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WHITEPAPER

ACCELERATING THE ENERGY TRANSITION:

APPLICATIONS OF VICTREX™ PEEK POLYMERS IN HYDROGEN INFRASTRUCTURE

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Introduction

Hydrogen is anticipated to become a major source of cleaner energy as the world seeks to limit the effects of climate change. Hydrogen may be used as fuel for power generation, residential and industrial heating, and transportation by land, air, and sea. To realize a future in which hydrogen comprises a major share of the world's energy requires efficient, reliable, and safe infrastructure. VICTREX™ PEEK and PAEK polymers, formulations, and composites are anticipated to support key applications including

- Seals and valves for handling of gaseous and liquified hydrogen
- Compressor components and bearings with low friction and long wear
- Rotors with high strength-to-weight ratio for efficient operation
- Compressor packing and wear components
- Bearings

A common idea is that the transition will begin with 'grey and brown hydrogen' produced from hydrocarbons in processes such as steam methane reformation followed by 'blue hydrogen' made in similar processes but with carbon capture and sequestration (CCS) to 'green hydrogen' produced by water electrolysis using renewable energy (wind, solar, geothermal…) (Table 1). Each stage of the transition will present a set of technical and commercial challenges.

Table 1. Types of Hydrogen.[1]

Grey & Brown	Blue	Green
Produced from fossil fuels (natural gas + coal)	Produced from fossil fuels (natural gas + coal)	Produced by electrolysis of water
Large amount of CO_2 emissions produced	Dependent on adoption of carbon capture and storage	Powered by renewable energy (e.g. wind + solar)
Relatively low in cost	An important step in energy transition from Grey to Green	Clean but very expensive

It is fortunate that infrastructure for compressed gases, including hydrogen, has already been developed for chemical and petrochemical operations.[2,3] Victrex polyether ether ketones (PEEK) based components have performed critical sealing, isolation, compression, storage, and distribution functions for many years. It is anticipated that translation and adaptation of PEEK-based technologies could enable accelerated development of future hydrogen supply chains.

1. Barth, R.R., Simmons, K.L., San Marchi, C.W. (2020, April) Heading for Hydrogen DNV.GL
2. Hicks, S., Gross, P. (January 20, 2016) Hydrogen for refineries is increasingly provided by industrial suppliers - Today in Energy - U.S. Energy Information Administration (EIA)
3. Hydrogen in Industry (2017) Hydrogen Europe

Hydrogen Supply Chain

For hydrogen to be cost competitive, secure, energy efficient, and environmentally and economically sustainable, options for technology need to be carefully considered. A future hydrogen supply chain will likely be complex – there may be multiple means of production, conversion, storage, transport, and end use (Figure 1).

Hydrogen Supply Chain Schematic

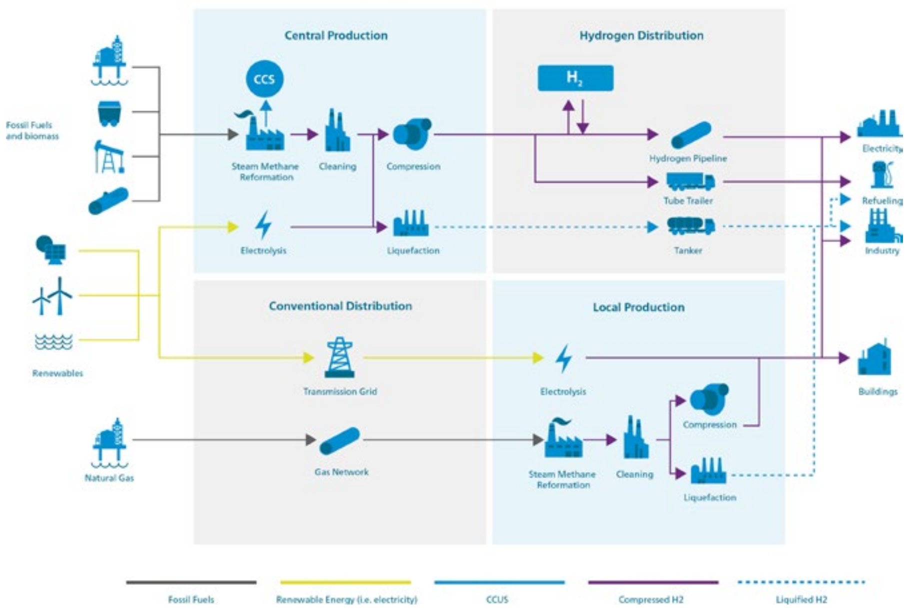


Figure 1. Production, distribution, and end-uses of hydrogen.[4]

Common goals for these multiple pathways are anticipated to include:

- **Reducing emissions (lower permeability)**
  Example: Leakage from seals, valves, pipes, and storage vessels must be minimal.

- **Increasing efficiency (high strength-to-weight ratio, low friction and wear);**
  Example: Compressors need to operate with minimal friction. Rotating equipment needs high strength-to-weight ratio components.

- **Increasing reliability and service life (chemical resistance, temperature resistance.)**
  Example: Materials of construction must not be susceptible to hydrogen embrittlement. Seals need to function at intended service conditions (e.g. cryogenic to elevated temperatures)

- **Mitigating environmental, health, & safety risk (EH&S, reduced emissions)**

From production of hydrogen to end-use there will likely be multiple stages of storage and offloading. Each stage demands reliable and safe transfer of hydrogen. Here thermoplastics and elastomers are essential components of the supply chain, from liquefaction to gasification.[1,5]

4. Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P.E., Elkins, P., Shah, N., Ward, K.R.(2019) . Energy Environ. Sci., 12, 463.
5. Aarnes, J., Eijgelaar, M., Hektor, E.A. (2018) Hydrogen as an Energy Carrier [white paper]. DNV.GL

VICTREX PEEK Polymer Solutions

PEEK is one of the world's highest performing thermoplastics. VICTREX™ PEEK and its formulations can meet multiple key engineering requirements simultaneously, without compromise, which makes these polymers popular for use in high-demanding and critical environments, from airplanes to medical implants. Its structure from molecular to macroscopic scales contributes to high strength and toughness at extreme temperatures, low permeability, low friction, and high wear resistance (Figure 2).

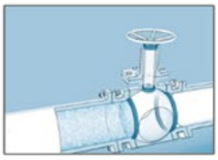
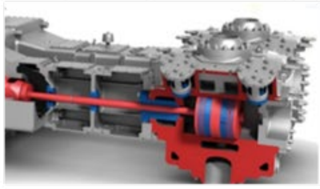
- **Extreme Temperature:** mechanical performance at very low (cryogenic) to high temperatures.
- **Weight Reduction at Equivalent Stiffness:** up to 70-85% lower weight at equivalent stiffness compared to some metals. Higher strength-to-weight ratio enables higher efficiency.
- **Tribological Performance:** ability to perform in hydrodynamic, mixed friction, boundary lubrication, and even dry conditions.
- **Stable Properties:** retention of properties over time in hydrogen at the intended service conditions.
- **Tunable Properties:** PAEK and PEEK polymers are thermoplastic and consequently can be melt formulated with additives to enable design of properties for purpose.

Figure 2. VICTREX PEEK Solutions – A Unique Combination of Properties.

PEEK Applications in Hydrogen

The properties of VICTREX PEEK polymers are anticipated to contribute to the performance of multiple applications in the future hydrogen supply chain (Table 2).

Table 2. Potential PEEK Solutions in the Hydrogen Supply Chain.

	Minimal Emissions / EHS		Efficiency		Reliability	
Step	Sealing Performance	Minimal Permeability	High strength-to-weight ratio	Minimal Friction	Low Wear Rates	Robust Mechanical Performance
Target Applications	*PEEK Seal* 		*PEEK composites*	*PEEK packing and bearings* 		*General PEEK-based components*
Liquifaction	✓	✓	✓	✓	✓	✓
Compression	✓	✓	✓		✓	✓
Transport	✓	✓		✓		✓
Dispensing	✓	✓				✓

Sealing Solutions

Hydrogen infrastructure is expected to present two distinct sealing challenges: sealing of gaseous hydrogen and of the cryogenic liquid state.

Low Permeability for Sealing Gaseous Hydrogen

Valves and seals are required to contain and control the flow of hydrogen. Losses can originate from leakage paths and permeation through the seal itself through permeation. The small size of H_2 can enable easier permeation through solid materials. Low permeability is generally required in static and dynamic sealing solutions to reduce emissions. PEEK is advantaged in low permeability applications due to its relatively high Tg (glass transition temperature) and semicrystalline solid-state structure.

In 2011, Entegris reported the permeation resistance of PEEK to hydrogen at ambient conditions.[6] Permeability, diffusion, and solubility coefficients were measured on two grades of VICTREX PEEK-based APTIV™ extruded films and compression and injection moulded VICTREX PEEK 150G (Table 3). The generally low permeability of all the PEEK samples can be attributed in part to the glassy state as the ambient temperature was below Tg. Crystalline PEEK materials (APTIV 1000, compression and injection molded VICTREX PEEK 150G), had lower permeability compared to the amorphous APTIV 2000.

6. Monson et. al., (2013) J App Polym Sci 127 1637-1642.

Table 3. Permeability, Diffusion & Solubility Coefficients of the Hydrogen Gas of PEEK Films at 25°C. [6]

Sample	Permeability Coefficients: P (10^{-10}cm³ cm/ cm² s cm Hg)	Diffusion Coefficients: D (10^{-8} cm² s^{-1})	Solubility Coefficients: S (10^{-3} cm³/cm³ cm Hg)
APTIV FILMS 1000 Series	1.81 ± 0.25	29.6 ± 3.4	0.61 ±0.04
APTIV FILMS 2000 Series	3.60 ± 0.05	53.2 ± 6.4	0.69 ± 0.09
VICTREX PEEK 150G (compression moulded)	1.16 ± 0.04	24.2 ± 4.9	0.50 ± 0.10
VICTREX PEEK 150G (injection moulded)	2.01 ± 0.04	51.6 ± 2.8	0.39 ± 0.02

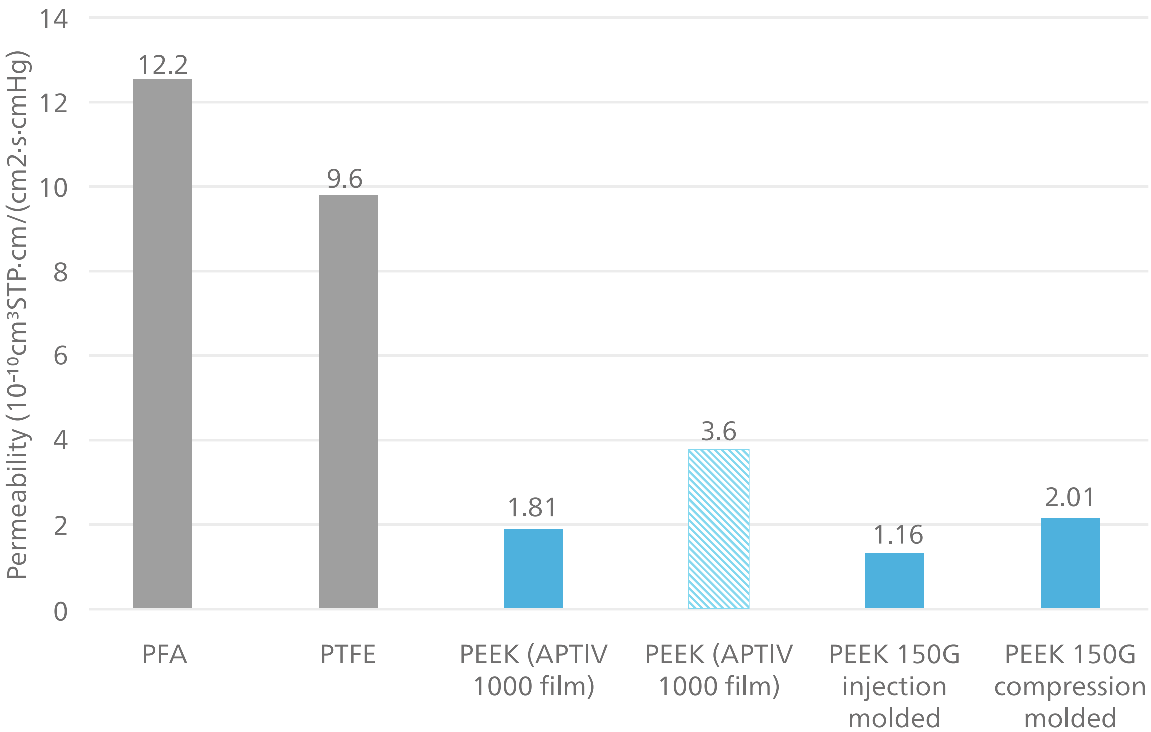


Figure 3. Permeability of PEEK, PFA, and PTFE to hydrogen gas at 25°C. [6,7]

PEEK has about 63-90% lower permeability to hydrogen gas compared to two fluoropolymers (Figure 3). Higher permeability can be attributed to the lower Tgs of PFA (at -80 and 90ºC) and PTFE (at 34 and 137ºC).[7,8] This result suggests that valves and seals made with VICTREX PEEK polymers will experience reduced loss of hydrogen through permeation compared to PFA and PTFE.

7. Menon, N.C., Kruizenga, A.M., Alvine, K.J., San Marchi, C., Nissen, A., Brooks, K. (2016) Proc of the ASME 2016 Pressure Vessels and Piping Conf:Behaviour of Polymers in High Pressure Environments as Applicable to Hydrogen Infrastructure(PVP2016-63713)
8. DuPont Teflon® PFA fluoropolymer resins – Properties Handbook (2002, February), Table 8

Materials Challenges for Cryogenic Hydrogen Service

An important part of the future hydrogen infrastructure will handle cryogenically cooled, liquified hydrogen. The higher energy density of the liquid state makes it an attractive form to store and transport hydrogen. Liquid hydrogen (~0.07 g/cm³) has about 2.3 times greater concentration of molecules and hence greater energy density than hydrogen gas compressed to the maximum pressures of conventional storage vessels (~0.03 g/cm³ at 50 MPa and 25°C).[9] A key material challenge is to provide sealing as gaseous hydrogen is cooled to cryogenic temperatures < 120 K (–153 °C) and finally to the liquid state at less than 20K (–253°C, –423°F).

The requirements for a good sealing material for use in cryogenic valves may be described as:

- Suitable stiffness to allow effective sealing at very low, ambient and high temperatures (i.e. a wide usage temperature range).
- Rapid recovery on removal of load
- Low friction / torque and high wear resistance
- Toughness and strength commensurate with the application
- Low thermal expansion to maintain fit with adjoining metallic components
- High thermal conductivity to allow rapid equalisation of temperature with surrounding components
- Minimal chemical and physical effects by the gases and fluids being conveyed

Fluoropolymers (i.e., PTFE, PCTFE) are used for sealing applications however their limited sources, processing by sintering and pultrusion, higher density, and mechanical properties can result in technical and economical disadvantages. Consequently, there is a need for different thermoplastic materials that offer lower density and improved mechanical performance at cryogenic temperatures to support efficiency and sustainability.

High-performance PEEK-based VICTREX CT™ polymers for cryogenic seals and valves include:

- VICTREX CT™ 100 for strength and ductility at cryogenic temperatures
- VICTREX CT™ 200 for low coefficient of friction while retaining sufficient strength and ductility.
- The lower density of VICTREX CT 100 (1.3 g/cm³) and VICTREX CT 200 (1.4 g/cm³) can enable up to about 40% material savings by weight compared to PCTFE (2.11-2.17 g/cm³) and PTFE (2.2 g/cm³) for a given volume.[10,11]
- Mechanical properties at cryogenic temperatures of these polymers can meet or exceed the performance of PTFE and PCTFE.

9. Lemmon, E.W., Huber, M.L., McLinden, M.O. (2013) NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP). National Institute of Standards.
10. Technical datasheets for VICTREX CT 100 and VICTREX CT 200. From Victrex plc.
11. Technical datasheets for Neoflon® PCTFE M-300P and Neoflon® PCTFE M-400H from Daikin Industries, Ltd.

Properties at Gaseous Hydrogen Temperatures (-150 to -252°C)

Tensile properties of VICTREX CT 100 and CT 200 grades were measured in liquid nitrogen at 77K (-196°C, -320.8°F) (Figure 3).

- The tensile moduli of VICTREX CT 100 (5.2 GPa) and CT 200 (4.6 GPa) are comparable to PCTFE (5.1 GPa) suggesting similar ability to form a seal.
- Strength of VICTREX CT 100 is about 70% higher while strength of VICTREX CT 200 is similar to PCTFE suggesting similar or greater ability to withstand differential pressure compared to PCTFE.
- Elongation at break of VICTREX CT 200 is 5.1% and VICTREX CT 100 is 7.8% while PCTFE breaks at 3.3%. This suggests that VICTREX CT polymers have 1.5-2.4× greater capacity to undergo deformation without breaking.
- Charpy impact performance is correspondingly 4× higher for VICTREX CT100 and 2× higher for VICTREX CT 200 compared to PCTFE indicating a greater ability to withstand sudden increases in stress such pressure excursions and spikes.
- Furthermore, the lower coefficient of linear thermal expansion (CLTE or CTE) and higher thermal conductivity are thought to facilitate design and sealing from cryogenic to high temperatures.[12]

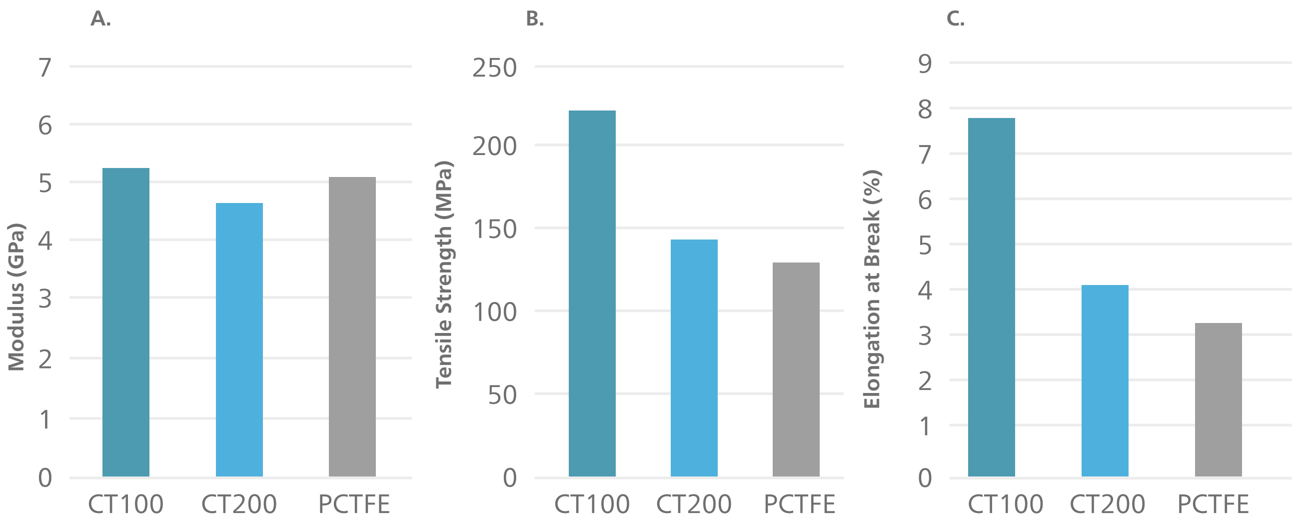


Figure 3. Tensile behavior of VICTREX CT 100, CT 200, and PCTFE at -196°C: (a) modulus; (b) tensile strength; (c) elongation at break.

12. "PAEK Polymers for Cryogenic Applications" by Geoff Small (AMI Oil & Gas Nonmetallics Conference, London, 2018).

Properties at Liquid Hydrogen Temperatures (-253 to -259.2°C)

To understand performance at liquid hydrogen temperatures, tensile tests were performed at 4K (-269.2°C, -452.5°F) using liquid helium (Figure 4).

- Modulus increased for VICTREX CT grades, but remained comparable with PCTFE suggesting similar sealing performance.
- Strength of VICTREX CT 200 remained similar while VICTREX CT 100 was more than 2x higher compared to PCTFE.
- Elongation at break continued to be higher for VICTREX CT polymers compared to PCTFE.

These results suggest advantaged mechanical performance for VICTREX CT polymer-based components for liquid hydrogen service.

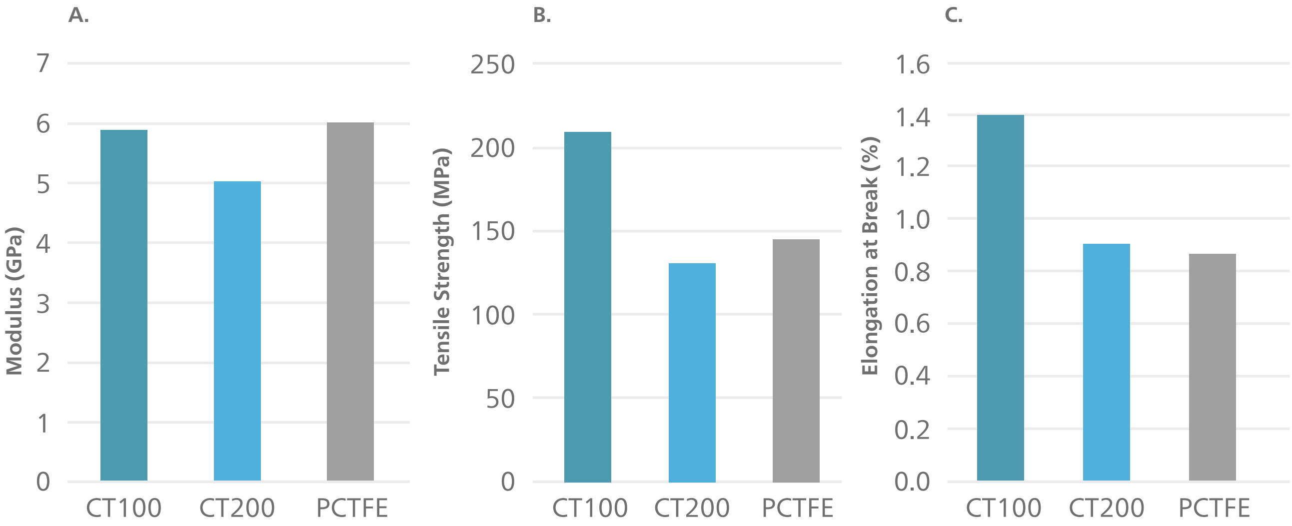


Figure 4. Tensile behavior of VICTREX CT 100, CT 200, and PCTFE at 4K (-257°C, -452.5°F): (a) modulus; (b) tensile strength; (c) elongation at break.

Origin of Ductility at Cryogenic Temperatures

The ductility (or brittleness) of polymers at cryogenic temperatures is strongly influenced by molecular relaxation mechanisms. Dynamic mechanical thermal analysis (DMTA) is a means to reveal and understand these transitions and relaxations.[13] The loss angle (tan δ) is the ratio of dissipated energy compared to stored energy as measured by moduli. Local maxima in tan δ correspond to relaxation mechanisms present in polymers at temperature and can indicate a polymer's ability to deflect and bend rather than break under stress such as impact conditions.

The low temperature relaxations identified in PEEK polymers by Adams and Gaitonde are reproduced along with additional data at higher temperatures in Figure 5. Designation of the relaxation peaks follow the convention of using Greek letters: α (transitions above Tg), β (Tg), and δ and δ for sub-Tg transitions.

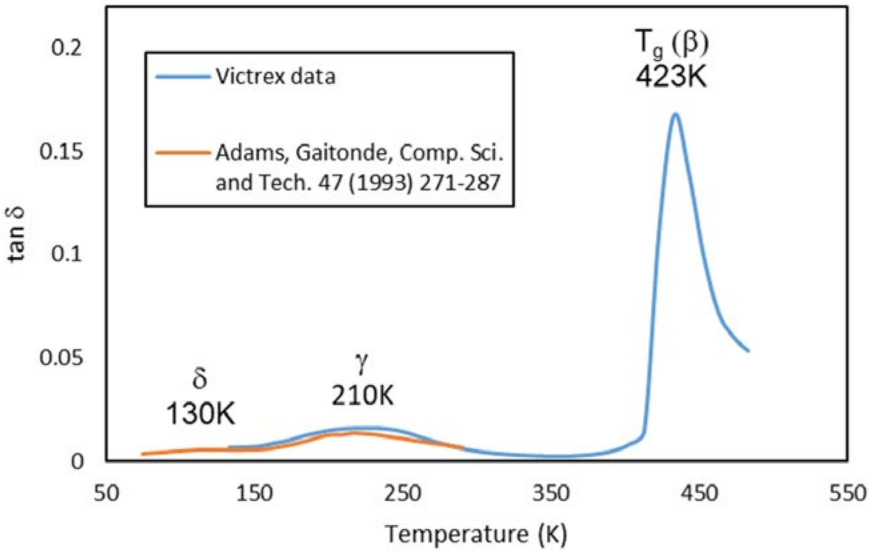


Figure 5. Dynamic mechanical thermal analysis of PEEK polymer.[14]

The Tg of PEEK is indicated by the β relaxation centered at 423 K (150ºC, 302ºF). Current applications of PEEK benefit from resistance to creep at temperatures below Tg. [15]

Relevant to properties at cryogenic temperatures, the γ relaxation in PEEK is centered at 210 K (-63°C) and the δ relaxation is at about 130K (-143°C). These relaxations are associated with mobility of polymer segments and side chains and can explain strength, toughness, and the ability to absorb vibrations at these lower temperatures.[2,16]

The transition temperatures of PEEK, PTFE and PCTFE are summarized Table 2. Although PTFE and PEEK have similar melting points, the 'glassy' region, between γ and δ for PEEK is around 2× broader than PTFE and 3× broader than PCTFE. Furthermore, the δ relaxation for PEEK is at significantly lower temperature albeit a less well-defined feature than for PTFE. Therefore, it can be suggested that molecular motion is more feasible in PEEK than PTFE and therefore that a greater level of ductility at low temperatures would be seen. PCTFE has been reported to exhibit a δ relaxation however, lack of suitable data prevents further comparison.

13. Boyer, R.F. (1968) Polym. Eng. and Sci., , 8 (3) 161-185.
14. Adams, R.D and Gaitonde, J.M. (1993). Compos. Sci. Technol. , 47, 271-287
15. Bershtein, V., Egorov, V., (1993). Differential Scanning Calorimetry in the Physical Chemistry of Polymers, Ellis Horwood, Chichester.
16. Nelson, F.C., (1994) Shock and Vibration Digest, 26 (2), 11

Table 2. Transition Temperatures of PEEK, PTFE, and PCTFE.

Material	δ (ºC)	γ (ºC)	Tg, β (ºC)	Tα (ºC)	Tm (ºC)
PEEK[12]	-143	-63	150	n/a	343
PTFE[17]	-97	19-30	127		327
PCTFE[18]	*[19]	-25 to 7[20]	38.2[21] to 99[20]	150	210 to 212[22,23]

Notes:
Transition temperatures defined by maxima in tan δ with DMTA.
'n/a' - denotes "not applicable".
'*' – lack of data collected by comparable methods.

Observations of greater strength and toughness of VICTREX CT 100 and VICTREX CT 200 suggests these mechanism can be more effective in PEEK than in PTFE and PCTFE.

Properties at High Temperatures

For the extreme of high temperature service, it is worth noting that both VICTREX CT 100 and 200 have melting points of 343°C and will exhibit corresponding high heat resistance as measured by heat deflection temperature of about 152-168°C and 1.8 MPa (ISO-75f).[10] In contrast, PCTFE melts at 210-212°C which correlates to lower heat deflection temperatures of 126°C at 0.46 MPa (ASTM D648).[9] Valves, seals and other components based on CT polymers consequently may be able to perform across broader temperature ranges compared to those based on PCTFE. VICTREX CT polymers might then enable fewer sealing products to serve the temperature range of the hydrogen infrastructure of the future. If realized, potential additional benefits could include simplification of supply chains.

In summary, VICTREX CT polymers are shown to be attractive alternatives to fluoropolymers such as PCTFE for cryogenic hydrogen service. Mechanical properties at cryogenic temperatures suggest similar or improved sealing performance, pressure resistance, and impact performance. Higher heat resistance of VICTREX CT polymers may enable increased upper service temperatures for broader applicability and specifications. Their thermoplastic nature enables efficient processing by extrusion, injection molding, compression molding, and other melt processing technologies. About 40% lower density may enable less material usage and weight reduction.

17. Mettler Toledo Thermal Analysis Application No. HB244
18. Kel-F is a registered trademark of 3M Corporation.
19. Hoffman, J. D.; Williams, G.; Passaglia, E. J. Polym. Sci., Part C, 226 (1966) 14, 173-235.
20. Khanna YP, Kumar R Polymer 32 (1991) 2010-2013.
21. Hoffman DM, DePiero SC, Lawrence Livermore National Laboratory. (2007) "Characterization and Qualification of New TATB and Kel-F 800 for LX-17" (UCRL-TR-228232)
22. Technical Data Sheet, Neoflon® M-300P.
23. Technical Data Sheet, Neoflon® M-400H.

Composites for Hydrogen Service

Energy intensive applications for hydrogen include impellers and rotors for the compression and expansion and of hydrogen. These operations are needed for the transport, storage, and distribution of hydrogen. VICTREX PEEK and PAEK-based composites exhibit up to 70-85% lower weight at equivalent stiffness compared to some metals. By reducing weight while maintaining stiffness, there is the potential for energy savings in performance of expansion and compression in the hydrogen supply chain.

Victrex offers PEEK and PAEK reinforced with carbon and glass fiber formulations in granules and micropellets suitable for melt processing (injection molding, compression molding, and extrusion). Powders and coarse flake are also available for customers who formulate.

VICTREX PEEK-based UD carbon fiber prepreg tape and the recently launched AE250 UDT which has shown increased lay-up speed while achieving industry levels of porosity (<2%) enable efficient composite manufacture with automated fibre placement (AFP) and hand lay-up methods.

Compressor Packing and Wear Components

VICTREX PEEK polymers have been used to compress and transfer methane and other gases through upstream, downstream, and industrial infrastructure for decades.

PEEK-based formulations are shown to enable a combination of required properties (Table 5). The mechanical properties (strength, creep resistance, fatigue resistance), tribological characteristics (low CoF) are believed to contribute to the pressure resistance, long service life, and operational efficiency needed in compressor applications (piston rings, piston rod rings, pressure packing, valve plates). For hydrogen to be a competitive source of energy, hydrogen compressors will need to operate at similar but more likely higher pressures (350-900 bar).[26] Further development of PEEK and PAEK-based formulations may extend these benefits to the future hydrogen infrastructures and economies. Victrex also offers HT (PEK) and ST (PEKEKK) grades for applications requiring even higher temperature service.

Table 5. Comparison of Properties of PEEK, PTFE, PI, and PPS-based Formulations.

	PEEK	PTFE	PI	PPS
Tensile Strength at Break (MPa)	55 - 90	11 - 17	76	76
Elongation at Break (%)	3 - 15	4 - 175	4	2
Specific Gravity (g/cm3)	1.32 - 1.48	1.82 - 2.18	1.41	1.51
Shore D	80 - 87	57 - 72	80	84
COF	0.25 - 0.3	0.08 - 0.25	0.28	0.35
CLTE (ppm/K)	45-63	72-99	~45	~63

24. Hyperbaric "What is hydrogen compression: HIGH-PRESSURE RENEWABLE HYDROGEN FOR SUSTAINABLE AND CARBON-FREE MOBILITY", https://www.hiperbaric.com/en/h2-compression/what-is-hydrogen-compression/

Bearings

The performance and reliability of the rolling-element bearings and bearings cages are dependent on the bearing component materials. VICTREX PEEK polymers can be used to replace metal, with the potential to reduce system cost and save weight. They can also outperform other polymers.

PEEK Bearing Cage for Roller Bearings

PEEK is chosen for bearing cages for their contribution to lower bearing friction, lower noise, and long service life. PEEK's low friction to other bearing components (races, ball bearings) which tend to be steel, contributes to low bearing friction and heat generation. Compared to some formulations based on PA6.6, PEEK-based formulations can be thermally more stable. Examples in the literature have shown about 50 and 100°C higher continuous use temperature resulting in orders of magnitude longer aging life at temperatures about 200°C. Moreover, the low density of the material reduces the weight which, in turn, reduces the moment of inertia force and gives greater angular velocity to the bearing. Tribologically optimized compounds allow the bearings to run dry for a brief period without the danger of friction wear or damage. This suggests that the amount of applied grease could be reduced to make a favourable environmental contribution while maintaining performance.

Figure 5. Example of a PEEK bearing cage.

VICTREX PEEK polymer as a bearing cage material provides the following benefits:

- Accommodates high continuous temperatures and very high speeds.
- Reduces heat generated by the bearing.
- Reduces energy consumption.
- Accommodates shock forces and high centrifugal forces.
- Enables bearing to survive longer under poor lubrication conditions.
- Extends bearing service life.

Hydrogen Embrittlement

Hydrogen embrittlement describes the process by which metals such as certain steels become lose ductility and fracture due to the ingress and diffusion of hydrogen. A significant consequence of this exposure can lead to a substantial reduction in ductility and load bearing capacity. Materials such a high strength steels, titanium and aluminium alloys are the most vulnerable to this phenomenon.[25]

VICTREX PEEK and CT polymers [7,26] are not expected to be permanently affected by exposure to hydrogen and consequently can be considered to extend the lifetime and reliability of components in hydrogen service across many applications such as seals, valves, and compressors.[27] To assess final fitness for purpose, validation by application is needed at the intended service conditions.

25. NACE® International, Hydrogen Embrittlement
26. Woishnis W.A., Ebnesajjad, S., (2012) Chemical Resistance of Specialty Thermoplastics edited William Andrew Publishing.
27. R. R. Barth, K.L. Simmons, C. San Marchi. (2013) Polymers for hydrogen infrastructure and vehicle fuel systems: Applications, Properties, and Gap Analysis. SAND2013-8904 U.S. Department of Energy Office of Scientific and Technical Information.

Conclusions

VICTREX PEEK (polyether ether ketones) based components have been used in infrastructure for distribution of gases including hydrogen for many years. Adaptation of existing PEEK-based sealing, isolation, and compression technologies is anticipated to be a practical means to realise the energy transition to hydrogen on an accelerated timeline.

In seals, valves, compressor packing and other components. VICTREX PEEK polymers offers the potential to:

- Reduce emissions (lower permeability);
- Increase efficiency (high strength-to-weight ratio, low friction and wear);
- Increase reliability and service life (chemical resistance, temperature resistance.);
- Mitigate EH&S risk (reduced emissions).

These benefits, technical attributes, and an established manufacturing base of processors/moulders, tier 1 suppliers, and OEMs should enable rapid development and scalable production. As the number one PEEK experts, Victrex can support customers with the development of the next generation of components needed for the hydrogen supply chain.

References:

1. Barth, R.R., Simmons, K.L., San Marchi, C.W. (2020, April) Heading for Hydrogen DNV.GL

2. Hicks, S., Gross, P. (January 20, 2016) Hydrogen for refineries is increasingly provided by industrial suppliers - Today in Energy - U.S. Energy Information Administration (EIA)

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6. Monson et. al., (2013) J App Polym Sci 127 1637-1642.

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8. DuPont Teflon® PFA fluoropolymer resins – Properties Handbook (2002, February), Table 8

9. Lemmon, E.W., Huber, M.L., McLinden, M.O. (2013) NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP). National Institute of Standards.

10. Technical datasheets for VICTREX CT 100 and VICTREX CT 200. From Victrex plc.

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12. "PAEK Polymers for Cryogenic Applications" by Geoff Small (AMI Oil & Gas Nonmetallics Conference, London, 2018).

13. Boyer, R.F. (1968) Polym. Eng. and Sci., , 8 (3) 161-185.

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16. Nelson, F.C., (1994) Shock and Vibration Digest, 26 (2), 11

17. Mettler Toledo Thermal Analysis Application No. HB244

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22. Technical Data Sheet, Neoflon® M-300P.

23. Technical Data Sheet, Neoflon® M-400H.

24. Hyperbaric "What is hydrogen compression: HIGH-PRESSURE RENEWABLE HYDROGEN FOR SUSTAINABLE AND CARBON-FREE MOBILITY", https://www.hiperbaric.com/en/h2-compression/what-is-hydrogen-compression/

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