



WHITEPAPER

VICTREX™ PAEK POLYMERS: SUPPORTING ENERGY TRANSITION TO CARBON CAPTURE, UTILISATION AND STORAGE (CCUS)

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ABSTRACT

The growing urgency to address climate change and reduce CO₂ emissions is one of the greatest challenges humanity is currently facing. Carbon capture, utilisation, and storage (CCUS) is an emerging means to combat climate change primarily through capturing CO₂ at the point of source, then sequestering the CO₂ underground or utilising the captured CO₂ for industrial purposes.

CCUS projects worldwide are at varying stages of development, with EPCs and investors requiring confidence in the long-term performance of the new infrastructure. **Victrex PolyEtherEtherKetone (PEEK)** and other polymers in the class of **PolyArylEtherKetone (PAEK)** are anticipated to contribute to the performance, efficiency, and reliability of the CCUS infrastructure with temperature, pressure, wear, chemical resistance, low permeability, and mechanical properties. Due to the demand from capture to transport to storage/sequestration, **VICTREX PAEK and PEEK polymers** are candidates for critical components within the CCUS infrastructure based on current application in valve seats, seals, composites wear rings for pumps, and piston rings, piston rod rings, packing for compressors.

INTRODUCTION

In the International Energy Agency's (IEA) report "Net Zero by 2050: A Roadmap for the Global Energy Sector"¹, CCUS is expected to play a crucial role in achieving the ambitious targets set by the Paris Agreement. The target outlined in the report is to sequester 7.6 gigatons of carbon dioxide annually by 2050.

CCUS plays a vital role as part of the overall solution to address the challenges posed by rising greenhouse gas emissions and combating climate change.

Carbon capture is primarily expected to take place at the point of source (power plants, oil refineries, steel manufacture sites) in 'clusters' or 'hubs' where high concentrations of CO₂ is emitted. The CO₂ is compressed to either liquid or supercritical form (sCO₂), purified, and transported via pipelines for either utilisation or storage purposes.

Utilisation is where captured CO₂ is put to productive use for example, production of chemicals, fuels, and enhanced oil recovery (EOR) techniques.

Storage is the sequestration of CO₂ underground in geological formations including aquifers, and depleted oil and gas fields, so that it is prevented from entering the atmosphere and contributing to climate change as a greenhouse gas.

KEY WORDS

Composite Wear Rings, Compressors, Permeability, Piston Rings, Piston Rod Rings, PolyArylEtherKetone (PAEK), PolyEtherEtherKetone (PEEK), Pumps, Rapid Gas Depressurisation (RGD), Seals, Swelling, Valves, Valve Seats.

VICTREX JOINING THE CCUS SUPPLY CHAIN

Collaboration with Victrex throughout the CCUS supply chain enables value creation, capture of application requirements, and business success for our customers (Figure 1). It is anticipated that the CCUS infrastructure will be realised with the support of established PAEK value chains of processors, machine shops, original equipment manufacturers (OEMs), and energy producing companies (EPCs) that currently serve the oil and gas industry. As the first company to commercialise PEEK over 40 years ago Victrex is the #1 PEEK expert and can advise customers on achieving and accelerating their objectives.



Figure 1. Victrex Industry Value Chain – Partnering for Success from Concept to Commercialisation.

Victrex is joining the CCUS supply chain by linking the intermediate processors, tier 1 suppliers, and OEM's of VICTREX™ PEEK together through our knowledge and expertise in the CCUS markets. Victrex typically participates at the early stages of a supply chain, as we manufacture the base polymer. From there, we work closely at each stage of the supply chain to ensure the final part meets specification.

WHAT IS THE ANTICIPATED ROLE OF VICTREX™ PAEK POLYMERS?

VICTREX™ PEEK polymers provide a unique combination and range of high-performance properties. PEEK’s structure from molecular to macroscopic scales contributes to low permeability, low swelling and chemical resistance at extreme temperatures and pressures.

CCUS is anticipated to present multiple material challenges, including chemical resistance to flue gases and its impurities, the need for low permeation to prevent fugitive emissions, mechanical strength in the presence of CO₂ in its gaseous and supercritical states, and the ability to retain properties in the event of severe service conditions of temperature, pressure, and rapid gas depressurisation events. During capture, transport, and eventual storage, the contributions of Victrex products could contribute to the performance; environmental health and safety (EHS); efficiency and reliability of seals/valves, pumps, and compressors.

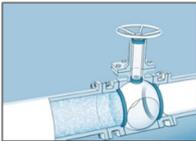
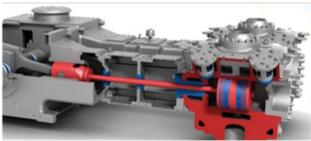
Need	Performance and EHS		Efficiency		Reliability	
Suitable Applications	<i>Seals, Valves</i> 		<i>Composites for pumps</i> 	<i>Compressors components</i> 	<i>General PEEK-based components</i>	
Benefits of Victrex Products	Robust Sealing Performance: broad service window, chemical resistance	Reduced Emissions: Low Permeability	Energy Efficiency: High strength-to-weight ratio	Energy Efficiency: Low Friction	Long Service Life: Low Wear Rates	Robust Mechanical Performance
Capture	✓	✓	✓	✓	✓	✓
Transport	✓	✓	✓	✓	✓	✓
Storage	✓	✓				✓

Figure 2. Suitable Applications and Benefits of Victrex Products for CCUS.



WHY VICTREX™ PEEK FOR CCUS?

Victrex manufactures PAEK and PEEK polymers, which have been used extensively in the oil & gas industry for over 40 years in some of the most demanding environments (high temperatures, high pressures, chemical corrosion). Translation of PAEK's unique properties make it an excellent choice for valves, seals, pumps, and compressor components for the CCUS infrastructure.

Customers usually choose PEEK when the application's performance requirements can be met by three or more material characteristics (Figure 3). For CCUS, the following properties are anticipated to be of value.



Figure 3. Advantages of VICTREX PEEK solutions – a unique combination of properties.

- ▶ **Low Permeability:** Provides an effective barrier to supercritical and liquid CO₂ as seals and compressor components at wide range of temperatures and pressures.
- ▶ **Chemical Resistance:** Withstands a wide range of acids, bases, hydrocarbons, and organic solvents. Highly resistant to carbonic acid, often present in CO₂ transport applications.
- ▶ **Mechanical strength & Dimensional Stability:** Excellent strength, stiffness, long-term creep, and fatigue properties. Highly resistant to supercritical CO₂ plasticisation effects.
- ▶ **Stable Properties:** Retention of properties in low/high temperature and pressure service conditions as measured by relative thermal index.
- ▶ **Tunable Properties:** PAEK and PEEK polymers are thermoplastic and consequently can be melt formulated with additives to enable design of properties for purpose.

LOW PERMEABILITY TO CO₂

Low permeability to liquid and supercritical CO₂ is a highly desirable property in CCUS applications which require static and dynamic sealing solutions (seals, valves, and compressor components). PEEK is highly resistant to CO₂ permeation due to its relatively high T_g (α transition) and semicrystalline solid-state structure, which results in reduced fugitive emissions.

Permeability is the product of diffusion (the ability of a gas to move through a material) and solubility (the ability of a gas to dissolve within a material). The flux of CO₂ through a part can be predicted based on understanding the effect of service conditions (primarily temperature) on diffusion and solubility coefficients, pressure gradient, and part geometry. Victrex can provide guidance on moulding and annealing conditions to control permeability.

In 1994, a study conducted by Candia et al.² found that crystalline **VICTREX™ PEEK polymers** at 30°C had a permeability coefficient 5.4x lower than PTFE measured by Sebok et al.³, 19x lower than PTFE (Dupont Teflon™) measured by Pasternak et al.⁴, and 36x lower than PTFE measured by Fitz et al.⁵ (see Figure 4). The permeability measured by Candia has since been found to have similar values in a Victrex study⁶. At the higher temperature of 60°C, the permeability of PEEK¹ was found to be 6.7x lower than that of PTFE². This suggests reduced fugitive emissions by permeation for CO₂ capture, transport, and storage/sequestration in CCUS applications.

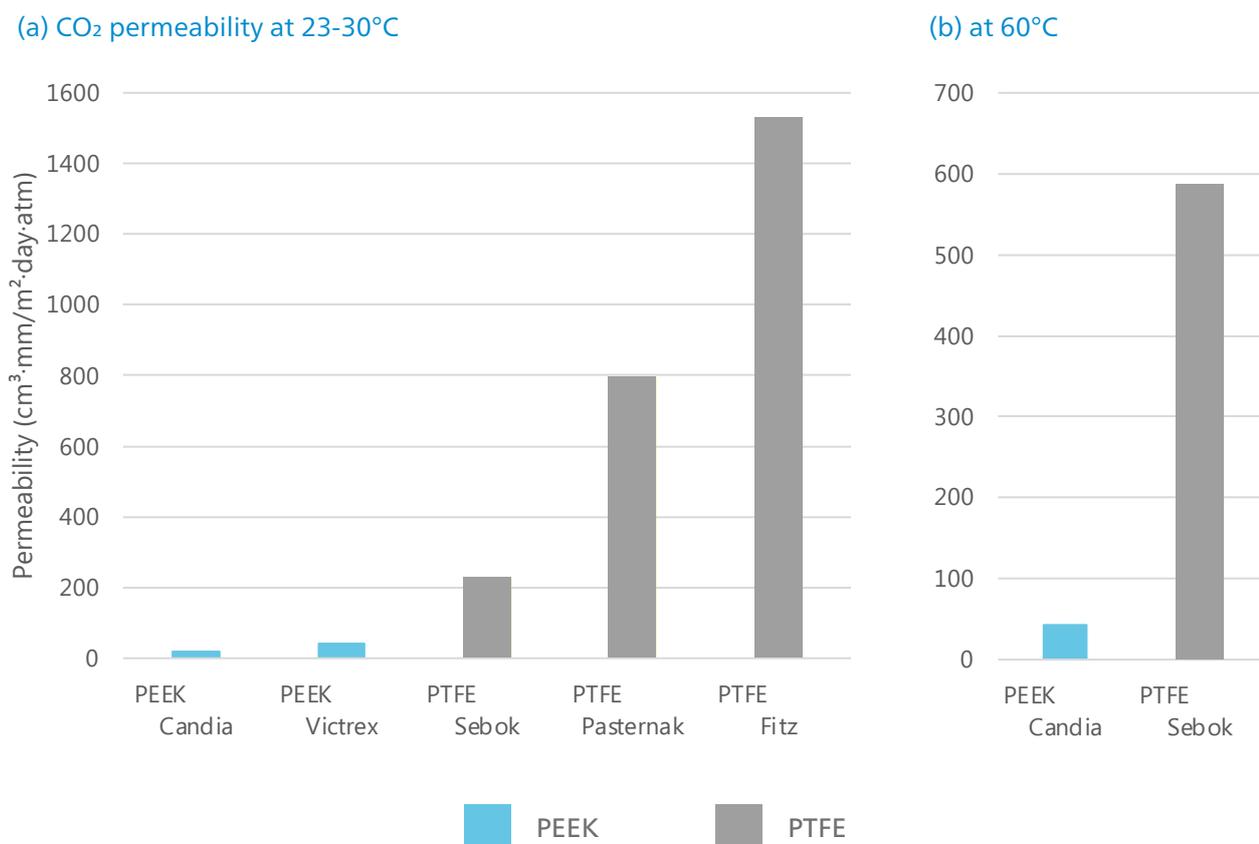


Figure 4. CO₂ permeability of PEEK vs. PTFE at (a) 23-30°C; (b) 60°C.^{2,3,4,5,6}

2. Candia F., Vittoria V., (1994) Permeability of PEEK to carbon dioxide. J. Appl. Polym. Sci., 51, 2103-2107.

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5. Fitz H., (1980) Fluorocarbon Films - Present Situation and Future Outlook, Kunststoffe with German Plastics, 70, 11-16.

6. Victrex Technical Paper – Victrex Permeability Measurements 09/2003.

Modelling CO₂ Permeability

Victrex has a 'CO₂ Permeability Model' to quickly predict material and component performance at relevant service conditions. This could lead to significant R&D expenditure savings (cost, labour, and time) when evaluating **VICTREX™ PEEK polymers** for CCUS applications, enabling materials to be fast-tracked to field trials. The model is designed to evaluate a range of service conditions that exist in the field and would substantially support operational efficiency.

Service conditions (temperatures, pressures, and other specifications) combined with Victrex proprietary data (material characteristics and properties) and technical know-how are inputted to the model. The model will output permeability, diffusivity, and solubility and has been shown to predict results to within one order of magnitude of empirical data. Instead of conducting resource intensive, time-consuming, lab-based experiments, the Victrex model provides our partners with quick indicative permeability data to accelerate decision making. To contact us, follow this [link](#).

EFFECTS OF EXPOSURE TO SUPERCRITICAL CO₂

Knowing the effects of CO₂ on material properties for the range of CCUS service conditions, it is necessary to choose a suitable material of construction for the intended application. For sealing and valve applications, these properties often include dimensions, mass, structure, and mechanical properties.

To understand how CO₂ affects properties, it is useful to recognise that polymers contain "free volume", the space in between molecular chains and amorphous regions, which can absorb CO₂ and other molecules. Absorption is thermodynamically driven and a function of temperature, pressure, and the energetic interaction with the polymer. Unless there is a chemical reaction involving CO₂, the effects tend to be reversible.

Mass and Dimensions

Maintaining seal integrity is the primary purpose of valves and seals, therefore minimising dimensional change is one of the most important factors to consider when selecting a material. Because PTFE is used in many sealing applications, it is a useful reference. Menon et al.⁷ examined the effect of exposure of polymers to CO₂ at 100°C and 200 bar for 200 and 1000 hours for a variety of polymers.

Menon⁷ found that after exposure to sCO₂, the mass of the PTFE specimens had not changed while the mass of PEEK specimens had increased by only about 1% (Table 1), which was determined to be insignificant for sealing applications. The increase in mass of PEEK was attributed to absorbed CO₂ which had not yet diffused away. Both polymers did not experience extraction of material by sCO₂ which could be indicated by a net loss of mass.

Table 1. Change in Mass (%) of PEEK and PTFE at Exposure Condition (sCO₂)

Polymer	Change in Mass (%) at Exposure Condition (sCO ₂)	
	200hrs 100°C	1000hrs 100°C
PEEK	1.2	1.0
PTFE	0.0	0.0

7. Menon N. C., Walker M., Colgan N., Anderson M., Nissen A., Massey L., (2020) Compatibility of polymers in super-critical carbon dioxide for power generation systems: High level findings for low temperatures and pressure conditions, SAND2020-0948C, The 7th International Symposium – Supercritical CO₂ Power Cycles.

After removal from sCO₂, the density of PTFE had decreased by about 2% while PEEK had increased by about 1.5% after 1000 hours of exposure to sCO₂ (Table 1). This corresponded to average dimensional changes of less than 1% for both PEEK and PTFE. Other studies of PEEK in sCO₂ conducted by Victrex⁸ and Mohammed et al.⁹ at higher temperatures, higher pressures and different exposure times showed similar, small dimensional changes after exposure to sCO₂ and return to ambient conditions. Practically, this suggests that PEEK can be used in applications which PTFE is currently employed.

Table 2. Dimensional Changes to PEEK and PTFE after Exposure to sCO₂.

Study	Material	Temperature (°C)	Pressure (Bar)	Exposure Time (hours)	Swelling (%)	Average Linear Dimensional Change (%)
Menon et al. ⁷	PTFE	100	200	200	-0.75	-0.25
	PTFE	100	200	1000	-2	-0.66
	PEEK	100	200	200	0.5	0.17
	PEEK	100	200	1000	1.5	0.51
Victrex Internal Study ⁸	PEEK	135	690	3528	5	1.64
Mohammed et al. ⁹	PEEK	200	1010	90	2.94	0.97

Mechanical Properties and Morphology

VICTREX™ PEEK polymers provide exceptional performance over a wide range of temperatures and pressures, whilst retaining excellent mechanical properties.

Dynamic mechanical thermal analysis (DMTA) of PEEK vs. PTFE was performed after aging in supercritical CO₂ at 100°C and 20MPa over 200 and 1000 hours by Menon et al.⁷

The modulus increased slightly after exposure to supercritical CO₂, despite small decreases in T_g as measured by loss modulus peak. This could be attributed to changes in crystalline morphology despite some plasticization by absorbed CO₂.

This result was consistent with optical microscopy which showed no cavitation or cracks at the microscopic scale.⁷

Storage Modulus of PEEK and PTFE after supercritical CO₂ exposure

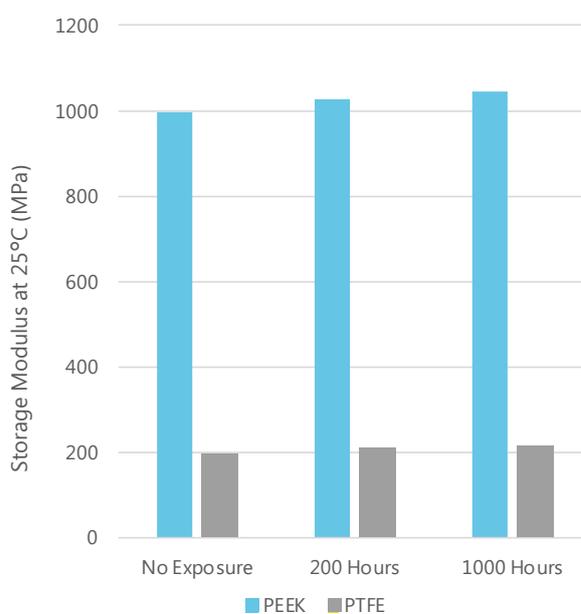


Figure 5. Storage Modulus comparison PEEK vs. PTFE.⁷

8. Victrex Report – The Long Term Aging Behaviour and Lifetime Prediction of VICTREX™ PEEK Polymer: A Review of the State-of-the-Art, 03/2020.

9. Mohammed M. H., Banks W. M., Hayward D., Liggat J. J., Pethrick R. A., Thomson B., (2013), Physical properties of poly(ether ether ketone) exposed to simulated severe oilfield service conditions. Polym. Degrad. Stab., 98, 1264-1270

RESISTANCE TO RGD EVENTS

Rapid gas depressurisation (RGD) or explosive decompression (ED) is the sudden loss of confining pressure to a system. Super-saturated gases can desorb from the polymeric matrix forming internal bubbles. If the diffusion of gases out of the polymer is insufficient, bubbles can form, coalesce, and initiate cracks resulting in blisters especially in certain elastomers and is a known risk in oil and gas operations. The risk for CCUS infrastructure is similar. An uncontrolled pressure drop (such as a blowout) could lead to seal and equipment failure resulting in health, safety, and environmental hazards including release of CO₂ to the environment. Valve and seals that are capable of resisting RGD events help to protect the integrity and lifespan of infrastructure thereby minimising the risk of damage, costly repairs, and unplanned downtime. **VICTREX™ PEEK polymers** are highly resistant to RGD events due to its relatively high T_g, high modulus and strength, and low solubility to CO₂. In addition, PEEK's crystalline phase is presumed to absorb negligible amounts of CO₂, further decreasing the potential damage effect of RGD events when used as seals.

Abas et al¹⁰ exposed PEEK and PTFE to supercritical CO₂ (80°C and 150 bar with 5,000 ppmv water for 14 days) followed by slow (0.3 bar/min) and faster (5 bar/min) decompression rates. Changes to dimensions and hardness of both materials were within measurement error and therefore considered to be statistically insignificant.

ISO 23936-2 provides an RGD test for elastomers - 100°C (or bespoke temperature), 150 bar (or bespoke pressure), 20 bar/min decompression rate, with 8 exposure cycles carried out over 4 days (see section B1.1.4). Mohammed et al.⁹ performed RGD testing on VICTREX™ PEEK test bars that were aged for 90hrs in a high temperature (200°C), high pressure (101 MPa, 1010 bar), 100% sCO₂ environment to replicate extreme oilfield service conditions, followed by the extreme decompression rate of 3.5 Mbar/min. VICTREX™ PEEK retained over 98% of its modulus and 96% of the tensile strength of the annealed control despite this severe RGD event (Figure 6).

Analysis of samples by DMTA and positron annihilation lifetime spectroscopy (PALS) suggested plasticization of the amorphous phase .

Mechanical Properties of VICTREX™ PEEK after severe RGD exposure

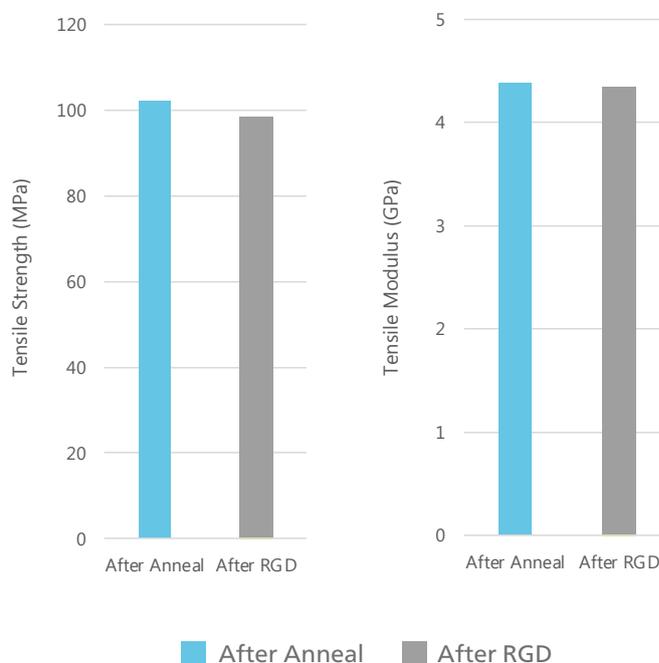


Figure 6. Mechanical properties of VICTREX™ PEEK after severe exposure to supercritical CO₂.

10. Abas A.Z., Nor A.M., Suhor M.F., Mat S., (2014) Non-Metallic Materials in Supercritical CO₂ Systems, OTC-24963-MS.

Following Mohammed's conclusion, it can be hypothesized that VICTREX™ PEEK specimens processed with little to no porosity provided minimal opportunity for void growth, coalescence, and blistering. Applying the model by Yersak et al.¹¹, it can be assumed that at equilibrium, pore pressure opposed by external pressure resulted in net zero forces. Upon RGD, the external pressure was significantly reduced, resulting in CO₂ in the few and small pores that were present to exert pressure on the surrounding PEEK. Pore pressure opposed by the strength of the surrounding PEEK matrix. Because the yield strength (pressure) of the surrounding PEEK exceeded the pore pressure, pores did not grow significantly. Rather, CO₂ diffused out of the PEEK driven by the pressure differential between the pores and the surroundings. It can be further argued that the minimal decreases in strength and modulus were due to minor irreversible effects (increased porosity and some disruption to the crystalline phase) and dominant reversible plasticization of the amorphous phase. If the excess CO₂ that plasticized the amorphous phase were given time to dissipate, the retained modulus and strength could be higher than 98% and 96%, respectively. The ability to retain mechanical properties after a severe RGD event suggests that **VICTREX™ PEEK polymers** should perform in even the most demanding CCUS applications and scenarios.

CHEMICAL RESISTANCE

CCUS applications require the handling of highly pressurised CO₂, often in the presence water and other impurities (H₂S, SO_x, and more) from capture of untreated flue gases to sequestration in corrosive salt brine in aquifers.¹² A variety of undesirable reactions can take place in the CO₂ stream, which can create highly corrosive environments for valve seals and compressor components to operate in. Examples of these reactions include:



VICTREX™ PEEK-based solutions are extremely resistant to CO₂, gaseous impurities and the corrosive acids which can form in the presence of water. The VICTREX™ PEEK Chemical Resistance guide¹³ details the level of chemical interaction PEEK has with chemicals typically found in the CO₂ stream. Test bars of unfilled VICTREX™ PEEK were immersed in chemicals at constant temperature for a minimum of 7 days. Chemical compatibility has been assessed via retention of mechanical properties, supplemented by weight or dimensional changes when applicable.

Compatibility was then classified into A, B, or C (Table 3). VICTREX™ PEEK receives 'A' ratings for high resistance to CO₂, H₂S, SO₂, H₂CO₃, and sea water. It receives a 'B' rating for < 40% H₂SO₄. Resistance is expected to increase with decreasing concentration of H₂SO₄.

11. Yersak T.A., Baker D.R., Yanagisawa Y., Slavik S., Immel R., Mack-Gardner A., Herrmann M., Cai M., (2017) Predictive model for depressurization-induced blistering of type IV tank liners for hydrogen storage, *Int. J. Hydrogen Energy* 42, 28910–28917.

12. Murugan A., Brown R. J. C., Wilmot R., Hussain D., Bartlett S., Brewer P. J., Worton D. R., Bacquart T., Gardiner T., Robinson R. A., Finlayson A. J., (2020) Performing Quality Assurance of Carbon Dioxide for Carbon Capture and Storage, *C.*, 6(4):76.

13. Victrex™ PEEK Chemical Resistance Guide

Table 3. VICTREX™ PEEK Chemical Resistance Guide to Anticipated CO₂ Stream Impurity Gases and Acids.

Chemical	Formula	23°C	100°C	200°C
Gases				
Carbon Dioxide	CO ₂	A	A	A
Hydrogen Sulphide	H ₂ S	A	A	A
Sulphur Dioxide	SO ₂	A	A	A
Acids				
Carbonic Acid	H ₂ CO ₃	A	A	NT
Sulphuric Acid (<40% Conc.)	H ₂ SO ₄	B	B	B
Other				
Water, Sea/Salt	H ₂ O/NaCl	A	A	NT

A – No interaction. Victrex materials are likely to operate in these chemicals. It is nevertheless recommended to validate the application performance.

B – Slight interaction. Victrex materials could be used in some applications exposed to these chemicals. It is necessary to evaluate the application specific performance criteria.

C – Severe interaction. Victrex materials should only be considered for applications with exposure to these chemicals under exceptional circumstances.

Murugan et al.¹² reported the maximum levels of impurities possible in flue gas captured from the combustion of nine different types of fuels. The maximum level of hydrogen sulphide (H₂S) possible was reported to be 3.2% mol. In the presence of water, this could produce very weak sulphuric acid. Users of VICTREX™ PEEK have reported no interaction to weak sulphuric acid below 135°C, and a slight attack above 135°C¹⁴.

Based on indicative chemical resistance to CO₂, impurities, and their potential reaction products, VICTREX™ PEEK is shown to perform well in corrosive conditions found in CCUS operations. Applications include seals, valves, composites, pumps, and compressor components needed to capture, transport, and storage of CO₂. By providing chemical resistance, VICTREX™ PEEK is expected to contribute to the performance, efficiency (cost), and reliability of operating CCUS infrastructure from capture clusters/hubs to offshore injection wells.

14. Greene Tweed (2011), WR®300/525/600, AR®HT & ARLON® 1000 Chemical Resistance Data, WR-AR-Arlon_ChemResistDa#1B.qxd (gtweed.com).

LOW COEFFICIENT TO THERMAL EXPANSION

Coefficient of thermal expansion (CTE) describes the dimensional change of a material in proportion to temperature change. Polymeric seal solutions with CTE similar to that of steel are anticipated to be desirable in the CCUS infrastructure.

Mismatched expansion and contraction of seals to steel in the CCUS infrastructure may lead to increased fugitive emissions and a decreased ability to effectively capture and sequester CO₂. Figure 7 shows the CTE of **VICTREX™ PEEK polymers** match much closer to steel than that of PTFE¹⁵ at typical CCUS service conditions, positioning **VICTREX™ PEEK polymers** as a better suited material to achieve highly compatible sealing in CCUS applications.

CTE Compatibility (PEEK vs. PTFE) with Steel

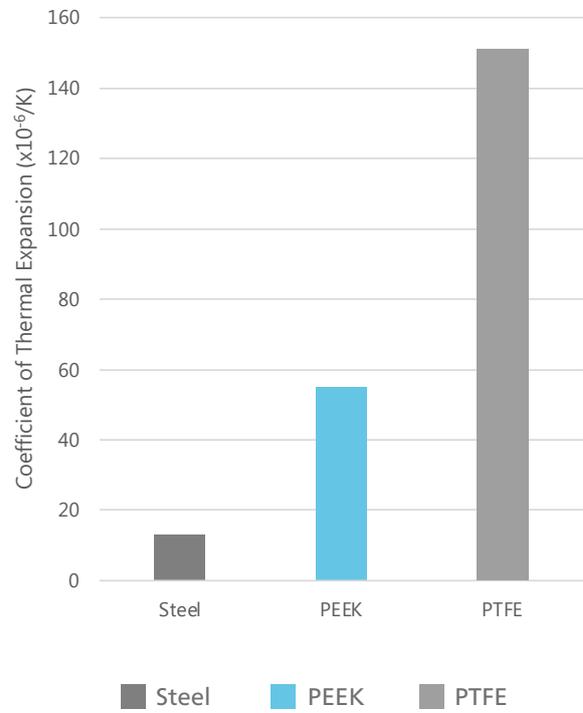


Figure 7. CTE comparison PEEK vs. PTFE at typical service conditions.

15. Hechtel K., (2014) Turning Up the Heat: Considerations for High Temperature Applications, The IAPD Magazine, 18-20.

CONCLUSIONS

High-performance **VICTREX™ PEEK polymers** can deliver multiple key engineering requirements for demanding CCUS sealing solutions, specifically in valves, seals, and compressor component applications. **VICTREX™ PEEK polymers** exhibit exceptional performance in several critical aspects of the CCUS applications, specifically:

- ▶ Low permeability to supercritical CO₂.
- ▶ Minimal dimensional change to supercritical CO₂.
- ▶ Retention of mechanical properties at a broad range of temperatures and pressures.
- ▶ Resistance to rapid gas depressurisation (RGD) events.
- ▶ High chemical resistance to CO₂, H₂CO₃ (carbonic acid) and other corrosive acids.
- ▶ Low coefficient to thermal expansion (CTE) in sealing applications.

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Victrex is open
to collaboration
to address material
challenges of the Energy
Transition. Contact us [here](#).



Victrex is a world leader in high-performance PEEK and PAEK polymer solutions. With over 40 years of experience in delivering innovative PEEK thermoplastic solutions for the Energy industry in application areas such as bearings, sealing and electrical components, Victrex understands the need for component reliability and efficiency in demanding conditions (high temperatures, high pressures, chemical corrosion).

Translation of PAEK's unique properties make it an excellent choice for valves, seals, pump, and compressor components for the CCUS infrastructure. Learn more at www.victrex.com/energy

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