RESINATE

SPECIAL EDITION

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RESINATE

Your quarterly newsletter keeping you informed about trusted products, smart solutions, and valuable updates.

NEW FOCUS ON FEP

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INTRODUCTION

Since the fortuitous discovery and later commercialization of polytetrafluoroethylene, or PTFE, in the 1940's, industry began to see the advantages of fluoropolymers. These polymer plastics are now almost synonymous with properties such as temperature and chemical resistance, abrasion protection, and generally excellent dielectric properties. After PTFE, manufacturers such as DuPont looked for other ways to expand upon commercially viable polymers containing fluorine. Work such as this lead to the fluoropolymer panorama of today. The most popular fluoropolymers generally fall into two groups: homopolymers, the result of polymerization – or combining – of identical monomers; and copolymers, polymerization incorporating two different monomers (**Fig. 1**). (Occasionally, commercially viable and useful fluoropolymers may even combine three different monomers). Fluorinated ethylene propylene, or FEP, falls into this second group. As a copolymer, FEP brings nearly all of the same preferred properties of the fluoropolymer "gold standard" PTFE but has several advantages.

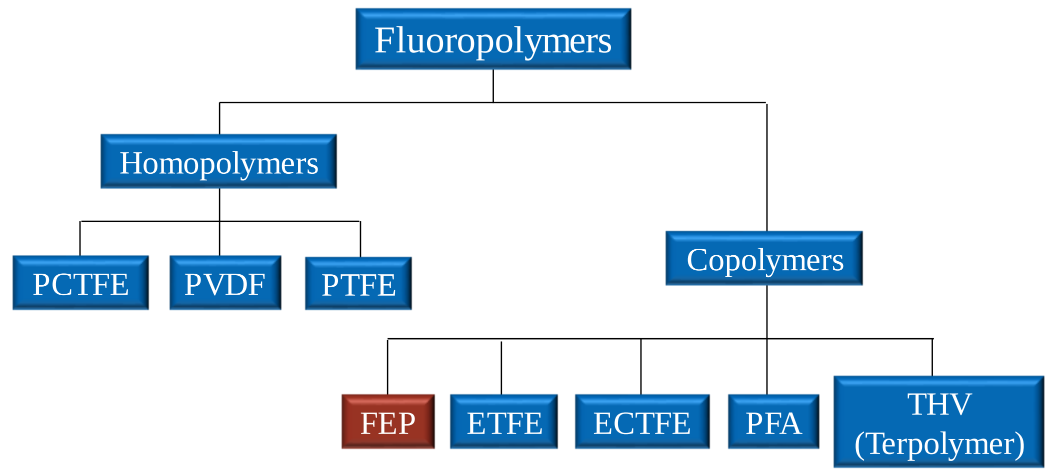

Figure 1: Landscape of popular fluoropolymers. Homopolymers are produced through the polymerization of identical monomer units. Copolymers incorporate two or more monomers to produce the final polymer material. FEP is a copolymer.

FEP SYNTHESIS AND STRUCTURE

Introduced in 1960, FEP was the first copolymer made using TFE, the monomer used to synthesize PTFE. Instead of identical TFE monomers, FEP substitutes a $–CF_3$ in place of one of the fluorine atoms of a TFE monomer changing it to hexafluoropropylene (HFP) (**Fig. 2**). Introducing the HFP monomer to PTFE reduces its ability to crystallize and reduces its melting point from 335 °C (635 °F) for PTFE to 260 °C (500 °F) for FEP. This lower melting point made FEP the first melt-processable perfluorinated polymer. An important aspect of FEP is that its monomers are not in a 1:1 ratio with HFP generally appearing at approximately 5%. Additionally, from a structural perspective, FEP is not symmetrical like PTFE, and the $–CF_3$

substituent (from HFP) may appear on either side of the polymer chain (**Fig. 3**). This randomized inclusion of $–CF_3$ limits crystallinity of FEP to generally no more than 70% compared to PTFE's crystallinity which can approach 95%. Overall, however, the similar outer sheath of unreactive fluorine atoms of both FEP and PTFE gives these fluoropolymers many similar attributes.

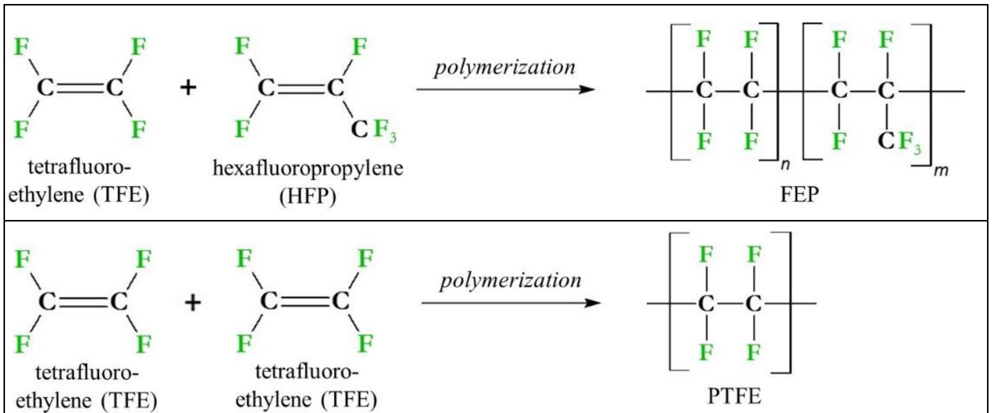

Figure 2: Synthesis of FEP (fluorinated ethylene propylene). ***Top*** FEP is made from the polymerization of tetrafluoroethylene (TFE) and hexafluoropropylene (HFP) monomers via a radical reaction. ***Bottom*** PTFE is synthesized from TFE monomers and bears a high degree of similarity to FEP. Note that TFE and HFP are not in a 1:1 ratio in FEP.

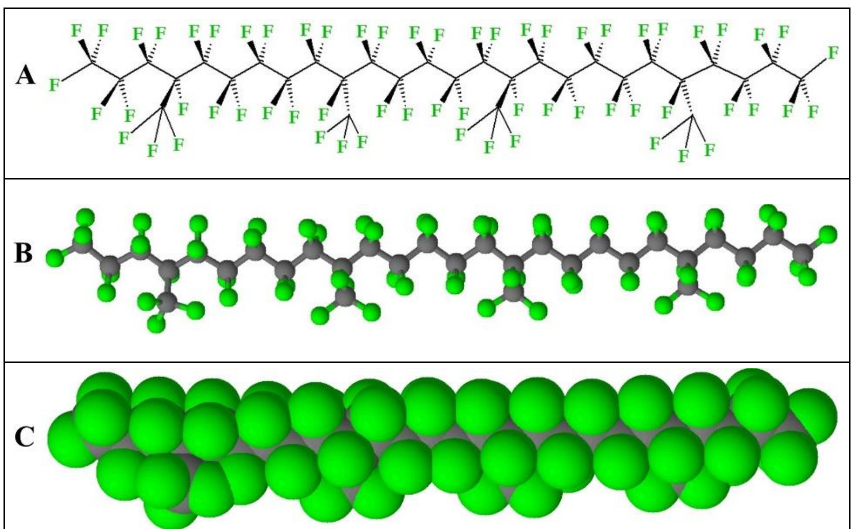

Figure 3: Structure of FEP. A) Stereo bond-line drawing, **B)** ball-and-stick model, and **C)** space-filling model of FEP. (*Shown as zig-zag depiction. Conformations are variable during melt and amorphous phases*).

PROCESSING

As a melt-processable material, FEP may be produced by most of the traditional plastics processing methods. FEP is produced in a variety of grades resulting from the particular processing method that was used. FEP is used extensively for extrusion, injection molding, coating, and impregnating of fabrics and metals, and specific grades are made directed toward these applications. Regardless of processing method, processing machinery must be appropriate for the high processing temperatures and high melt viscosities required for FEP. Molten FEP is corrosive to many metals, and corrosion resistant materials are highly recommended for parts and machinery that may come into contact with molten FEP. Nickel-based alloys, for example, are especially endorsed for FEP melt-processing.

Processing Method	Suitability
Injection molding	**Yes**
Extrusion (profiles, films, sheet, tubing, heat shrink tubing, and cable coating)	**Yes**
Blow molding	**Yes**
Compression molding	**Yes**
Impregnation and coating	**Yes**

Table 1: FEP processing. FEP's melt-processability allows it to be used with multiple different thermoplastic processing methods.

FEP PROPERTIES

PHYSICAL AND MECHANICAL

FEP possesses many of the hallmark properties so preferred for fluoropolymers. These properties largely stem from FEP's fully fluorinated structure (the carbon bearing the $-CF_3$ of HFP notwithstanding) (**Tables 1 and 2**). FEP's rigid chain structure imparts very good temperature stability and durability against wearing. FEP's strong and unreactive C–F bonds also support excellent chemical resistance against a broad spectrum of acids, solvents, and even ozone. (FEP is not recommended for uses with molten alkali metal, elemental fluorine gas, and some halogenated organic compounds). FEP is optically clear with good transmittance of both visible and UV spectrum wavelengths (UV resistant). FEP's translucence also makes it a good choice for food packaging, and it is also FDA-compliant. FEP has very low permeability to liquids, gases, and moisture which are particularly beneficial towards these latter industries. FEP's transparency is also often a deciding factor in choosing FEP over PTFE. FEP's optical characteristics and chemical resistance make it durable against weathering, and FEP has been shown to last 20 years or more when used outdoors with little to no measurable property changes. FEP is comparatively more costly among the most frequently used fluoropolymers but is suitable for use within the body. FEP is a USP Class VI-approved (biocompatible) plastic, and it is amenable to a number of sterilization protocols including gamma and e-beam irradiation and autoclaving. (FEP is not recommended for permanent implantation within the body, however). FEP's perfluorinated and unreactive nature plus its transparency place it in a unique class among fluoropolymers.

Property	Method	Value (natural polymer)
Appearance	–	**Transparent**
Density (g/cm^3)	D792	**2.12 – 2.17**
Specific Gravity	D792	**2.1 – 2.2**
Water Absorption (50% rh; %)	D570/ISO 62-1	**$\leq$ 0.01**
Refraction Index	D542	**1.34**
Limiting Oxygen Index (LOI)	D2863	**> 95**
Biocompatible	*USP Class VI	**Yes**
Chemical Resistance	–	**Excellent**
Sterilization	–	**gamma, e-beam, autoclave**

Table 2: FEP typical physical properties. FEP has many physical properties similar to PTFE with the exception of FEP's translucent appearance. (–) = not applicable. (Methods are ASTM test standards except those indicated by *).

Polymer crystallinity influences many of its mechanical properties. Crystallinity affects such things as density (molecular weight aside), hardness, brittleness, elastic properties, and flexural attributes. Crystallinity is also highly connected to traits such as glass transition temperature and melt temperature – two key factors when working with polymer plastics. Increased crystallinity, as an example, is usually accompanied by increased mechanical strength. Despite FEP's comparatively lower crystallinity, it possesses a strength similar to the more crystalline PTFE. Thus, FEP represents another option in lieu of PTFE where strength is a consideration.

Property	ASTM	Value (natural polymer)
Tensile Strength (MPa)	D638	**20 – 34**
Elongation at Break (%)	D638	**300 – 400**
Modulus Of Elasticity (MPa)	D638	**343**
Flexural Modulus (MPa)	D790	**539 – 637**
Flexural Strength	D790	**No Break**
Hardness (Shore D)	D2240	**55**
Impact Strength (23 °C)	D256	**No Break**
Coefficient of Friction	D1894	**0.04 – 0.06**

Table 3: Typical mechanical properties of FEP. Among fluoropolymers, FEP has many favorable mechanical attributes including comparable tensile strength to PTFE and a comparatively low coefficient of friction.

THERMAL

FEP demonstrates exceptional utility at high and low temperatures. FEP's reduced crystallinity compared to PTFE does result in FEP's lower melt and working temperatures of 260 °C (500 °F) and 204 °C (400 °F), respectively. On the other hand, FEP shows excellent low temperature performance down to temperatures of at least -200 °C (-328 °F). In this same vein, FEP has high heat performance, and it is UL 94-0 rated for flammability. This means that burning FEP will extinguish itself within ten seconds and does not produce flaming drips – a critical feature for such applications as the aerospace industry. When burning, the heat of combustion for FEP is quite low with minimal smoke and minimally corrosive decomposition gases. A contributing feature of FEP's burning behavior is that it has a very high limiting oxygen index (LOI) of >95. For perspective, this means that there must be at least 95% oxygen in the air to sustain FEP combustion. (Note that normal air contains only about 21% oxygen). These factors make FEP particularly favorable for applications where the consequences of burning are of paramount consideration.

Property	Method	Value (natural polymer)
Thermal Conductivity (W/m-K)	D433 / ISO 22007-4 / C-177	**0.25**
Maximum Service Temperature (°C)	UL 746	**200**
Minimum Service Temperature (°C)	UL 746	**-200 to -240**
Melting Point (°C)	D4591 / D3418/ ISO 12086 / DOW Method	**260 to 275**
Glass Transition Temperature (°C)	E1356 (DSC) or E1545 (mechanical)	**80**
Decomposition Temp (°C)	E1131	**380 to 430**
Coefficient of Thermal Expansion, linear (µm/m-°C)	D696	**83 – 112**
Flammability Rating (UL 94)	D2863	**V-0**

Table 4: FEP thermal properties. FEP retains many of its preferred properties throughout a temperature range spanning more than 450 C°. (Methods are ASTM test standards except where indicated).

ELECTRICAL

Among the most commonly used fluoropolymers, FEP also has very good dielectric traits. FEP's many strongly polar C−F bonds give FEP exceptional insulating properties including a very low dielectric constant across a broad range of frequencies. This attribute makes FEP especially adapted as a heat shrink for electronic insulation such as for high speed data transmission cables. As an added benefit of FEP used in this way is its low coefficient of friction. When covered with FEP, the smooth surface of FEP facilitates the laying of cables, covered wires, and wiring bundles into confined spaces. FEP insulation is also used for thermocouples and other high temperature sensing applications because of its heat tolerance. These electrical applications have made FEP highly prominent in these associated industries.

Property	Method	Value (natural polymer)
Dielectric Constant (1 MHz)	D150	**2.0 – 2.1**
Dielectric Strength (V/mil)	D149 / IEC 60243-1	**500 – 2023**
Volume Resistivity (Ω–cm)	D257 / IEC 60096	**< 1 × 10^{18}**

Table 5: FEP electrical properties. The many polar C–F bonds of FEP give it exceptionally beneficial electrical properties including low dielectric constant. (Methods are ASTM except where indicated).

FINISHING

FEP's melt-processability lends itself to many different forms and products. As a thermoplastic polymer, FEP is available extruded as rods, tubes, heat shrinks, and sheets and films. Transparent FEP films can be heat sealed, vacuum formed, laminated, or thermoformed. These films can even be used as a hot-melt adhesive. FEP extrusions and formed parts can be machined using conventional tools. Diamond and carbide tipped tooling produce an excellent finish for FEP parts for prototype and small production runs. Slow speeds and feeds are recommended for FEP plastics to minimize tooling heat. FEP is also available pigmented. Almost all colors are available for use with FEP, but these are generally limited to inorganic pigments because of the high heat necessary FEP processing. Considering the diverse nature of FEP extrusions and other products, an FEP product can be created for almost any application environment.

APPLICATIONS

From coatings to military specification grade heat shrinks, FEP has been commercialized for wide range of industry applications. As a close cousin to PTFE, FEP has many similar uses as PTFE. FEP's primary advantages, however, are that it is melt-processable and more transparent than PTFE. These traits allow FEP to reach certain niche usage environments that PTFE cannot. FEP heat shrink has a lower recovery temperature than PTFE, a key deciding factor when using this material such as for catheter jackets. Regardless of application, FEP is highly adaptable and easily produced in a variety of forms.

Application or Industry	Key Benefits
Semiconductor, pharmaceutical	Chemical resistance, purity
Protective linings (piping, tubing)	Chemical resistance
Wire and cable insulation • computers, electronics • high-speed data transmission	Dielectrics Low coefficient of friction
Films (as release surfaces)	Non-stick
Roll covers	Non-stick, surface protection
Glazing film (solar energy collectors)	Transparency
Environmental monitoring	Purity, inertness
Heat shrink	Encapsulation, protection (AMS-DTL-23053™/11 compliant)
Catheter jackets	Weldable, thermoformable

Table 6: Survey of FEP applications. FEP's properties give it the versatility to function in a wide range of industries.

SUMMARY

With its development in the years following the discovery of PTFE, FEP represented a significant step towards commercialization of fluoropolymers on a much larger scale. As a melt-processable fluoropolymer, FEP was the first to incorporated TFE monomers. With its high degree of similarity to PTFE, FEP and PTFE share many common attributes including chemical resistance, dielectric properties, and flammability. On the other hand, FEP's transparency, thermoformability (bondability), and comparatively lower hardness allow FEP to succeed in environments that are not appropriate for PTFE (**Table 7**). Available in a variety of forms including extruded tubing, heat shrinks, rods, sheets, and films, FEP is found nearly everywhere. Indeed, FEP's distinguishing properties have made this benchmark fluoropolymer plastic highly popular in industries spanning medical, aerospace, automotive, energy, and more.

Advantages / Benefits (+)	Limitations (–)
• Temperature stability • Chemical resistance • Weather resistance • Low coefficient of friction • Toughness • Dielectric properties • Optically clear, translucent	• Lower mechanical strength • Lower service temperature than PTFE • Requires corrosion-resistant processing equipment • High comparative cost

Table 7: FEP advantages and limitations. FEP excels in many areas over other fluoropolymers. FEP however, like most fluoropolymers, cannot fulfill all industrial thermoplastic application niches.

ABOUT ZEUS

Zeus is the world's leader in polymer extrusion technologies. For over 50 years, Zeus has been serving the medical, aerospace, energy exploration, automotive, and fiber optics industries. Headquartered in Orangeburg, South Carolina, Zeus employs approximately 1,500 people worldwide and operates multiple facilities in North America and internationally. You can find us at www.zeusinc.com.

CONTACT US

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