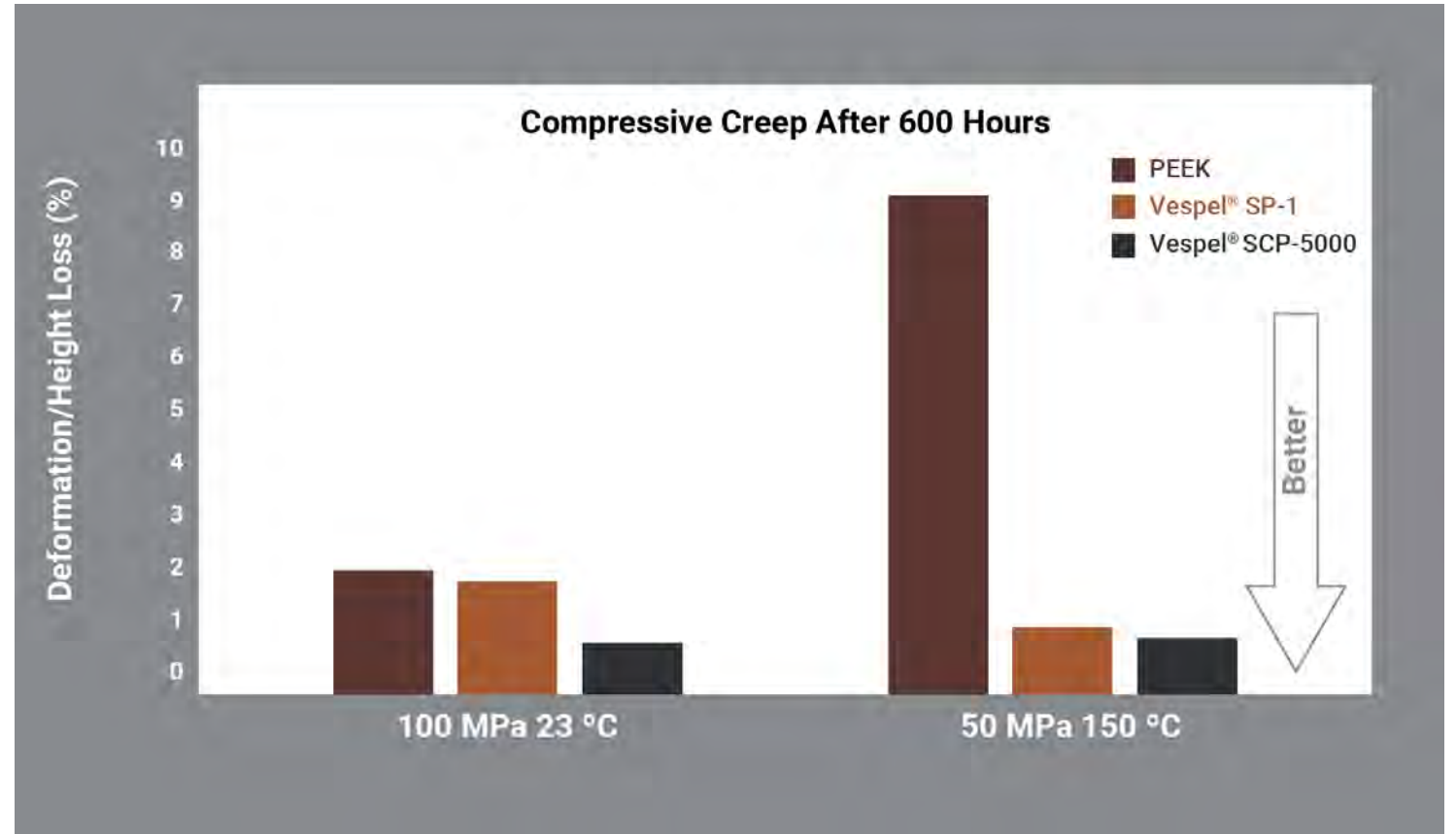


Source: Paul McDonald (1987)
Institute of Cryogenics, University of Southampton

Creep Characteristics



Creep Strain of Vespe[®] SP-1, Vespe[®] SCP-5000, and PEEK



Source: Chickola, J., Jackowiak, R., & Liekens, P. (2024). Provided courtesy of DuPont™.



Outstanding High
Temperature
Performance
(modulus, thermal
stability, creep)

High Temperature Performance (modulus, thermal stability, creep)



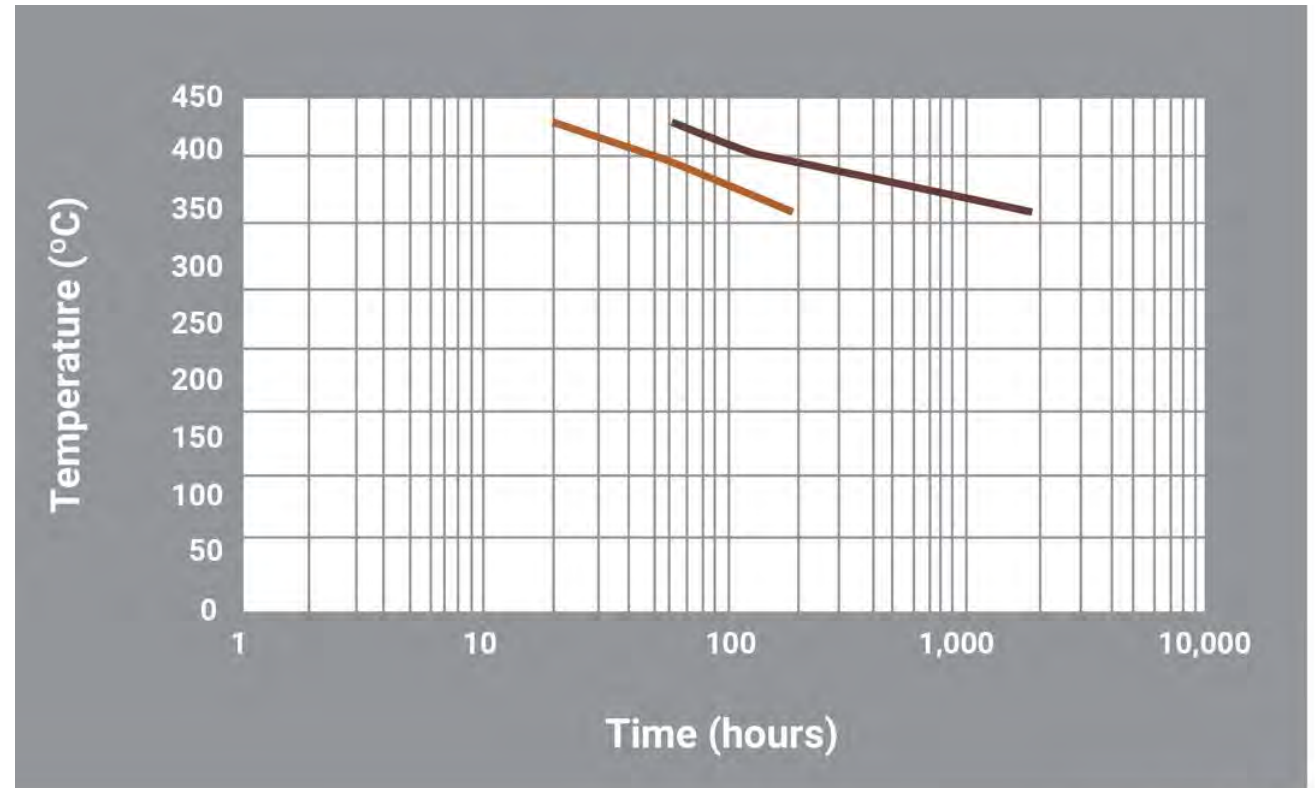
BEFORE

AFTER

Compressive Load, 700°

High Temperature Performance (modulus, thermal stability, creep)

Vespel® SCP-5000 and Vespel® SP-1 – Time to 50% Reduction in Initial Tensile Strength at Various Temperatures

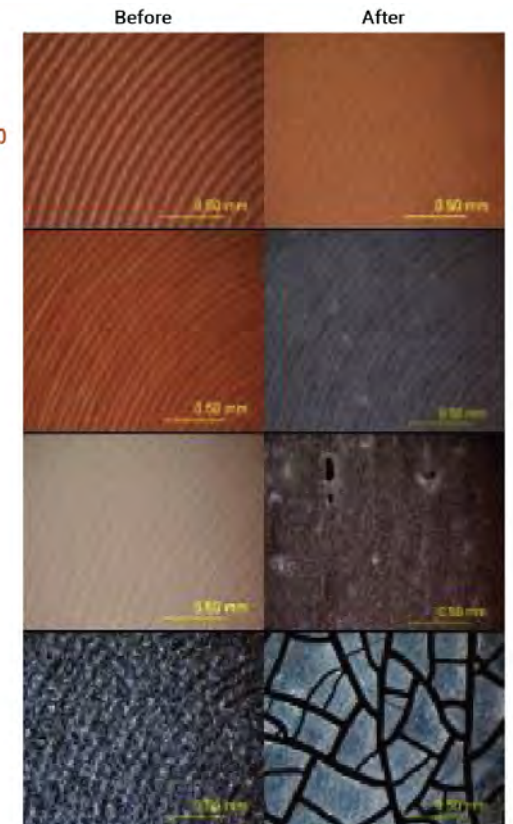
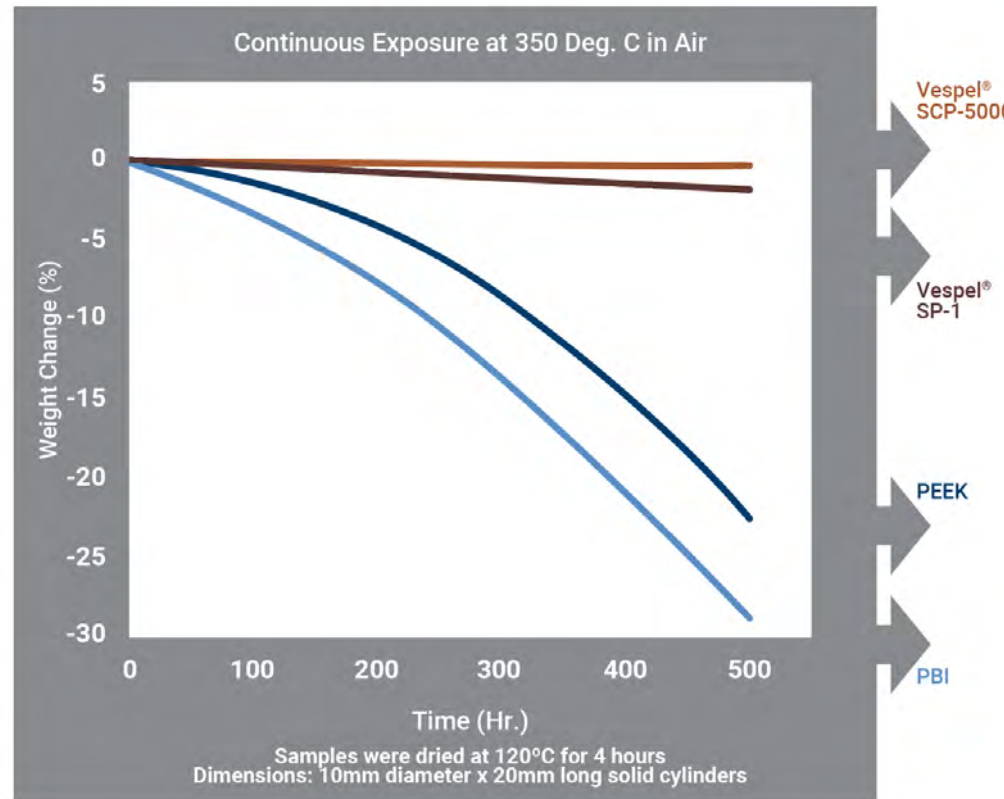


Source: E.I. du Pont de Nemours and Company.
Provided courtesy of DuPont™.

— SCP-5000
— SP-1

High Temperature Performance (modulus, thermal stability, creep)

Resistance to Degradation at Elevated Temperatures for Vespel® SP-1, Vespel® SCP-5000, PEEK, and PBI



Source: Hechtel & Loudin (2013). Provided courtesy of DuPont™.

High Temperature Performance

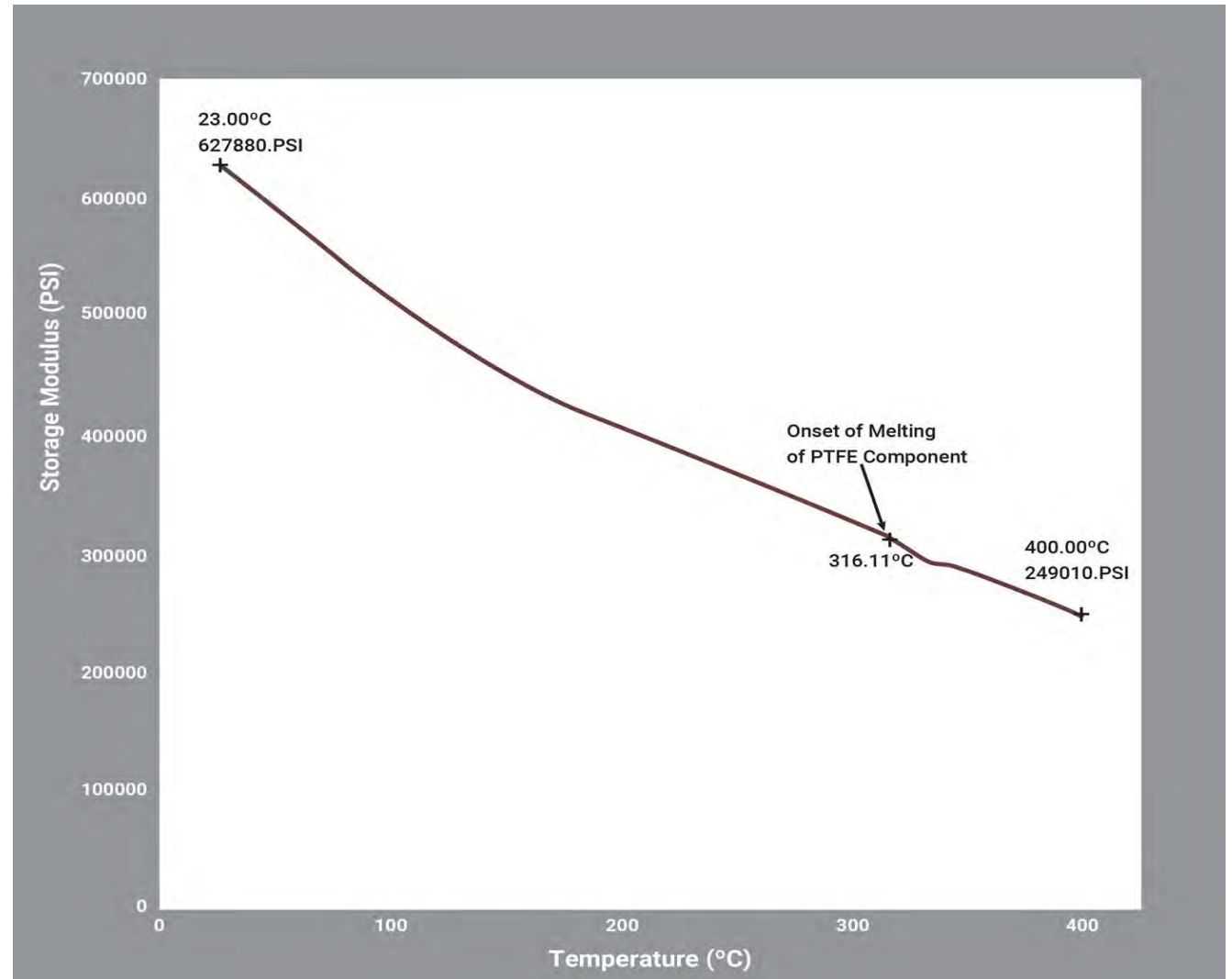


Source: Doug Wingard (2013) - NASA

- DuPont™ Vespel® SP-211 polyimide was selected as the top candidate seal material for use in the Oxidizer Turbine Bypass Valve (OTBV) on NASA's Ares I Upper Stage J-2X engine
- The seal material would get exposed to temperatures up to 750°F for ~10 minutes at a time
- Dynamic mechanical analysis (DMA) was one of several test techniques used to characterize Vespel® SP-211 to help prove its worthiness for use on the OTBV of the J-2X engine

High Temperature Performance

Dynamic Mechanical Analysis of Vespel® SP-211



Source: Adapted from Doug Wingard (2013) - NASA

High Temperature Performance



- Radome for gun-launched military projectile
- Transparency to RF
- Frictional heating from the atmosphere at hypersonic velocities (up to Mach 5)
- Vespel® selected as the leading candidate for the application

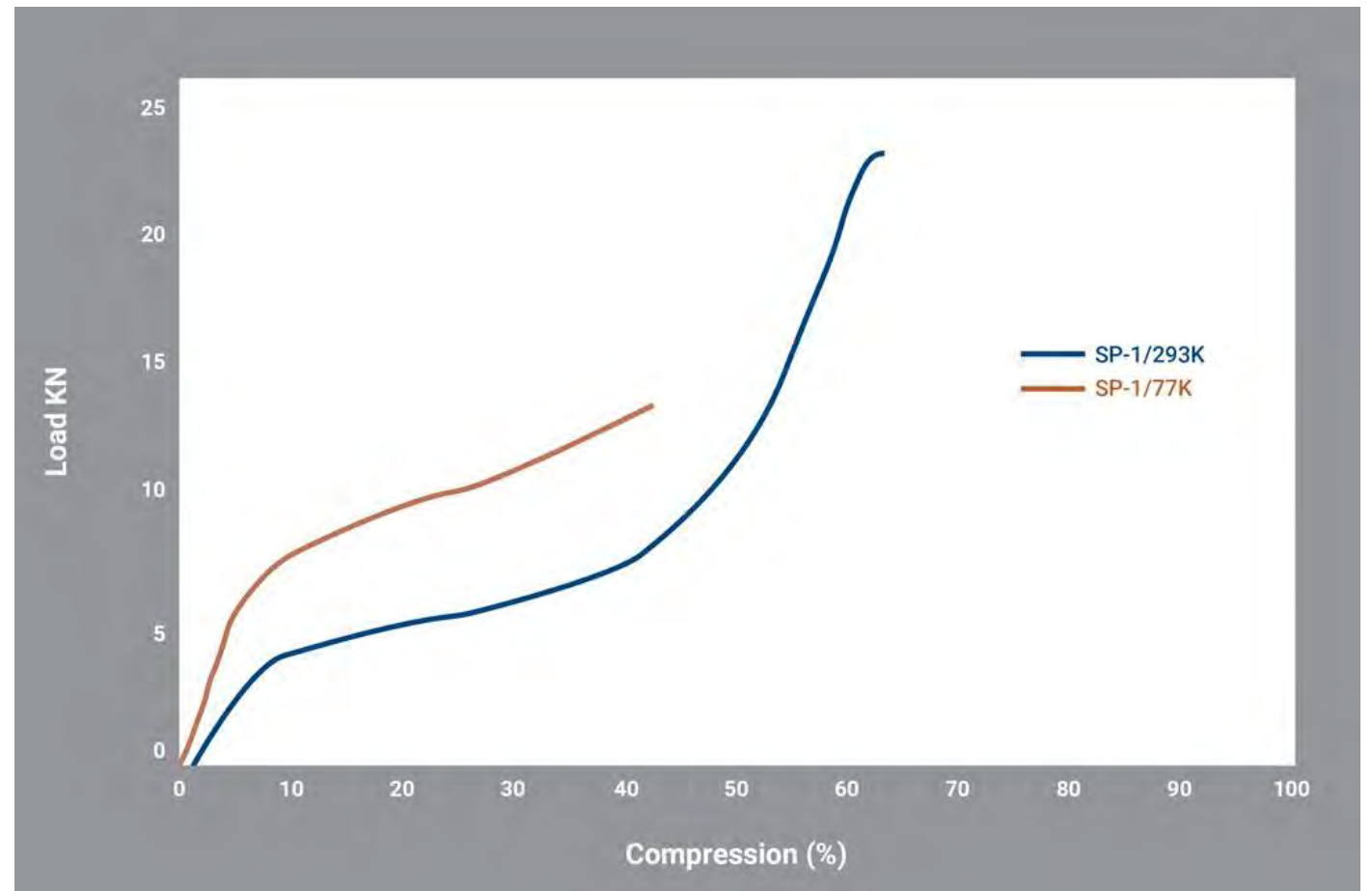
Source: Adapted from Michael Hollis (2001)
Army Research Lab



Low Temperature
Performance
(ductility, low thermal
conductivity)

Low Temperature Performance (ductility)

Ductile Compressive Strain of Vespel® SP-1 at 77 and 293 Kelvin



Source: Adapted from Paul McDonald (1987)
Institute of Cryogenics, University of Southampton

Low Temperature Performance (low thermal conductivity)



Low Temperature Performance (low thermal conductivity)

Thermal Conductivities of Various Plastics and Composites at Cryogenic Temperatures

	Material	Thermal Conductivity @ 0.3 K (mW/m K)	Thermal Conductivity @ 1.4 K (mW/m K)	Thermal Conductivity @ 4.2 K (mW/m K)
→	Vespel® SP-1 (unfilled)	0.553	3.21	9.74
→	Vespel® SP-22 (40% graphite)	0.217	2.46	14.3
	PEEK	1.00	5.31	12.0
	PEEK (30% carbon fiber filled)	0.823	4.66	10.6
	PEEK (30% glass filled)	0.812	6.20	19.6
	Pulltruded Glass/Epoxy Rod	1.08	17.8	73.2
	Torlon® 4301	1.06	11.8	28.5
	G-10/FR-4	1.64	20.6	65.6

Source: Adapted from Marc Runyan (2008) - Caltech

Low Temperature Performance (low thermal conductivity)



- Evaluating cryogenic supports for scientific instrumentation.
- Temperatures ≤ 5 Kelvin
- *"Vespel® SCP-5050 offers an attractive combination of ductility, stiffness, dimensional stability, and low cryogenic thermal conductivity, arguing for its use in low temperature structural support applications."*

Source: Miguel Daal (2019).
University of California, Santa Barbara

Low Temperature Performance (low thermal conductivity)

- Heat Switches for Adiabatic Demagnetization Refrigerators
- Operate at temperatures <20 Kelvin
- Vespel® SP-1 Support

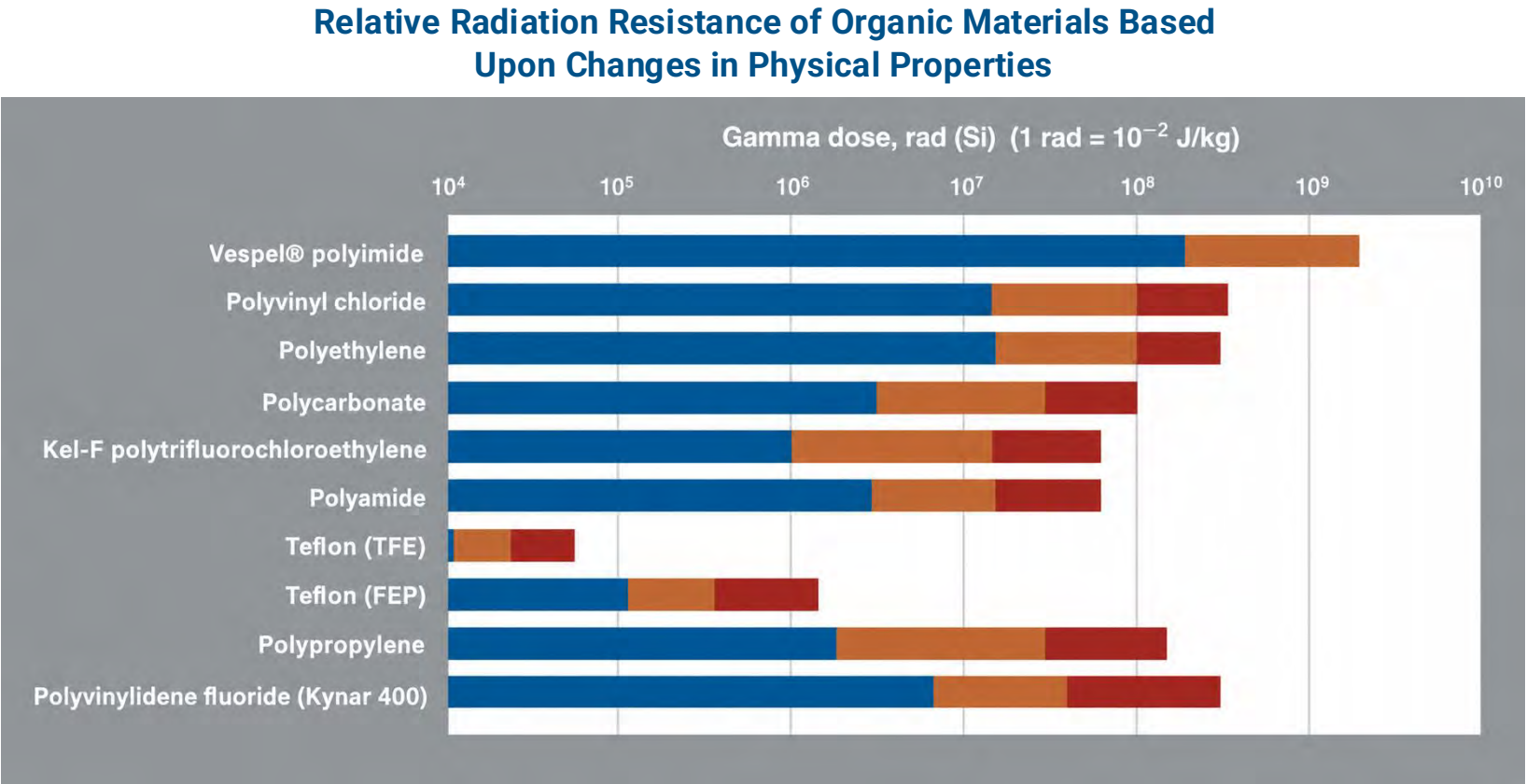


Source: Adapted from Michael DiPirro (2014)
NASA Goddard Space Flight Center



Radiation Resistance

Radiation Resistance



Source: Adapted from Herman Shulman (1970) – NASA Publication

Extent of damage		Utility of organic materials
	Incipient to mild	Nearly always usable
	Mild to moderate	Often satisfactory
	Moderate to severe	Limited use

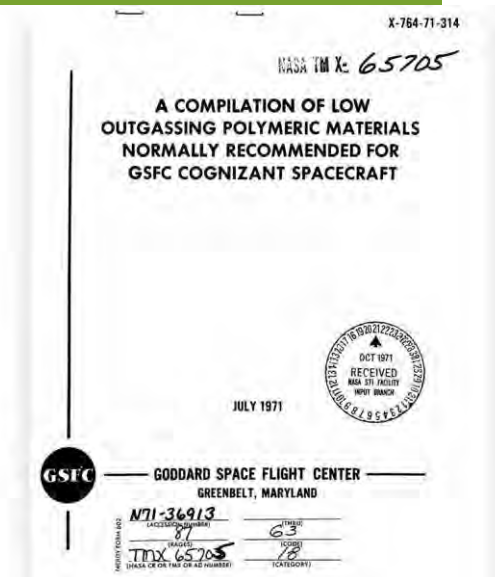


Vacuum Capability
(sealing, low
outgassing, and
friction and wear)

Low Outgassing

Vespel® has a submarginal total outgassing of 1.24%, this is primarily moisture.

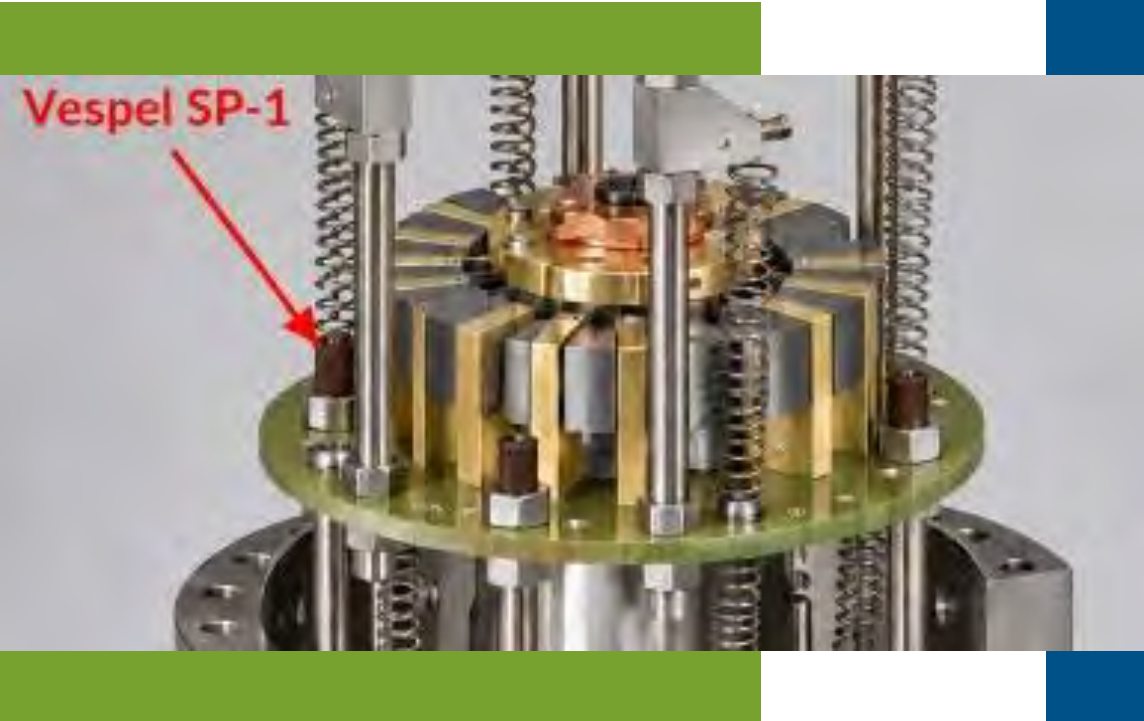
It may be considered for use where it's excellent combination of properties, low condensables, low friction coefficient, excellent ultraviolet, particulate radiation and high temperature resistance are essential to spacecraft function.



Source: Aaron Fisher (1971 - NASA)

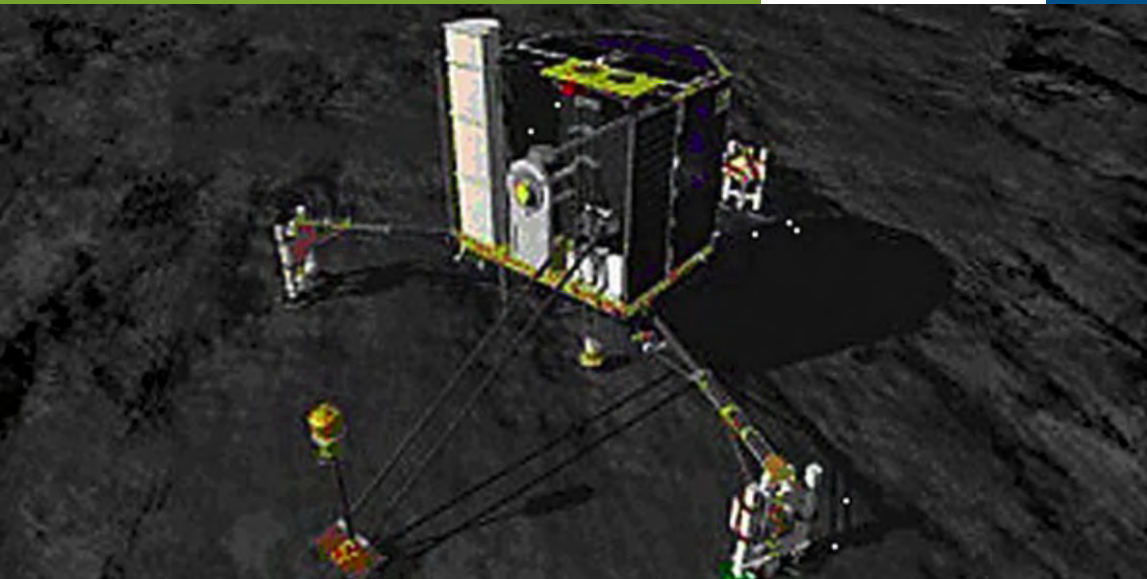
Thermal Conductivity, Vacuum Compatibility

- UHV Scanning Tunneling Microscope
- Operating Temperatures as Low as 80 K
- Ultrahigh vacuum
- Vespel® used as a thermal isolator



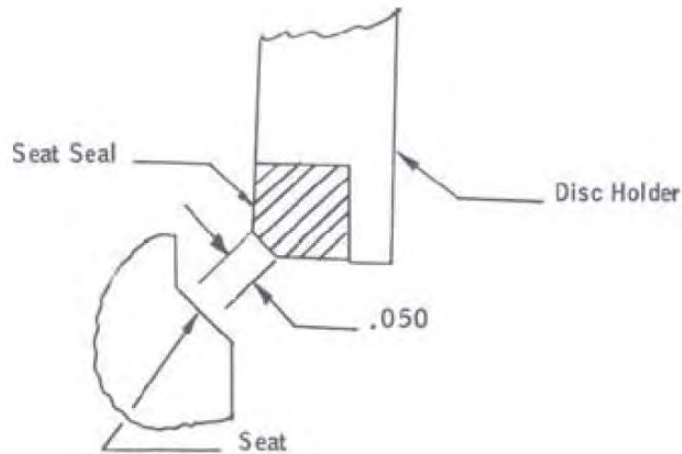
Source: Adapted from Bogdan Diaconescu (2007)
University of New Hampshire

Low Temperature, Friction and Wear in Vacuum



- Sampler, Drill and Distribution System for Rosetta Mission to Sample a Comet
- Severe environmental conditions including very low temperature and high vacuum
- Self lubricated bearings made of Vespel® SP-3 or PTFE

Sealing Performance



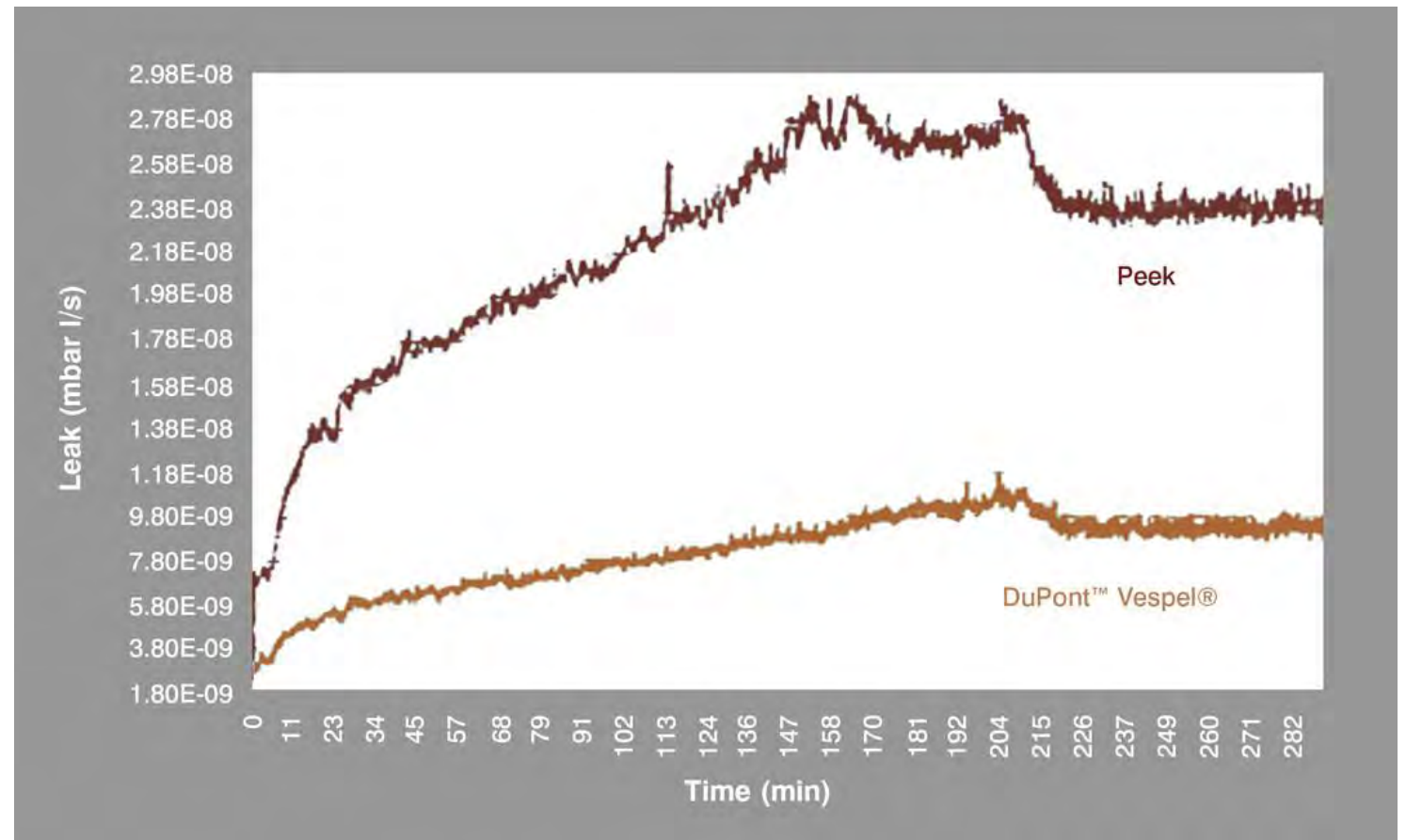
- Vespel® High Vacuum Valve Seal for Space Shuttle Propellant Lines
- Operating Temperature Range: -300 to 300°F
- Low Outgassing
- Low CTE
- Resistance to cold flow
- Sealing and resealing capability
- No leakage occurred during testing

Source: David Martindale (1978)

Vacuum Sealing Capability

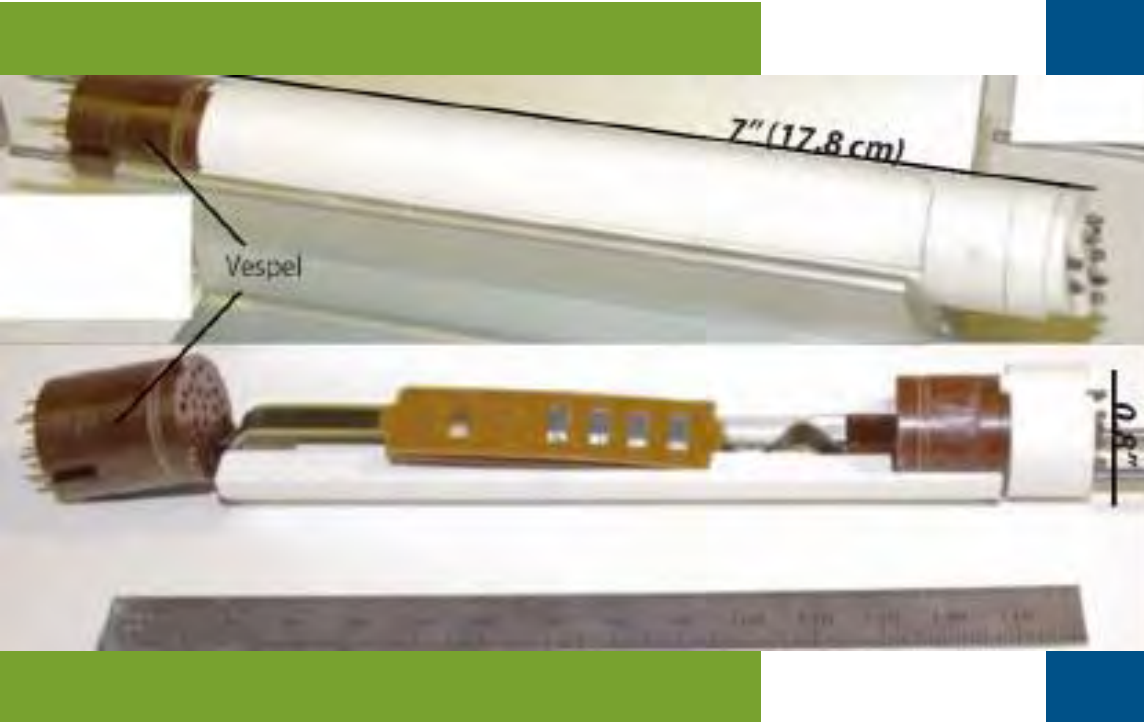


Comparison of the He Permeation at Room Temperature for Vespel® SP-1 and PEEK



Source: Adapted from Andrea Murari and Andrea Barzon (2004)

Vacuum Sealing, Machinability, and Elevated Temperatures



- Probe Head Assembly for Fast Scanning Probe for the NSTX Spherical Tokamak
 - Vespel® is an easy-to-machine material, lightweight and strong, resists high temperature and has a very low outgassing rate

Source: Adapted from Jose Boedo (2009)
University of California, San Diego



Friction and Wear Characteristics

Friction and Wear Performance in Vacuum (Vespel® SP-3)



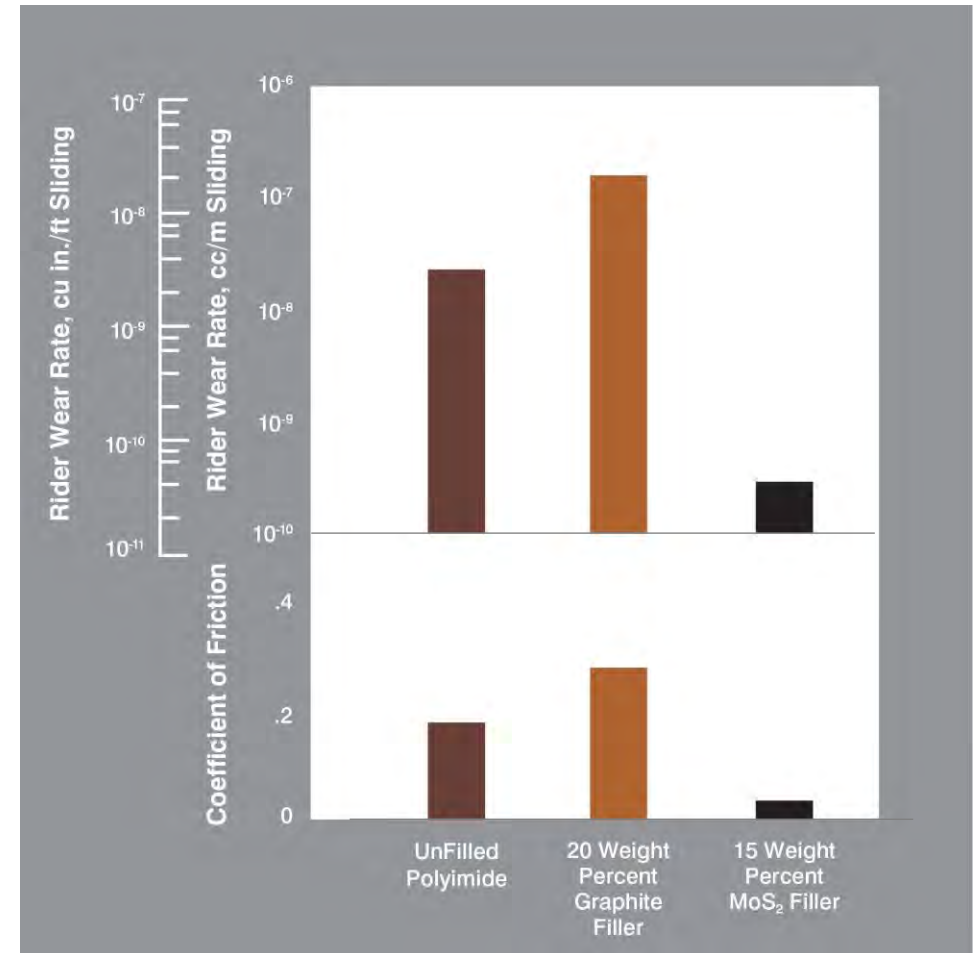
Source: Alain Poncet (1980) - CERN

- Tests of Bearing Materials in UHV
- The best polyimide material tested both in air and vacuum appeared to be Vespel® SP31 (old name for Vespel® SP-3) polyimide MoS₂ mixture

Photo: [“Overview of the Antiproton Accumulator \(AA\) at CERN”](#) by CERN, licensed under [CC BY 4.0](#). Cropped from the original.

Friction and Wear Performance in Vacuum (Vespel® SP-3)

Friction Coefficient and Rider Wear for Solid-Lubricant-Filled Polyimide Compositions Sliding on 440-C Stainless Steel in Vacuum



Source: Buckley (1966)

Friction and Wear Performance in Vacuum (Vespel® SP-3)

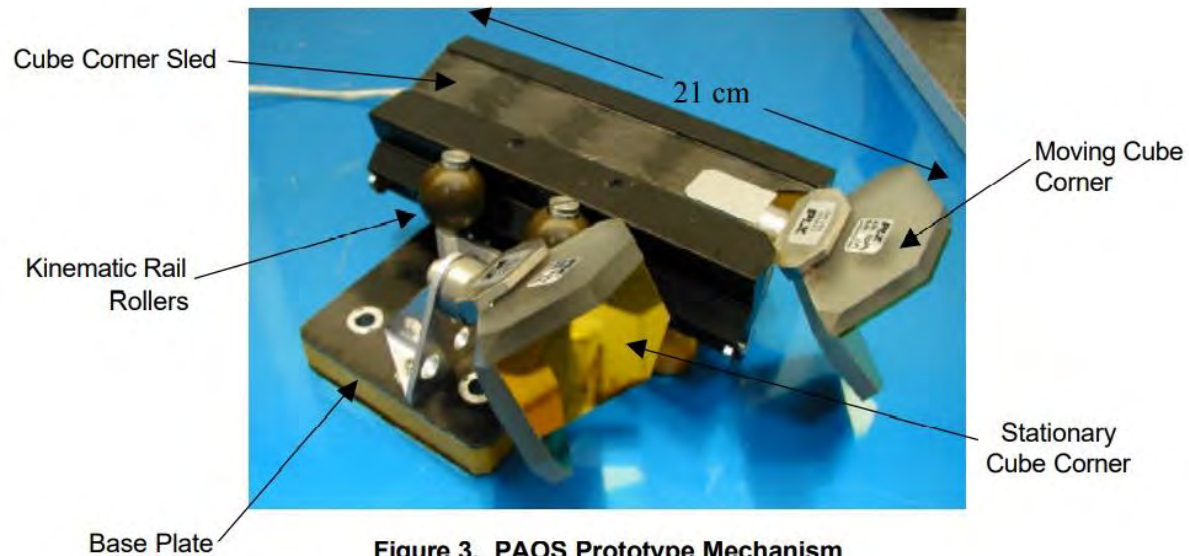


Figure 3. PAOS Prototype Mechanism

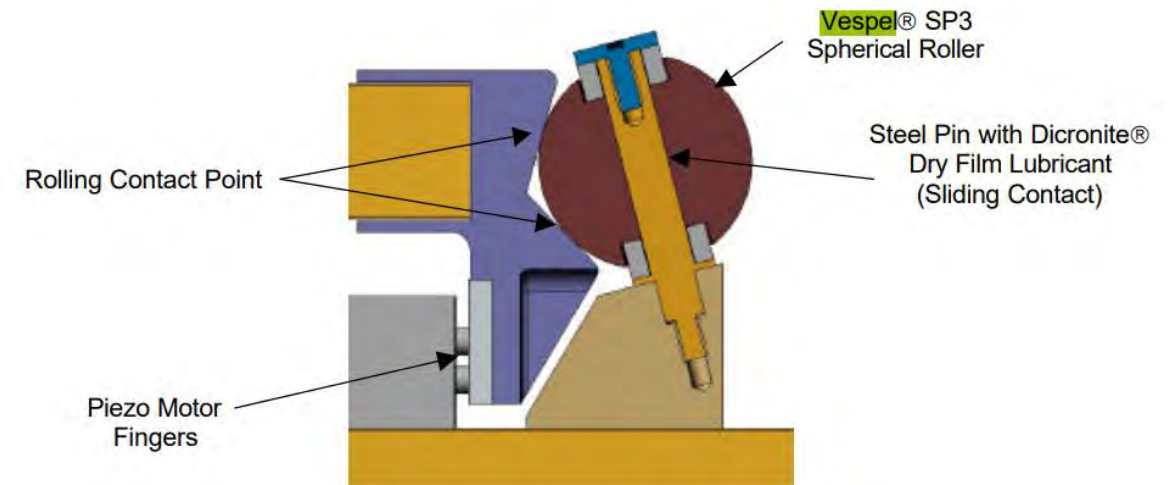
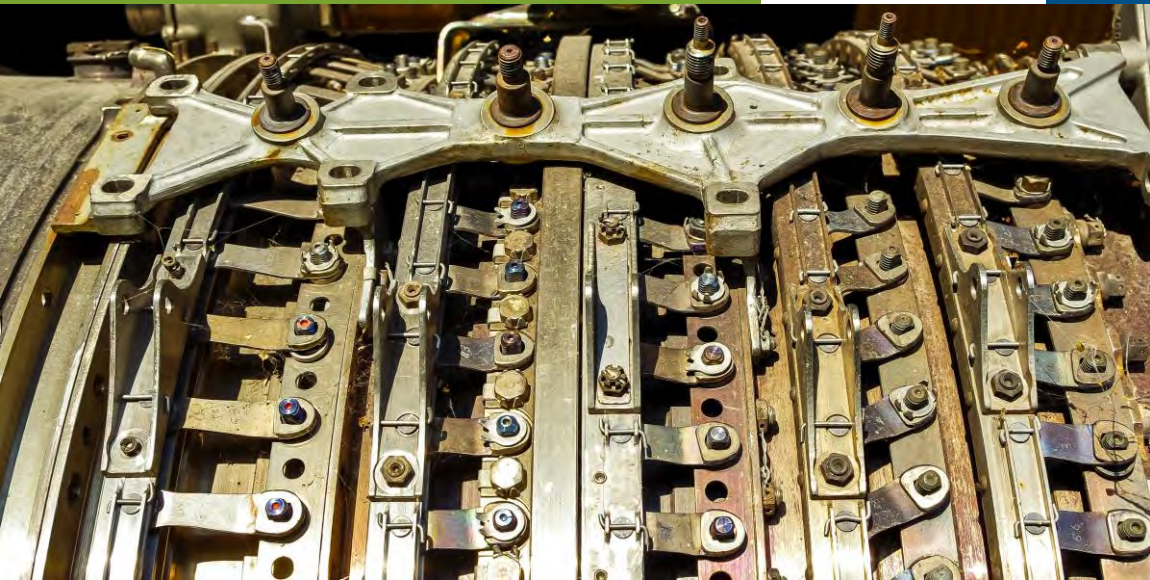


Figure 12. Spherical Roller Cross Section

Source: Matthew Heverly (2004)

“The kinematic Vespel® rail system provides a solution that is fault tolerant and insensitive to structural misalignments due to thermal distortion or manufacturing tolerances.”

Friction and Wear Properties (high PV, vacuum, etc.)



Friction and Wear

- A system property - not a material property
- Counterface chemistry, roughness, and hardness
- Loads and speeds
- Mechanism of wear (sliding, abrasion, rolling contact, etc.)

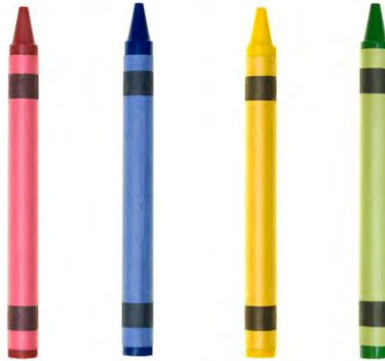
Additives

- PTFE
- Graphite
- MoS₂
- Proprietary Additives

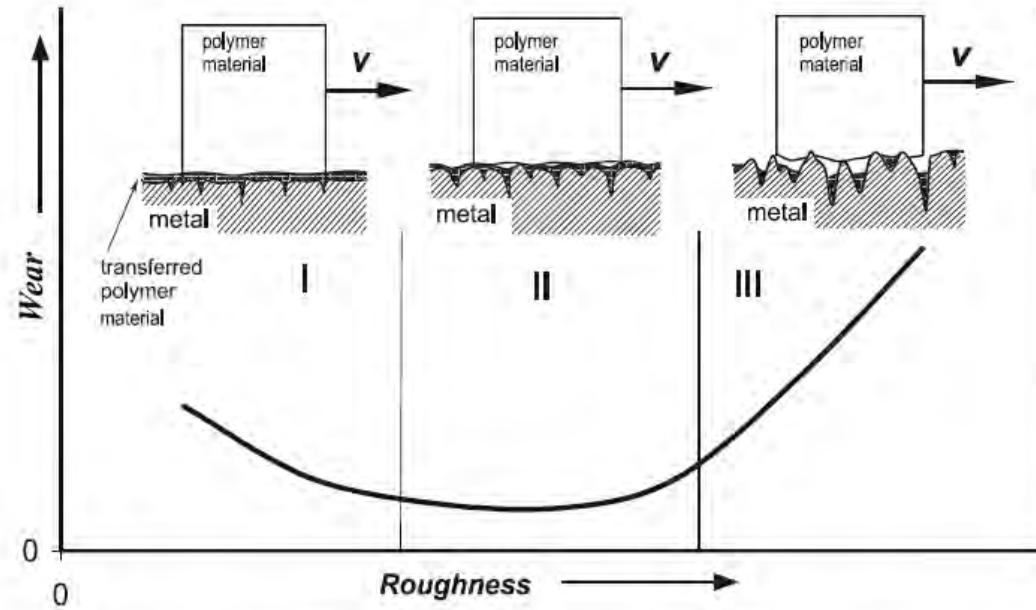
Friction and Wear Properties (high PV, vacuum, etc.)



PTFE

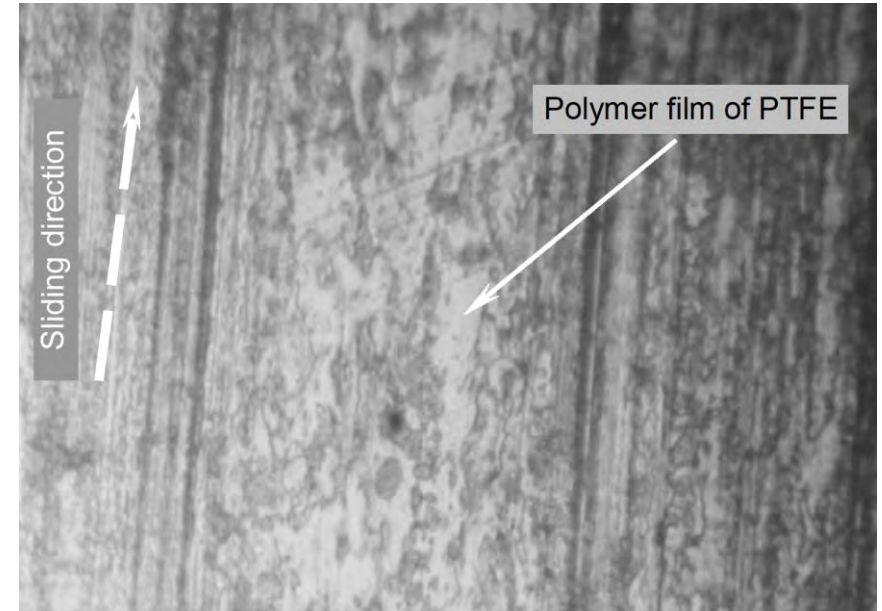


Friction and Wear Properties (high PV, vacuum, etc.)



Wear Rate vs. Surface Roughness

Formation of the Polymer Layer on the Surfaces with Different Roughness



Polymer Film (PTFE) on the Surface of Steel After the Friction Process

Friction and Wear Properties (high PV, vacuum, etc.)

Maximum Unlubricated PV Limits for Various Grades of Vespel® and Several Other Engineering Plastics Under Conditions of Continuous Motion

Material	Filler	lb-ft	Maximum Contact Temperature °F
		in ² -min	
Vespel® SP-21	15% Graphite	300,000	740
Vespel® SP-211	15% Graphite, 10% PTFE	100,000	500
Nylon	Unfilled	4,000	300
Acetal	Unfilled	3,500	-

*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.

Source: DuPont™ . Provided courtesy of DuPont™ . DuPont™ and Vespel® are trademarks of affiliates of DuPont de Nemours, Inc.

Friction and Wear Properties / Moderate Modulus



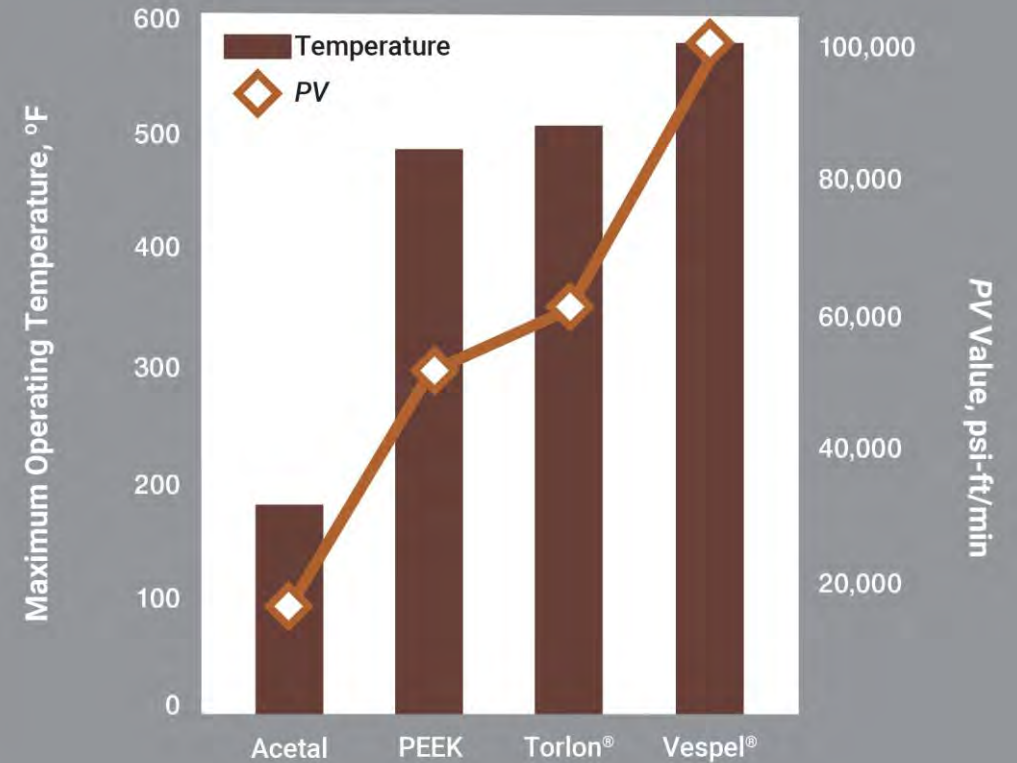
- Valve with operating temperature of -195 °C
- Moderate modulus and low COF
- Changing seal from PCTFE to Vespel® SP-21 reduced actuation torque by 28%

Source: Geoff Lewis (2015)

Friction and Wear Properties (high PV)



High PV Limit of Vespel®



Source: Adapted from Jeff Anderson (2005)

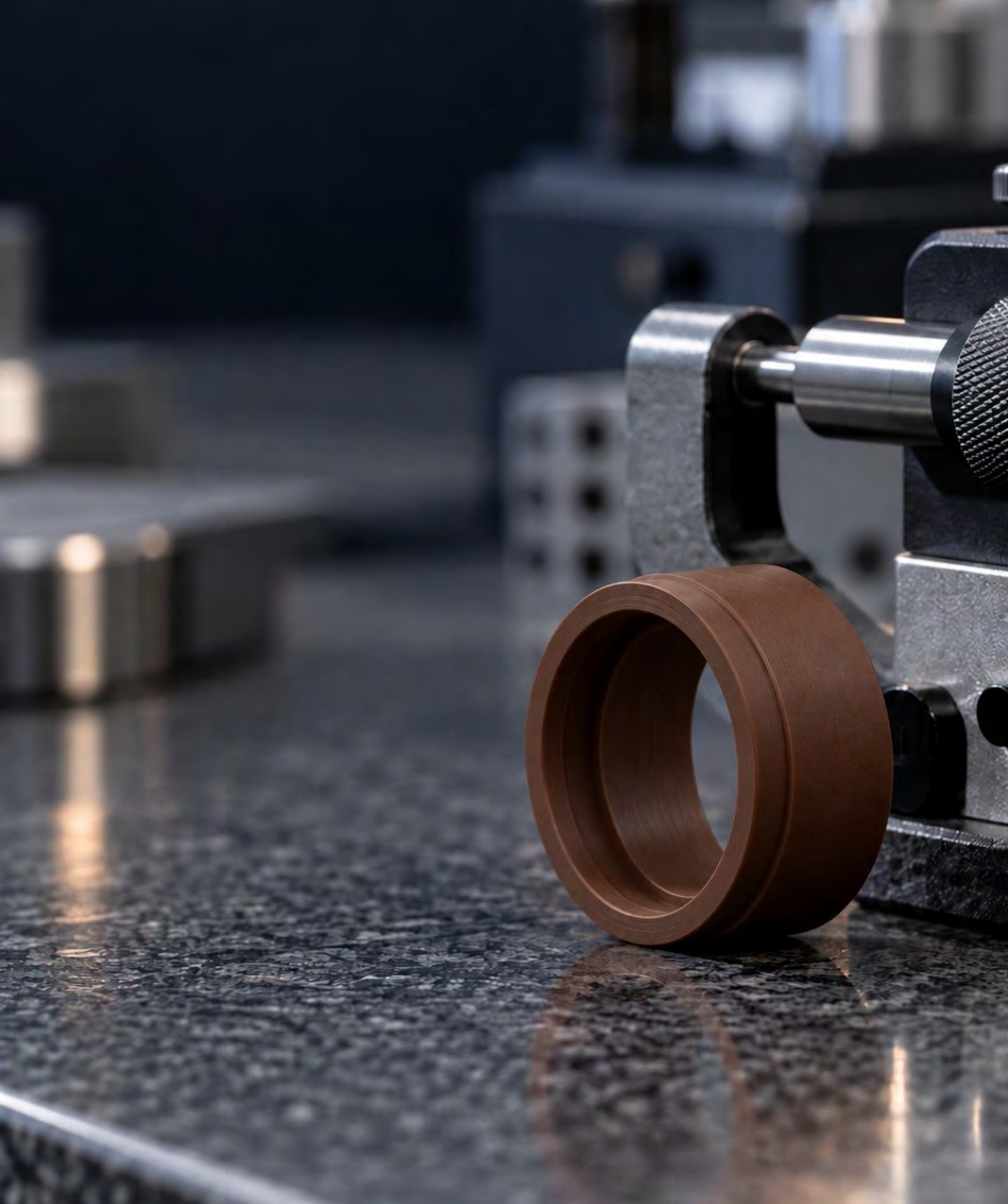
Friction and Wear Properties (high PV, Vacuum, etc.)



- Durability Tests of Solenoid Valves for Digital Actuators
- NASA Technical Memorandum 81522
- *“The graphite composite poppet in combination with a Vespel® seat was considered the most promising combination for use in digital electronic controls for gas turbine engines.”*

Adapted from Figure 8. – Vespel® Poppets

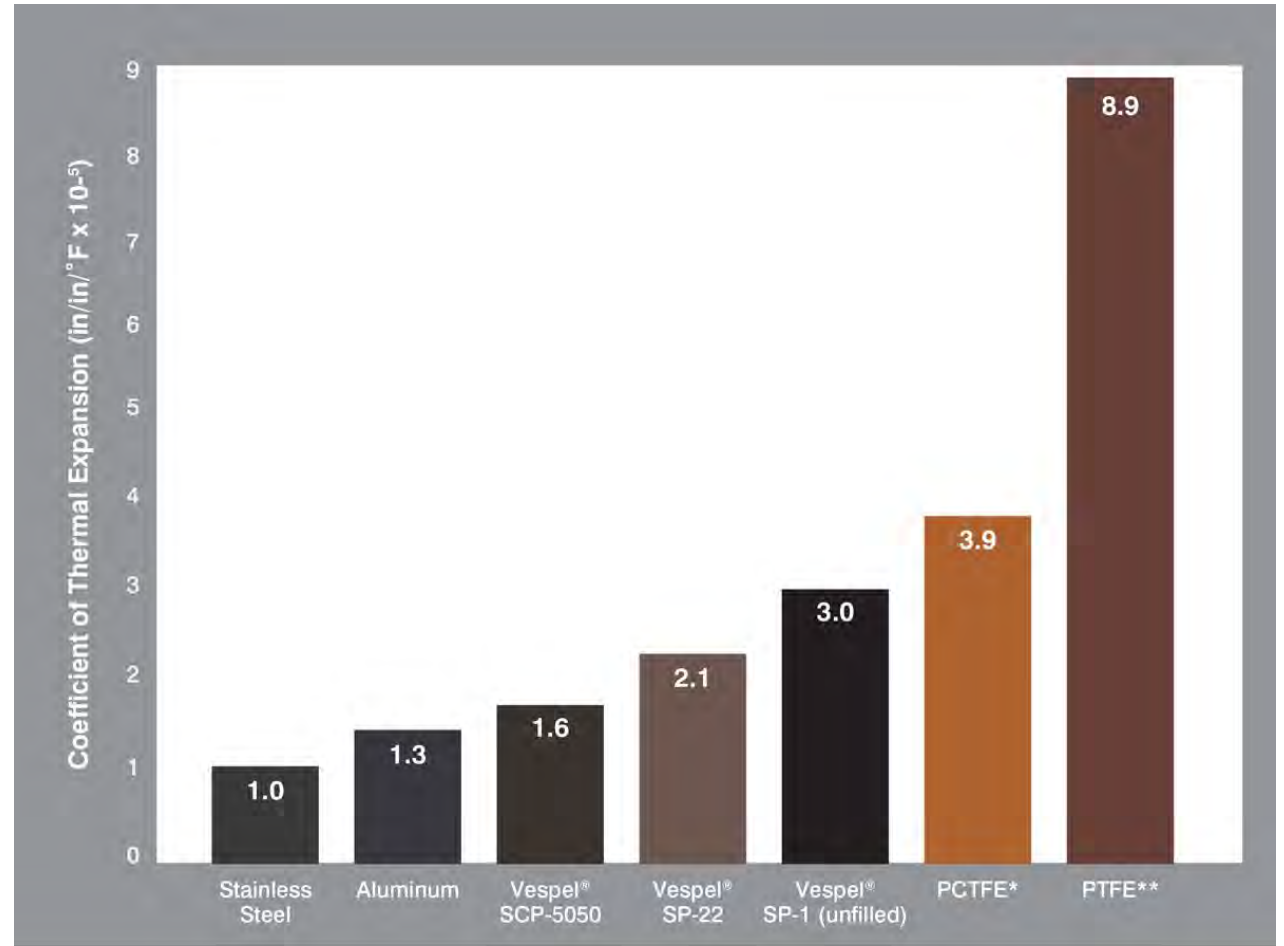
Source: Adapted from Anastacio Baez (1980)
NASA



Low and Consistent
CTE

Consistent CTE

Coefficient of Thermal Expansion (CTE) of Various Materials

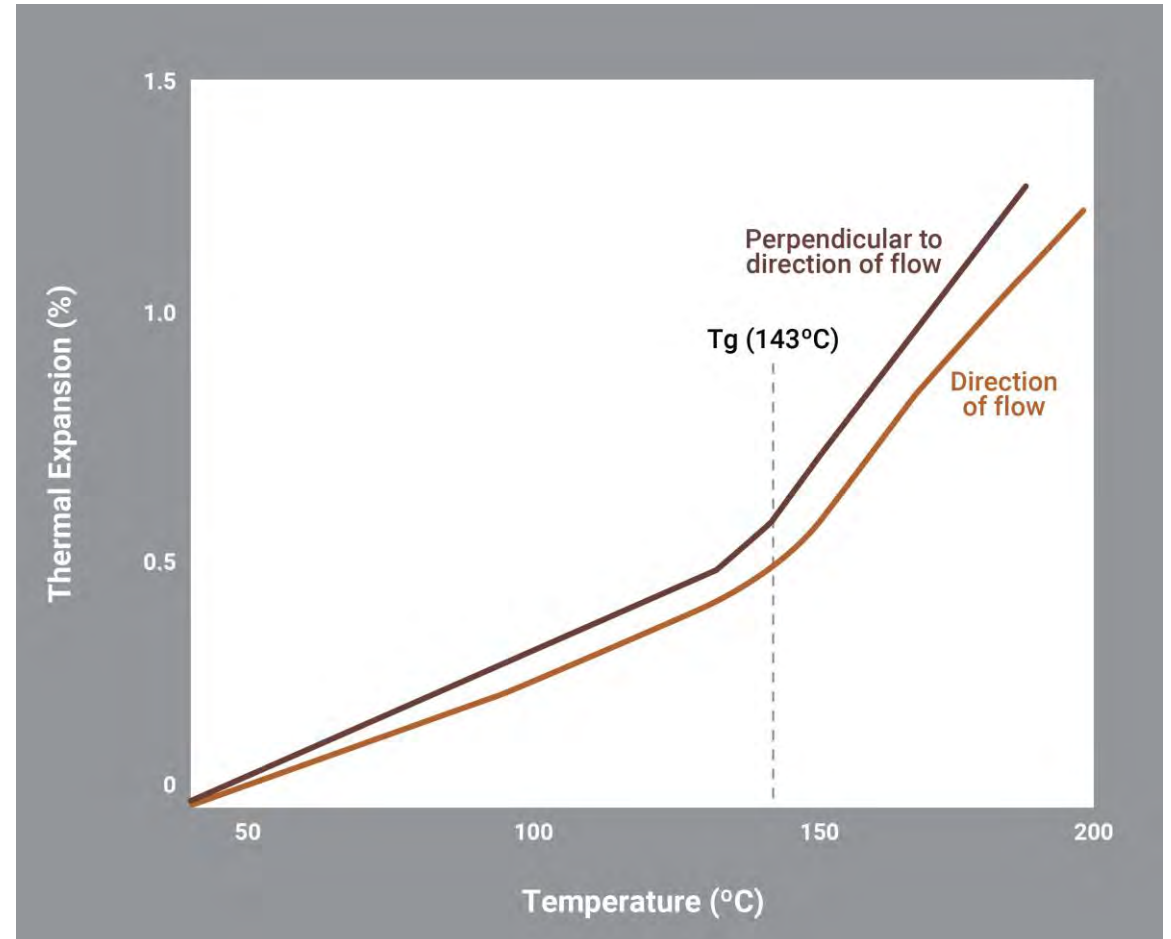


Source: DuPont™, Properties of DuPont™ Vespel®

* Polychlorotrifluoroethylene
** Polytetrafluoroethylene

Consistent CTE

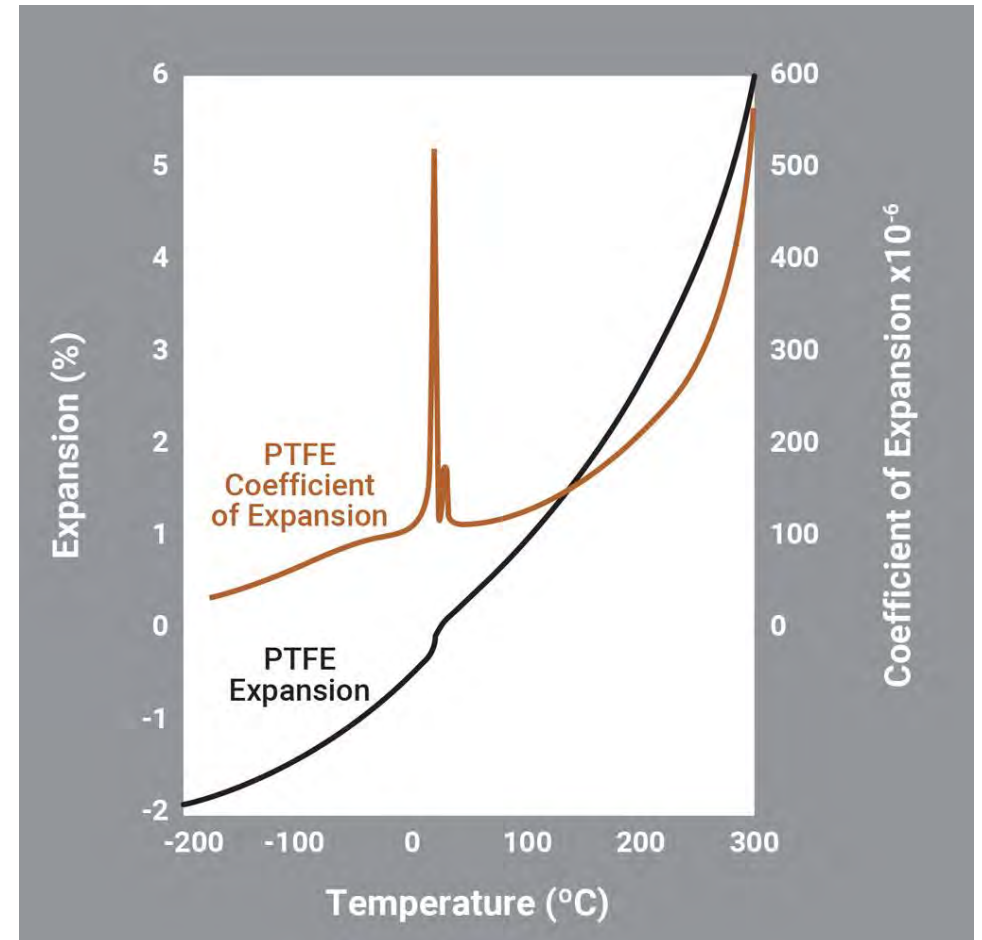
Thermal Expansion Curves for PEEK in the Direction of Flow and Perpendicular to the Direction of Flow, Both Above and Below the Material's Glass Transition Temperature



Source: Adapted from Zhiyuan Jiang (2021)

Consistent CTE

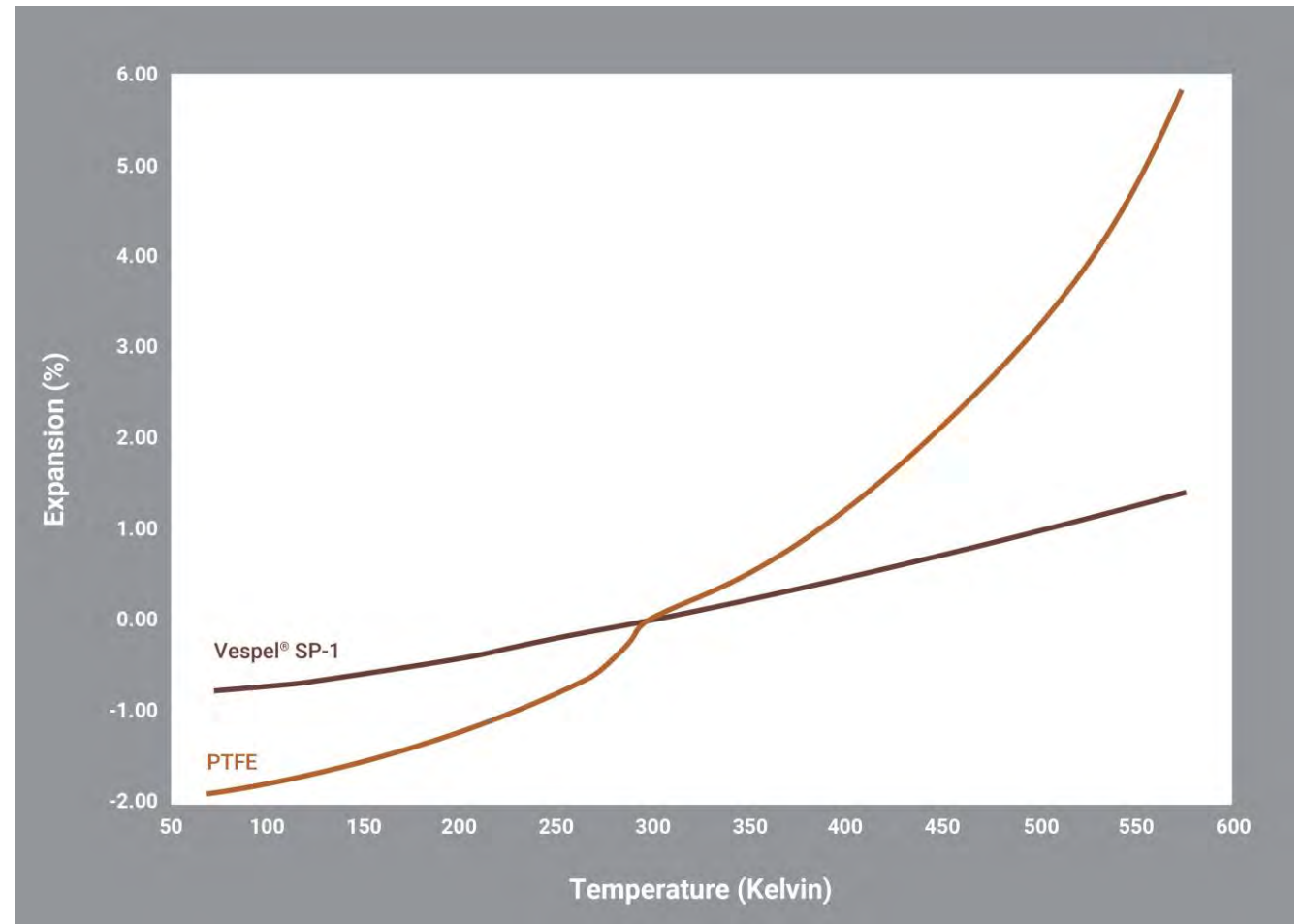
Linear Thermal Expansion and Coefficient of
Linear Thermal Expansion of Annealed Teflon®



Source: Adapted from Richard Kirby (1956) –
National Bureau of Standards

Consistent CTE

Linear Thermal Expansion of Vespel® SP-1 and PTFE from 73 K to 573 K

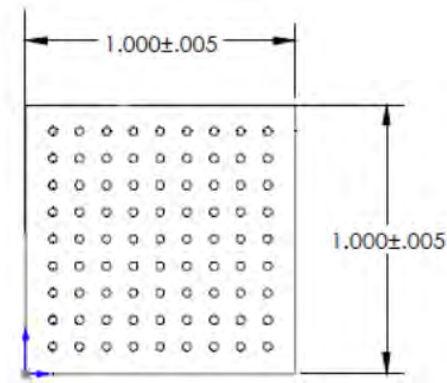


Source: Adapted from McDonald & Rao (1987), Kirby (1956), and DuPont™ (2022)



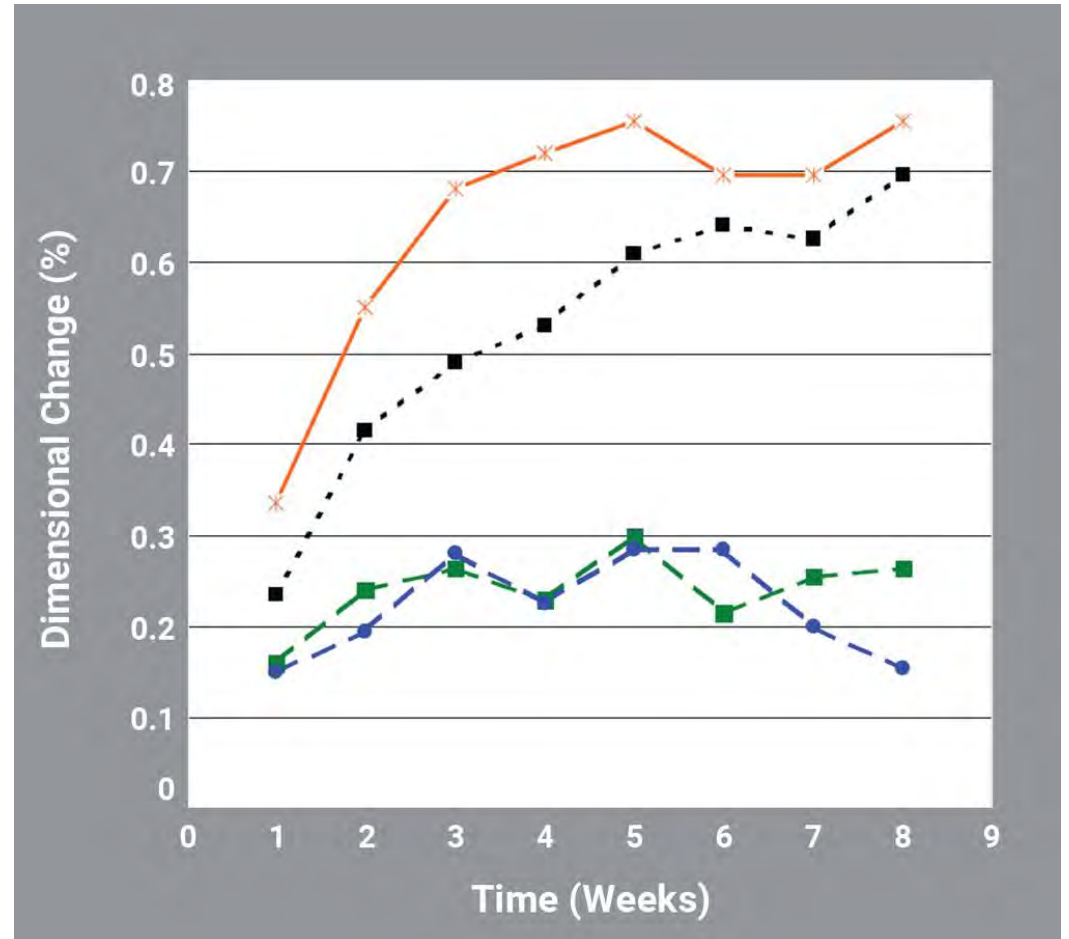
Dimensional Stability in Humid Environments

Dimensional Stability in Humid Environments



- x— Torlon® 4203 “with holes”
- Torlon® 4203 “no holes”
- Vespel® SP-1 “with holes”
- Vespel® SP-1 “no holes”

Dimensional Change vs. Exposure Time
100F/90% RH – 1" x 1" x 1/8" Coupon

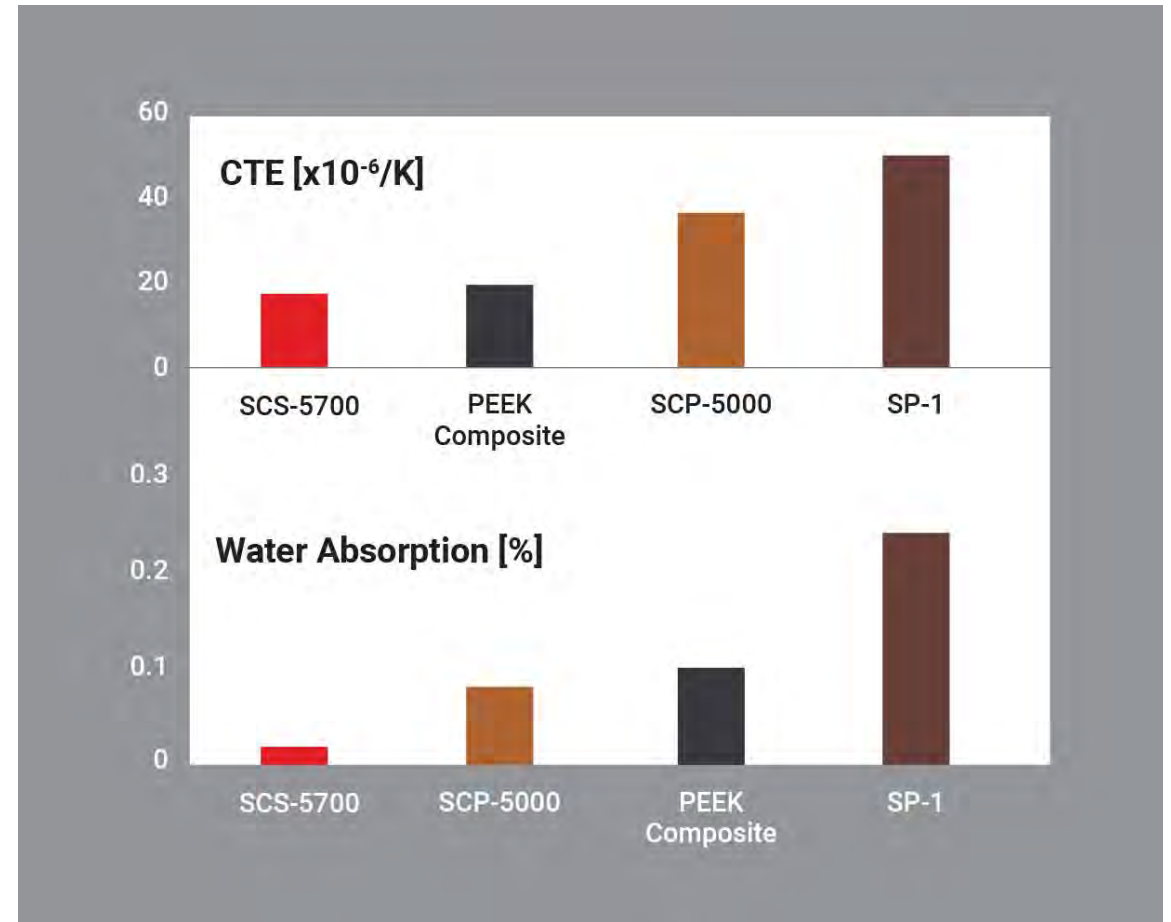
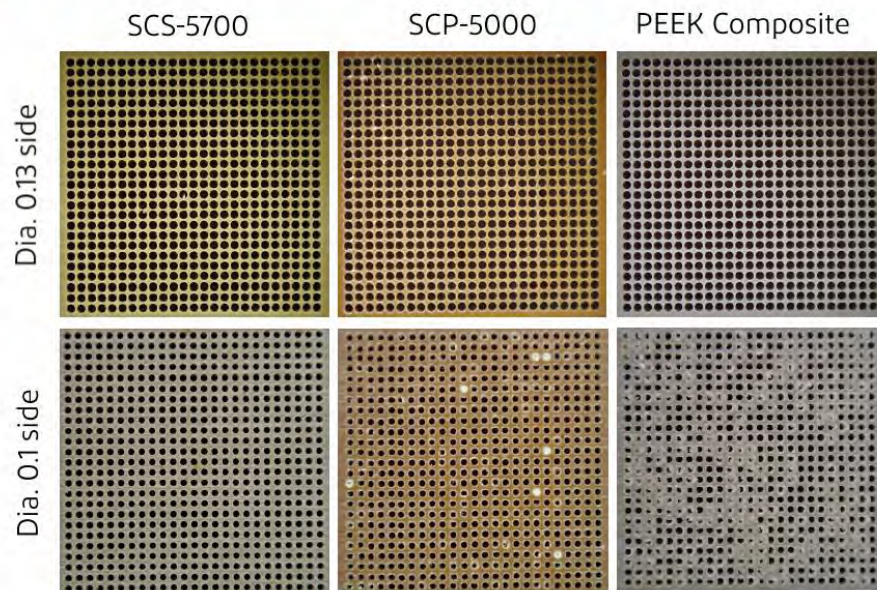


Source: Adapted from Paul Kane (2004)

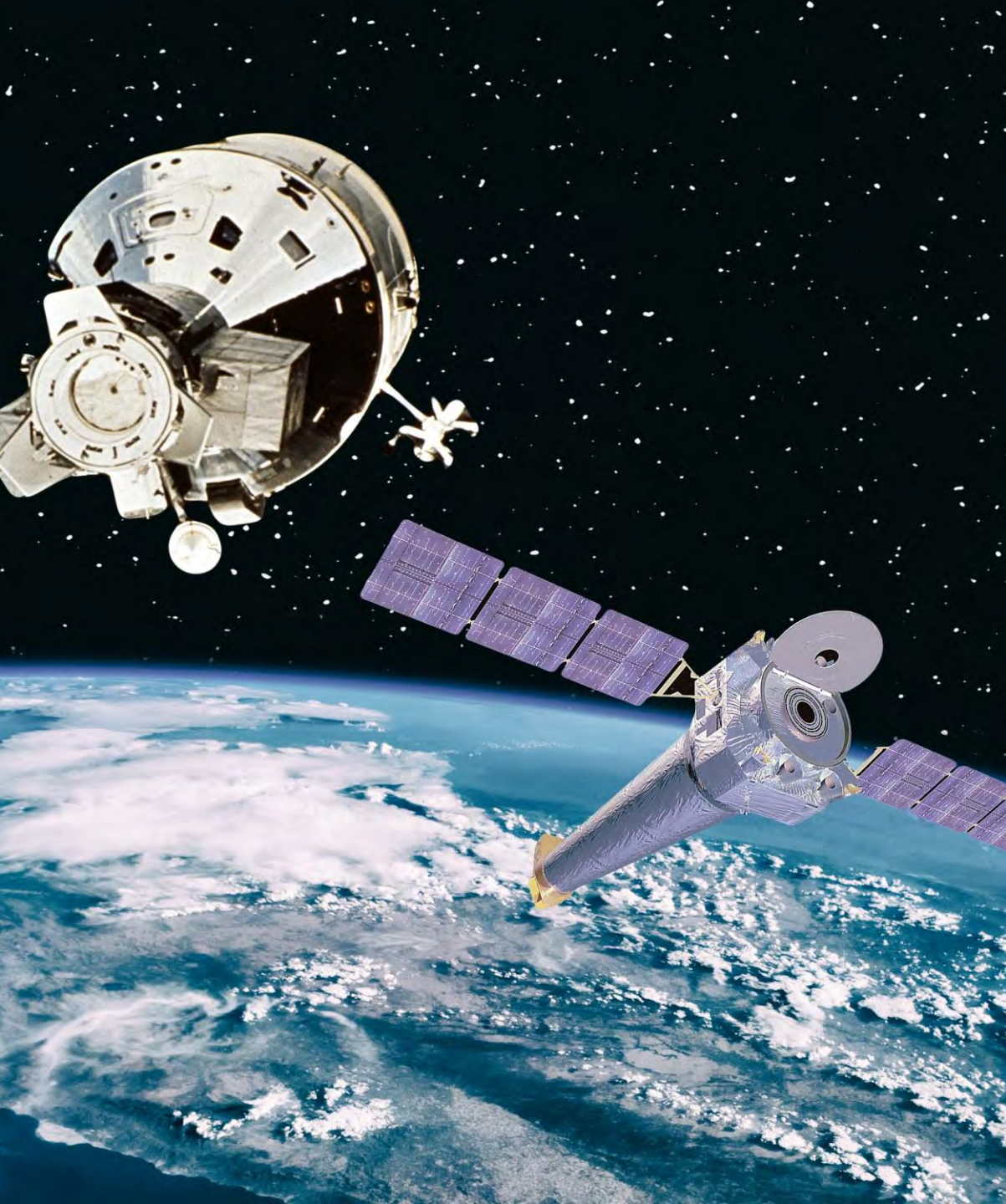
Dimensional Stability

SCS 5700

Precise and Micro Machinability

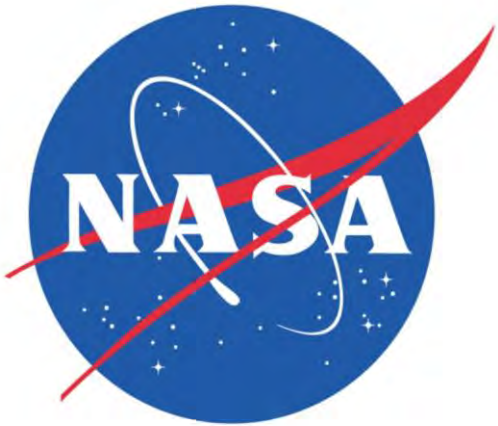


Source: DuPont™



Flammability Characteristics

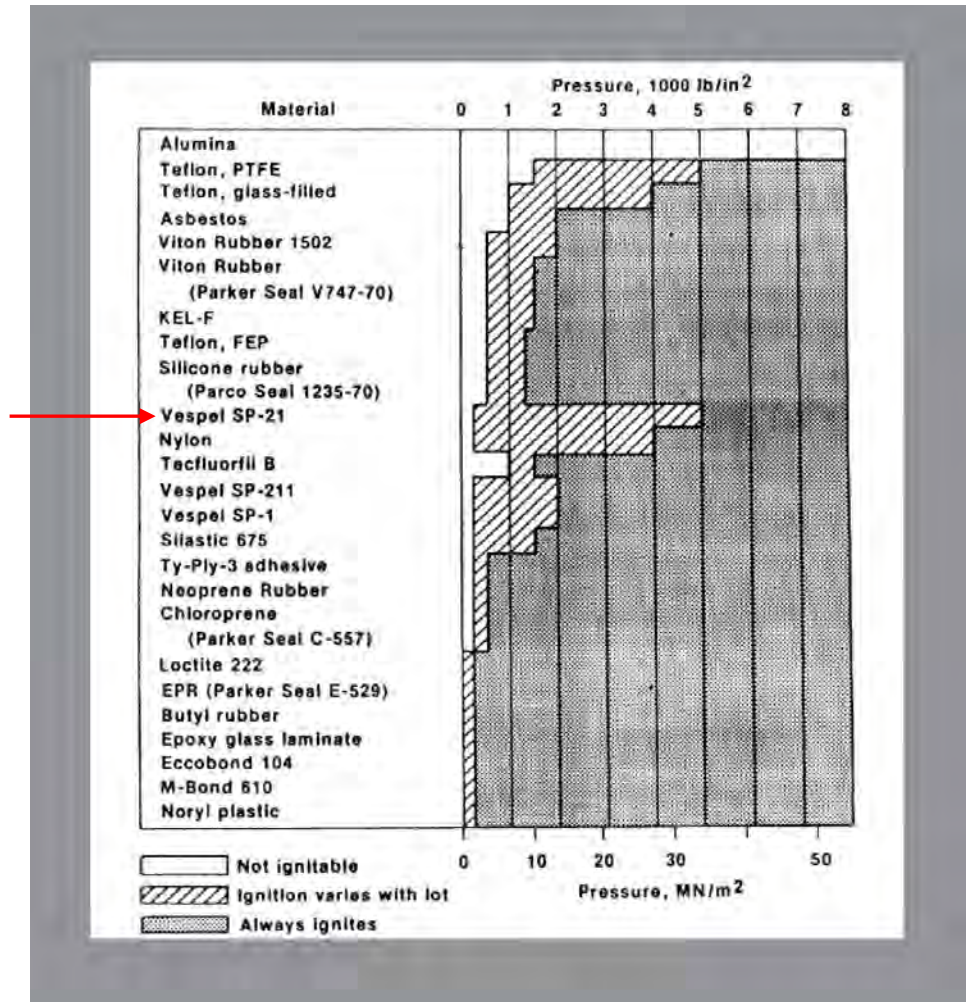
Flammability Characteristics / Oxygen Compatibility



- SP-21 has been tested by the National Aeronautics and Space Administration and meets MSFCSPEC-106B, "Testing Compatibility of Materials for Liquid Oxygen Systems". At present time this approval is on a selected-lot basis
- 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"

Flammability Characteristics / Oxygen Compatibility

Final Report Oxygen Materials Compatibility Testing



Source: Leonard Schoenman (1989) - NASA

Flammability Characteristics / Oxygen Compatibility

Liquid Oxygen Compatibility of Materials for Space Propulsion Needs

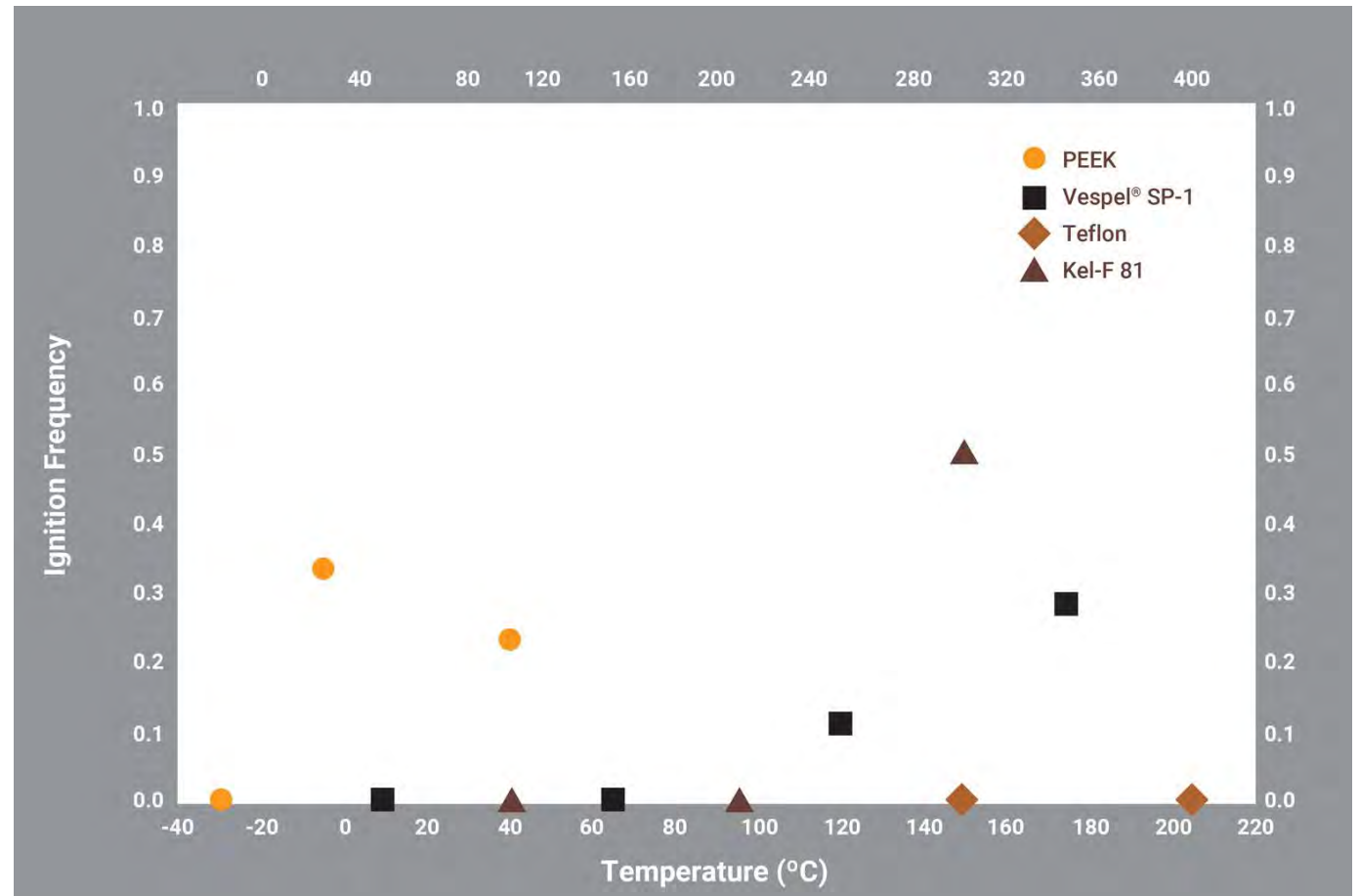
Materials	Amount of Ignition/Amount of Impact						
Polyamide-imide Torlon® 4203	5/20						
PTFCE	0/20	0/20	1/40	4/20			
PTFCE 302	0/20	3/20	0/20	4/20	1/20	4/20	3/20
	7/20	5/20	0/39	1/40	0/20	4/20	2/20
	0/20	7/20	3/20	0/20	0/20	0/20	1/40
	1/40	0/20	3/20	1/40	1/40	3/20	0/20
	0/20	0/20	1/20	0/20	0/20	0/20	0/20
	0/20	0/20	0/20	0/20	0/20	0/20	2/27
	0/20	0/20	0/20	0/20			
VespeI® SP-21	0/20	0/20	1/40	0/20	0/20	0/20	0/20
	0/20						
PTFE	0/20	0/20	0/20	0/20	0/20	0/20	0/20

“Impact tests clearly state that polyimide VespeI® SP-21 is compatible in liquid oxygen. The conclusion is the same for PTFE. As for PTFCE,...the conclusion...is less straightforward.”

Source: Bozet (2011)

Flammability, Oxygen Compatibility

Ignition Frequency of Polymer Targets as a Function of
Temperature at 27.5 MPa (4000 psi)



Source: Adapted from Forsyth (2000)

Hydrogen Compatibility

Rocketdyne International – Space Division

Two space division GH_2 facilities were visited; the Control Components Test laboratory in Downey, California, and the Main Propulsion Test facility at the National Space Technology Laboratory in Bay St. Louis, Mississippi.

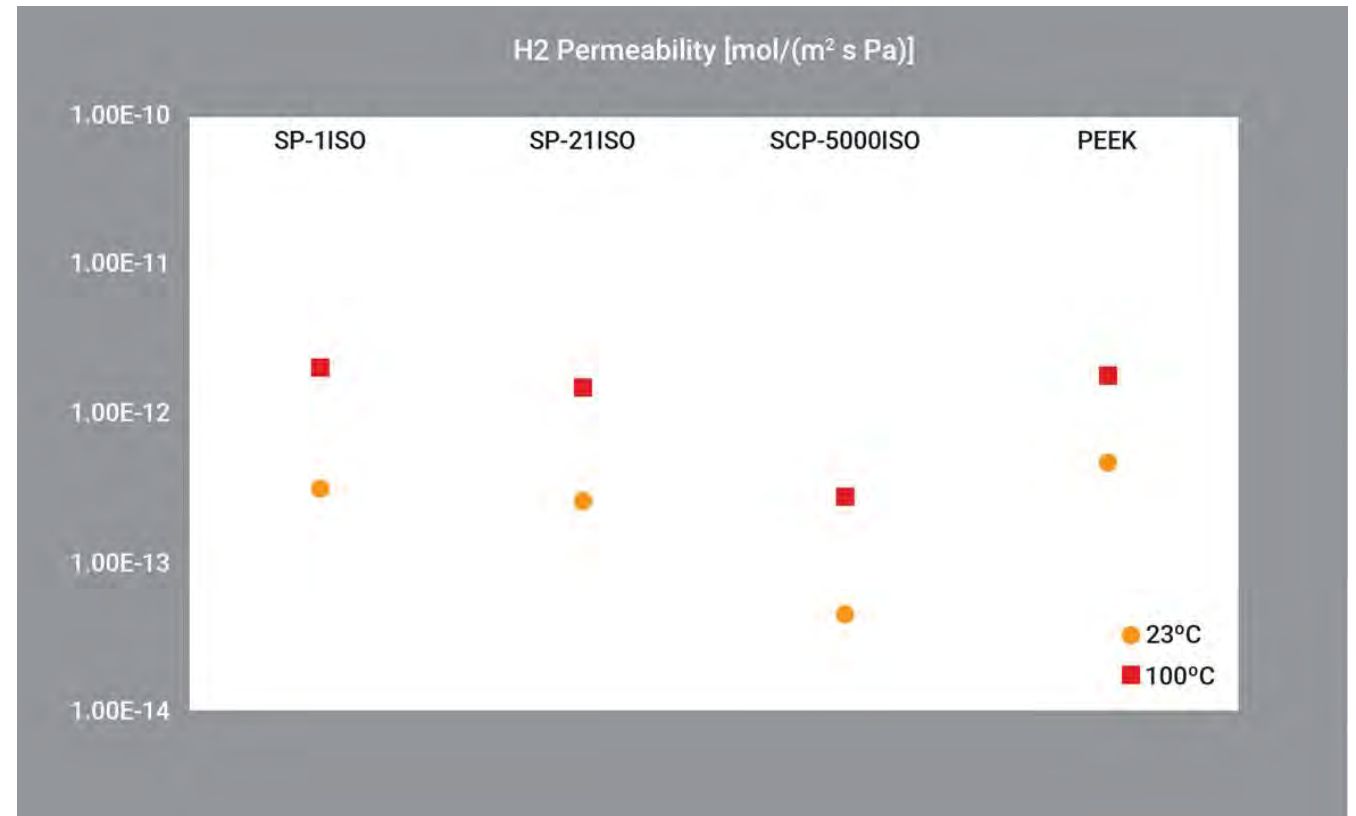
The test facility in Downey has the capability to operate with GH_2 at pressures up to 2500 psig and at temperatures from -420 to $+100^\circ\text{F}$. Manifolds range from 0.25 to one inch OD and are constructed from aluminum or conventional CRES using mechanical fittings and flanges.

Space Division has had significant experience with conventional components in gaseous hydrogen service which indicates that the major precautions necessary with the use of aerospace-quality components involve safety considerations for the high-pressure and the flammability limits. Two secondary precautions require the use of austenitic CRES for highly-stressed membranes and bellows and the minimum use of elastomers when permeability is a concern. Acceptable elastomers for hydrogen service include Buna "N", Neoprene, Viton, Teflon and Vespel. The use of metal (copper, aluminum, CRES, nickel, etc.) is preferred when possible.

Source: Kelley (1978)

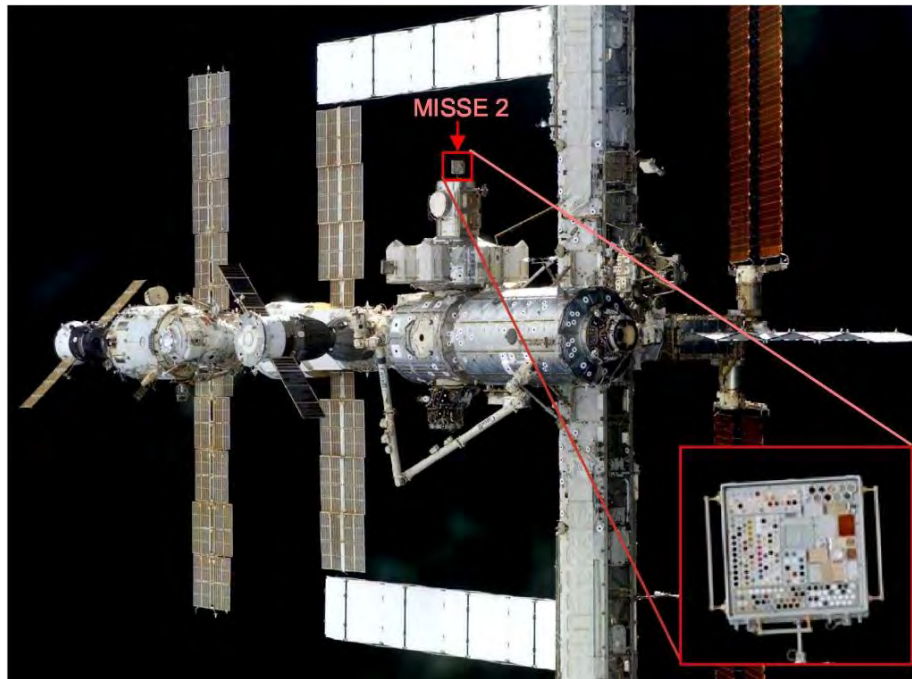
Sponsored by U.S. Department of Energy Assistant Secretary for Energy Technology Division of Energy Storage Systems Washington, D.C. 20545		CONF-771131 UC-94d
Proceedings of the DOE Chemical/Hydrogen Energy Contractor Review Systems		
Held November 16-17, 1977 Hunt Valley, Maryland		
August 1978	NOTICE This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.	
Proceedings prepared by Jet Propulsion Laboratory California Institute of Technology Pasadena, California 91109		
		

Hydrogen Compatibility



Source: DuPont™

Resistance to Erosion from Atomic Oxygen



Polymer Erosion and Contamination Experiment



Figure 2.—Photograph of the MISSE 2 PEACE Polymers experiment prior to flight. The labels shown indicate the materials defined in Table I.

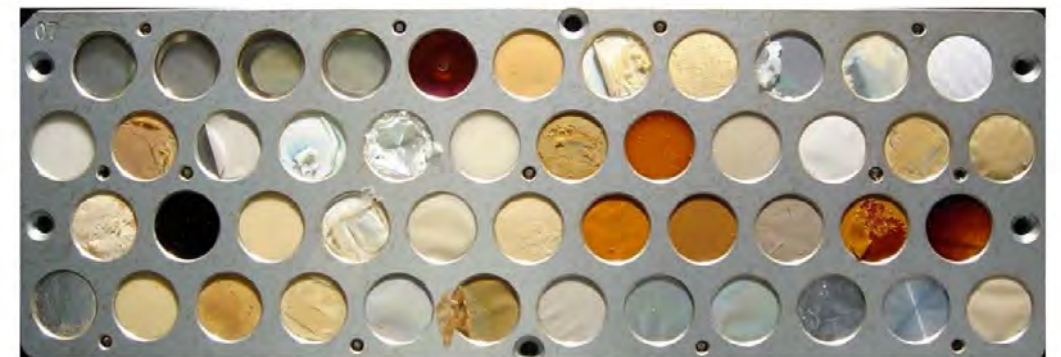


Figure 3.—Photograph of the MISSE 2 PEACE Polymers experiment post-flight.

Source: Banks (2009)

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