TegraCore™

TegraCore™ PPSU Structural Foams

Design & Processing Guide

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TegraCore™ PPSU Structural Foams

TegraCore™ R-1050 Foam used as a structural foam core prevents uncontrolled crack propagation upon impact and withstands prolonged exposure to water, chemicals, and temperatures from – 40 to 180 °C (– 40 to 356 °F). This innovative technology is based on Solvay's Radel® PPSU polymer, a super-tough thermoplastic used for over 25 years in structural and decorative aircraft interior components, among other high-performance applications.

TegraCore™ R-1050 foam, referred to hereafter as TegraCore™ PPSU foam, is manufactured using a proprietary extrusion technology. Its compressive strength at a nominal density of 50 kg/m^3 (3.12 lb/ft^3) is 0.63 MPa (91 psi) at room temperature. PPSU foam can be thermoformed between 210 to 220 °C (410 to 428 °F) with 2.3 MPa (334 psi) of pressure. For additional information about PPSU foam, please reference our technical bulletin entitled *TegraCore™ PPSU Foam for Aircraft.*

Key features

- Stable mechanical properties up to 180 °C (356 °F)
- Minimal moisture and resin pickup during processing
- Resistance to Skydrol® and other aerospace fluids
- Excellent fire, smoke and toxicity (FST) performance
- Closed cell morphology eliminates edge filling (vs. honeycomb)
- Minimal spring back or shrinkage
- Thermoformability under strains up to 25 %
- Ease of machining, bonding, repairing and recycling
- Not friable or brittle and generates negligible dust
- Improved processing vs. other high-performance foams

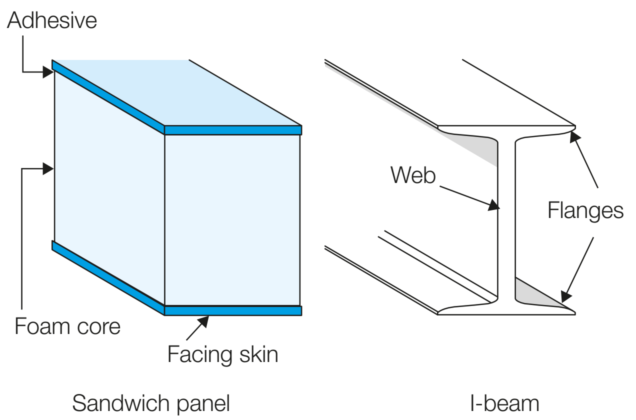
Sandwich Panel Design Considerations

I-Beam Analogy

Benefits of the core/rigid thin-skin sandwich panel construction can be described by drawing an analogy to an I-beam construction (Figure 1) where the flanges of an I-beam provide resistance to bending stresses from an imposed load. The web of the I-beam provides resistance to shear loads, thereby increasing the stiffness and resistance to deformation of the I-beam. The ability to deliver load-bearing performance makes the I-beam an effective and efficient structural element.

In an analogous fashion, the composite facesheets in a core/rigid thin-skin sandwich panel construction resist the bending stresses from an imposed load, similar to the flanges in the I-beam. The core material provides resistance to shear loads and increases system stiffness, similar to the web in the I-beam. The continuous support provided by the core material in a sandwich laminate construction is an improvement over the more limited benefit the web material provides in the I-beam, thereby offering more isotropic behavior than the I-beam. These mechanical improvements add minimal weight to the system.

Figure 1: Sandwich panel construction compared to I-beam construction



Design Guidelines for Load-bearing Panel Construction

The basic concepts used to design sandwich laminate composite parts are detailed in several publications, including:

- Handbook of Composites, ed. by George Lubin, Van Nostrand Reinhold, New York, 1982, pp. 557 - 601.
- Handbook of Sandwich Construction, ed. D. Zenkert, Engineering Materials Advisory Services Ltd. (EMAS), 1997.

There are several important elements to consider that can impact the performance of sandwiches made from TegraCore™ PPSU foam.

Key considerations

- Define the imposed loads and required stiffness of the composite laminate as well as the related thermal and environmental requirements.
- Define the type of sandwich construction and materials to be used:
  - Construction of composite face sheets (type of reinforcement, matrix resin, geometry of lay-up, etc.) and associated material properties.
  - Core material for sandwich (foam, honeycomb, balsa, etc.), thickness and associated material properties.
  - Potential adhesion system used to bond the core to the facesheets (matrix of facing may provide sufficient adhesion).
- Identify important boundary conditions as well as physical and environmental constraints for the composite part to ensure they have been addressed in the design process.
- Conduct optimization calculations to achieve the desired performance for the composite part.
- Note that TegraCore™ PPSU foam can be used with or without skins. Skins reinforced with carbon fiber or glass fiber can be used, as well as unfilled thermoplastic or epoxy skins. Unskinned foams are suitable for low impact applications, such as ducting.

Structural Comparison Using FEA

A simple composite can be examined using Finite Element Analysis (FEA) techniques to compare the deflection of a sandwich construction with a TegraCore™ PPSU foam core and a Nomex® Honeycomb core of the same thickness.

The skins are assumed to be made of 0.5-mm (0.02-inch) thick aluminum with a 25.4-mm (1.0-inch) thick core. A beam measuring 2 meters (6.6 ft) long and 0.5 meters (1.6 ft) wide is clamped at both ends. A central line load is then applied in the middle of the beam, producing a total force of 1,500 N (337 lbf).

The material properties used for the FEA evaluation are shown in Table 1. An elastic modulus of 70,000 N/mm^2 (10 × 10^6 psi) was used for the aluminum skin.

Table 1: FEA material properties at room temperature

Variable	Unit	TegraCore™ PPSU Foam	Nomex® Honeycomb
Compression modulus	N/mm^2	25	25
Poisson ratio		0.39	0.30
Shear modulus			
Normal to transverse direction	N/mm^2	9	1
Normal to direction of applied load	N/mm^2	9	30
Normal to ribbon direction	N/mm^2	9	30
Bulk density	kg/m^3	50	48

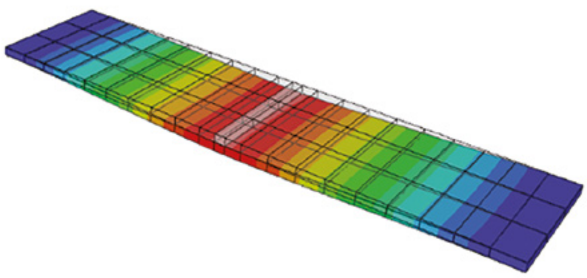
FEA model

A half-beam was modeled to conserve resources. The left side was clamped and the middle edge received symmetry boundary conditions. A line load equivalent to 1,500 N (337 lbf) was applied to the middle edge. Composite shell elements were used and the different materials and thickness of the composite beam were specified as layers of the shell elements.

FEA results

As seen in Figure 2, the computed deflection contours show that the maximum displacement is in the middle section of the beam, as expected. The maximum displacement was 14.9 mm (0.59 inch) with the TegraCore™ PPSU foam core and 11.4 mm (0.45 inch) with the Nomex® Honeycomb core. Thus, for the case of equal skin and core material thicknesses, the TegraCore™ PPSU foam core has a 21 % greater deflection than the same thickness of the Nomex® Honeycomb core. In order to achieve the same deflection as the Nomex® Honeycomb, the PPSU foam core thickness would need to be increased from 25.4 to 31.0 mm (1.0 to 1.2 inch).

Figure 2: FEA simulation of deflection under a load for sandwich panel composite with a TegraCore™ PPSU Foam core



Pre-fabrication

The following are examples of common mechanical techniques that can be used to prepare TegraCore™ PPSU foam for the fabrication of cores and structural components:

- High-pressure water jet cutting
- Sharp knife cutting
- Belt or band sawing
- Jigsaw and vibrational cutters
- Routing
- Drilling with a simple metal drill
- Skiving to provide thin-gauge foam (using a belt knife) with a minimum thickness of 1 mm (0.04 inch)
- Hand sanding using orbital, belt or drum sanders with grit ranging from #80 to #300
- Welding (hot-knife technology)

Cutting with a high-pressure water jet eliminates the localized stress and deformation that can occur with other methods. For a 15-mm (0.6-inch) thick panel, suitable cutting can be achieved using a water jet cutting machine with a 0.8-mm (0.03-inch) diameter nozzle, operating at a water pressure of 3,000 bar (43,500 psi) and speeds up to 2 m/min (6.6 ft/min). No suspended abrasives are required.

Welding PPSU Foam Panels

TegraCore™ PPSU foam can be easily welded by means of hot-knife technology using the following guidelines:

- Knife temperature ranges between 300 to 330 °C (572 to 626 °F)
- Special coatings are required to avoid sticking issues
- Excellent strength can be achieved using optimal welding conditions (Figures 3 and 4)
- Note that stiffness increases slightly along the weld line, which is typically < 1 mm (0.04 inch) thick.
- Weld bead is very small and can be removed with a router

Figure 3: Weld strength of butt-welded TegraCore™ PPSU foam

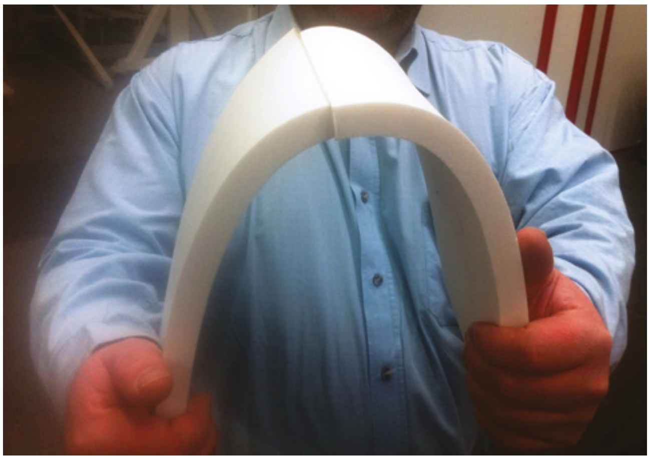
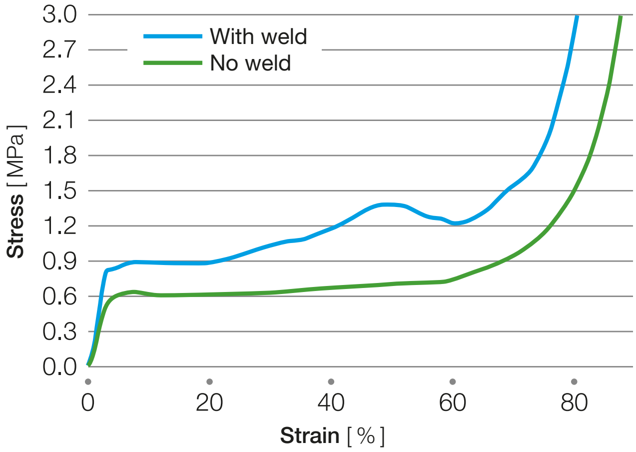


Figure 4: Compressive strength of TegraCore™ PPSU foam with and without a butt weld*



** Measured on 30 x 30 x 15 mm (1.2 x 1.2 x 0.6 inch) test samples at 20 °C (68 °F).*

Adjacent PPSU foam panels can be joined using the proper selection of butt welding equipment. Hot-knife/contact welding of two foam pieces requires a specially-coated hot blade that can operate at 320 °C (608 °F). The bonding pressure should be well below the compressive strength of the foam, which is less than 0.6 MPa (87 psi). Note that while the welding joint makes the PPSU foam stiffer and stronger, it can also add complexity during thermoforming, especially if elongation or bending of the weld should take place.

Bonding PPSU Foam Panels

PPSU foam pieces can be joined using conventional adhesives, which may have sophisticated and proprietary compositions. Manufacturer recommendations should be followed for temperatures and pressures used during application and cure.

Several things should be considered when selecting an adhesive, such as the mechanical, thermal, and environmental requirements of the end-use application. High-temperature applications need adhesives that are able to withstand prolonged exposure to high temperatures. The bonding strength must withstand stresses imposed on the finished part, and the adhesive must tolerate chemicals found in the end-use environment.

Chemical compatibility of the substrate and foam must also be considered. Adequate adhesion must be achieved without solvation or degradation of the foam or substrate. Curing and end-use temperatures must be compatible with PPSU foam as well as any substrate or surface to which it will be bonded. When bonding PPSU foam to PPSU foam, several adhesives can provide bond strengths in excess of the tensile strength of the foam itself.

Pressures greater than 0.14 bar (2 psi) are required to achieve a good bond using adhesives.

General classes of suitable adhesives to adhere PPSU foam to surface layers include but are not limited to the following:

Suitable adhesive classes

- Epoxies
- Phenolics
- Polyurethanes
- Polyesters
- Vinyls
- Acrylics

Certain classes of adhesives and adhesive precursors should be avoided as they can cause solvation of the PPSU foam. These include but are not limited to the following:

Adhesive classes to avoid

- Cyanoacrylates
- Methylmethacrylates
- Solvents in formulations that are not compatible with PPSU (e.g., elevated concentrations of ketones and chlorinated hydrocarbons
- Select amine hardeners/curing agents, as in RTM6

Commercial adhesives that have been evaluated and show acceptable adhesion are listed below.

Liquid adhesives (one-part and two-part)

- 3M Scotch-Weld™
  - 9323 A/B, 9323-2 A/B
  - 1099
  - DP 8005
  - DP 8010
  - DP 125
  - DP 460
  - DP 490
- 3M EC-2216 B/A (BMS5-92)
- 3M EC-3532 B/A (BMS5-105)
- Huntsman Araldite® AV138 and hardener HV998
- Huntsman Araldite® 1570 A/B
- Lord® 7545 A/B
- Lord® 7542 A/B
- Henkel Hysol® 9620 (BAC5-101)

Film and web adhesives

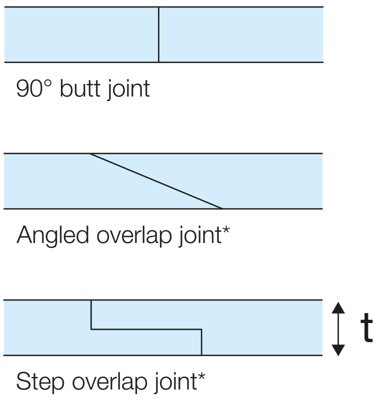
- 3M Scotch-Weld™ AF 163-2K (BMS5-101)
- 3M Scotch-Weld™ AF 163-3M (BMS5-101)
- Bostik PE-120-30
- Bostik Sharnet® 4275 FR

Edge Joining PPSU Foam Panels

PPSU foam panels are often joined to expand the length and width of the foam panel. The ability to customize the size and shape of foam panels may benefit certain applications. Note that when using thermoset skins on the PPSU foam core, the excess skin resin can also bond foam panels together.

In lateral joints, design and adhesive selection are important. The type of joint used depends on how stresses or loads will be applied. Maximizing the joint surface parallel to the direction in which the load or tension are applied will maximize the strength of the joint. Adhesive selection can also be driven by joint design, as complex joints may not allow the use of web or film adhesives. Several joint options are shown in Figure 5.

Figure 5: Variations of lateral foam joints



The joint overlap should be three times the thickness (t)

In vertical joints like the 90° butt joint, care should be taken to finish the panel edges so both surfaces match. Panels should be laid up without trapping air between the panels, as air pockets can lead to performance deficiencies. Adhesives should be applied in thicknesses recommended by the manufacturer and then cured. This is most easily done using a wet adhesive, as films and webs that require heat to cure can require long processing times due to the insulating nature of the foam. Removable paper tape can be used to fixate the panels during the assembly process.

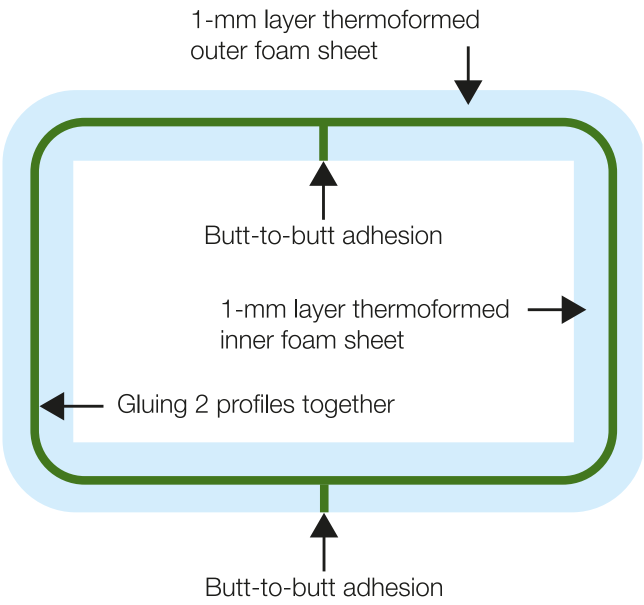
Surface Joining PPSU Foam Panels

The surface of foam panels can be joined in addition to joining the panel edges in order to increase panel thickness. An example of this is a foam conduit used for cable encapsulation or a ventilation duct. Surface joining can also be used for thermoformed structures by using a spray adhesive like those used to make wood laminates (e.g., 3M Scotch-Weld™ 1099).

Joining can also be done using thermoset film or web adhesives, as well as lower temperature thermoplastic films. Heat-activated web or film adhesives can be used in situ while forming the foam, provided that it can be activated at the appropriate forming temperature.

A schematic of a conduit prepared using a combination of edge and surface joining is shown in Figure 6. The part can be assembled and formed at 210 to 220 °C (410 to 428 °F); the interfaces must reach this temperature to maximize adhesion. Higher bonding temperatures are not recommended as foam deformation can occur. Thermoset film and web adhesives should be used as directed by the manufacturer.

Figure 6: Conduit prepared using edge and surface joining



Design Guidelines for Thermoforming

Change in mechanical properties caused by change in temperature allows materials to be formed into a desired shape. As shown in Figure 7, foam strength decreases as temperature increases. Data points indicate that PPSU foam should be thermoformed between 205 to 230 °C (401 to 446 °F). Experimental stress-strain curves (tensile and compression) in this temperature range are shown in Figure 8. These results were used to conduct Finite Element Analysis (FEA) calculations in order to model vacuum-bag thermoforming of PPSU foam. In these calculations, the uniform temperature of the foam was considered to be 205 °C (401 °F).

Figure 7: Compressive strength at 10 % strain for TegraCore™ PPSU foam at various temperatures

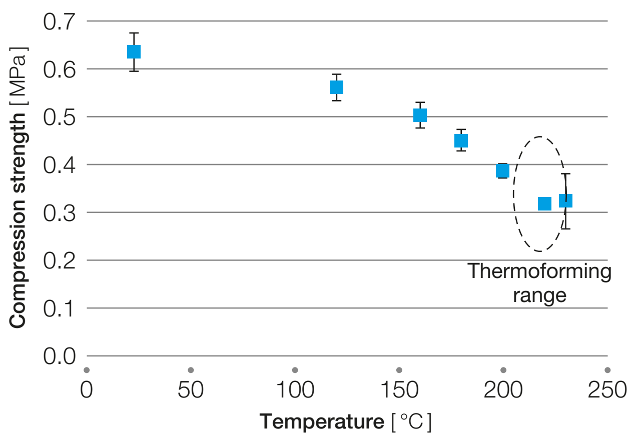
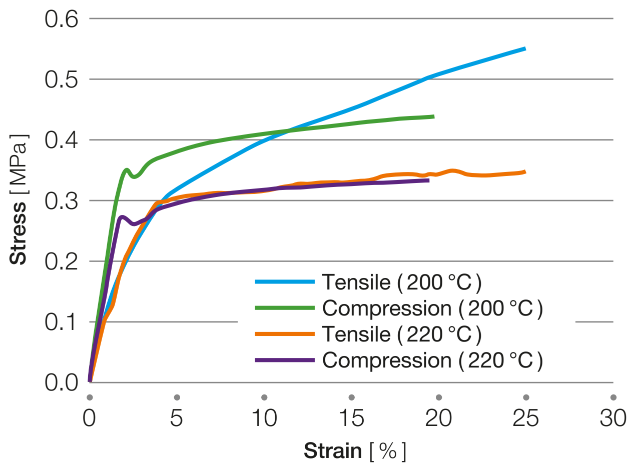
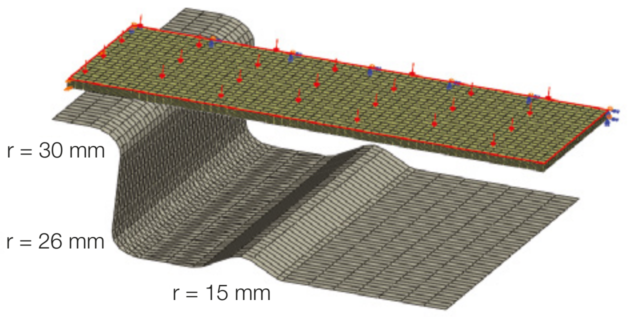


Figure 8: Experimental stress-strain curves for TegraCore™ PPSU foam at 200 °C and 220 °C



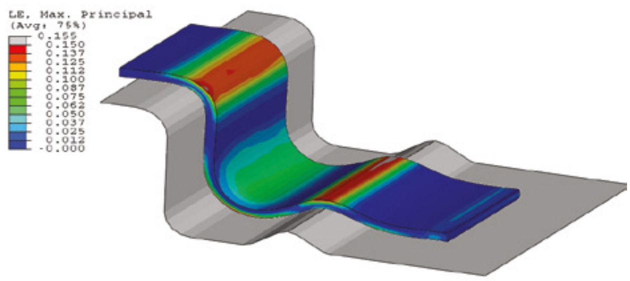
Based on the TegraCore™ PPSU foam stress-strain curve, a maximum pressure of 1 bar (0.1 MPa) is applied to the foam panel in this simulation. The stress-strain curve provides a simple macroscopic failure criterion at about 20 % compressive strain and about 25 % tensile strain. Strains imposed at or above 25 % risk tearing and causing the foam to collapse. Figure 9 shows an example of such an FEA calculation. Figure 10 shows the corresponding results with strain distribution shown.

Figure 9: FEA simulation of thermoforming a PPSU foam panel*



**r = radius of curvature*

Figure 10: FEA simulation of thermoforming PPSU foam with strain distribution shown



Key considerations for thermoforming PPSU foam

- Forming occurs as a result of the reduction in modulus and the increase in ductility that occurs near the heat deflection temperature without exceeding the glass transition temperature of 220 °C (428 °F).
- Foam surface temperature must be maintained to draw without cracking.
- Temperature controlled tooling or insulation for the foam is required.
- Gentle pulling of vacuum is required.
- Cooling in place will limit spring back; spring back is not observed at sufficient mold temperatures.
- Foam shrinkage is < 1 % below 200 °C (392 °F) and a uniform thickness is maintained.
- Molding shapes with a smaller radius of curvature and foam boards with a higher thickness will generally result in larger strains during matched molding, according to the equation $\gamma = t/(2r_c)$, where t is the thickness of the board, r_c is the radius of curvature of the mold, and γ is the resulting strain. Strains of 25 % or greater may damage the part, while strains that are too low (i.e., in the linear regime of the stress-strain curve) may result in spring back.
- Depending on part geometry, cycle times are approximately 2–3 minutes for matched die molding, 10 minutes for open tool vacuum forming, and 30 to 60 minutes for vacuum-bag assisted thermoforming.
- Substantial loss of thickness may occur during matched mold processing at temperatures ≥ 215 °C (419 °F) in combination with pressures ≥ 5 bar (0.5 MPa).
- Some degree of foam shrinkage is observed at temperatures > 210 °C (410 °F).

Thermoforming

TegraCore™ R-1050 Foam can be readily formed into 3-D shapes using a variety of thermoforming methods. The processing window depends on the thickness of the original sheet, the stretching applied, the geometry of the final part, and the thermoforming method used. Depending on the method used, foam panel temperatures ranging from 205 to 230 °C (401 to 446 °F) and processing times ranging from a few minutes to 1 hour are typical.

Thermal properties must be considered during thermoforming. Compared to PPSU polymer in its solid state, PPSU foam has about 10 times lower thermal conductivity and about 20 times lower density, resulting in a thermal diffusivity for PPSU foam that is twice that of solid PPSU polymer.

PPSU foam heats and cools significantly faster than a similar article made of solid PPSU polymer. Typical heating behavior of PPSU foam, shown in Figure 11, is based on internal foam panel temperatures plotted over time during oven heating at 215 °C (419 °F). The free cooling behavior of a PPSU foam panel having a thickness of 21 mm (0.8 inch) is shown in Figure 12. Because the foam cools so quickly, it is necessary to insulate it or to form it on heated tooling.

Figure 11: Heating times for varying thicknesses of TegraCore™ PPSU foam panels

Measured in 215 °C oven with thermocouple placed at the core of the panel

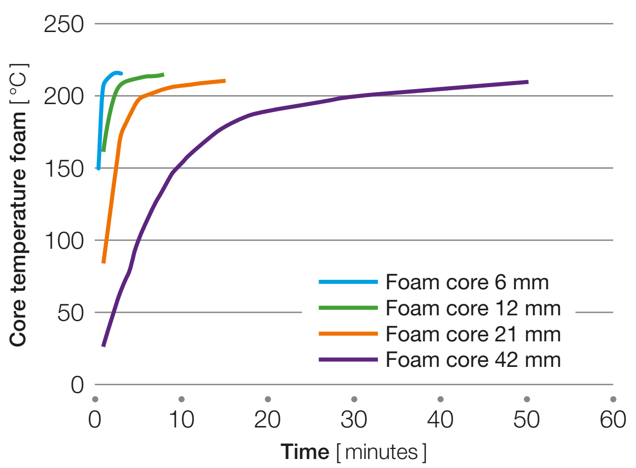
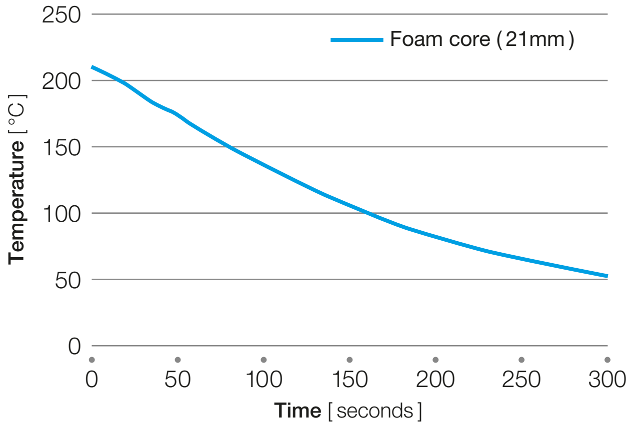


Figure 12: Cooling time in air of TegraCore™ PPSU foam panel*



** After 15 seconds, core temperature drops from 215 to 200 °C (419 to 392 °F).*

The thermoforming method used will depend on desired part geometry, quantity of parts produced, available equipment, and operator expertise. Common methods to process TegraCore™ PPSU foam are discussed below.

- **Vacuum bag-assisted thermoforming:** Tool cost can be very low. Because it's a manually-intensive process, cycle times are longer (30 to 60 minutes). Cycle times can be reduced by using pre-heating systems or heated tools.
- **Open tool vacuum forming in an oven:** This method can offer an attractive balance between up-front investment and process cycle time. However, there are limitations regarding possible geometries of the finished part. Material handling is straightforward and cycle times are around 10 minutes.
- **Thermoforming machines with matched molding tools:** Thermoforming machines can produce large quantities of identical shapes with cycle times as fast as 2 to 3 minutes. Higher equipment and tooling costs along with the time and expertise needed to start up this process can be prohibitive.

Vacuum Bag-assisted Thermoforming

Tool materials consisting of aluminum, deep-drawn steel, or high-temperature carbon fiber or glass fiber composites (e.g., D-Form) are suitable for thermoforming PPSU foam by vacuum bagging. Consumables rated up to 230 °C (446 °F) are generally required. Examples include polyamide 6 vacuum bags (Solvay A6200), polyester breathers (Econoweave® 44), either polytetrafluoroethylene (PTFE) or perfluoro methyl alkoxy polymer (MFA) vacuum tubing, and a variety of high-temperature sealant tapes.

Typically, the foam is first fixated to the tool at room temperature by bending the foam over the tool; vacuum is then applied. It is recommended to bend the sample by hand before applying the vacuum to ensure that the bag is not drawn between the tool and the foam.

When cold bending foam, follow the guidelines outlined in Table 2. For a given part radius of curvature, if the thickness of the foam board is less than the value in the right-hand column, the foam can be bent manually over the tool prior to adding vacuum. Thicker foam boards should be bent only after heating in the oven in order to avoid breakage.

Table 2: Maximum foam board thickness for manual cold bending at different radii of curvature.

Part Radius of Curvature [mm (inch)]	Maximum Thickness [mm (inch)]
40 (1.6)	15 (0.6)
20 (0.8)	12 (0.5)
10 (0.4)	8 (0.3)

The tool and foam are heated in an oven while vacuum is applied. Depending on the heating rate of the tooling, which is usually longer than that of the foam, the cycle time can range from 30 to 60 minutes at 210 °C (410 °F).

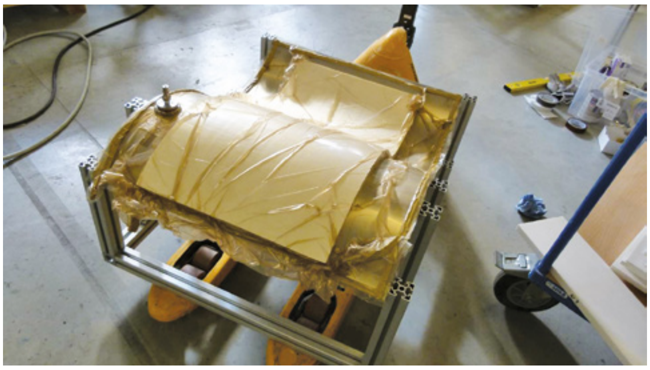
Aluminum tools without additional electrical heating should be minimized to a 5-mm (0.2-inch) tool thickness to reduce heating time. Additional electrical tool heating will reduce the heating time. After removing from the oven, the tool and foam should cool under vacuum at room temperature for 10 to 15 minutes before demolding.

Figure 13 shows the steps for thermoforming PPSU foam into an L-shaped part by vacuum bagging. Figure 14 shows a vacuum bag thermoformed S-shaped part.

PPSU foam boards with thicknesses ranging from 8 to 15 mm (0.3 to 0.6 inch) have been tested for vacuum bag thermoforming using a bowl-shaped tool. For this process, the oven is set to 225 °C (437 °F) and no vacuum is applied for 10 to 15 minutes, allowing the foam temperature to reach 215 °C (419 °F). Vacuum is applied in the vacuum bag to form the foam into the bowl shape, and then the part is cooled under vacuum for 10 minutes. Special care must to be taken to avoid drawing the vacuum bag between the tool and foam board.

Figure 13: Vacuum bag thermoforming an L-shaped part from TegraCore™ PPSU Foam on an aluminum tool

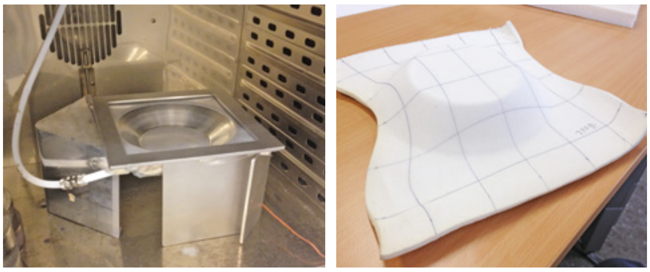
Figure 14: Vacuum bag thermoforming an S-shaped part from TegraCore™ PPSU foam (600 × 900 mm/2.0 × 3.0 ft)



Open Vacuum Forming in an Oven

Bowl-shaped articles have also been formed from TegraCore™ PPSU foam boards with thicknesses from 6 to 15 mm (0.2 to 0.6 inch) using open vacuum thermoforming in an oven (Figure 15). For this process, a vacuum is applied through 1-mm (0.04-inch) diameter holes in the tool. A flat flange is required for loosely fixating the foam on the tool and minimizing vacuum leakage. Weights, clamps or toggle clamps can be applied to fix the flat edges of the part and to ensure a tight connection between the foam and the tool. The assembly is heated in an oven for about 10 minutes to 220 to 230 °C (428 to 446 °F). Vacuum is then applied on the cavity for 20 seconds and the foam is drawn into the cavity. Upon releasing the vacuum, the thermoformed part can be demolded from the tool at the processing temperature and allowed to cool.

Figure 15: Open vacuum thermoforming bowl-shaped tool and TegraCore™ PPSU Foam part



Matched Mold Thermoforming Machine

Matched mold processing techniques can be used to form PPSU foam parts with small details. Foam board heating must be precisely controlled to avoid top-to-bottom temperature gradients, which will cause the foam to bend. Because of this, aluminum matched mold tooling with oil tool heating or electrical cartridges is recommended.

A Geiss machine with a halogen heating system on the upper and lower sides was used to match mold thermoform TegraCore™ R-1050 foam using the following procedure:

- Pre-heat equipment to improve temperature control.
- Lower side requires more heating than the upper side due to the protective glass typically installed on the lower side. A power distribution ratio of 40 % (upper) to 70 % (lower) is a good starting point.
- Target a foam board temperature of 210 to 220 °C (410 to 428 °F).
- 50-second ramp up followed by a 50-second hold is recommended for heating a 12-mm (0.5-inch) thick PPSU foam board.
- Tool temperatures of 180 to 200 °C (356 to 392 °F) and pressures up to 2.3 MPa (334 psi) are generally adequate for proper molding. Note that strong compression can lead to localized softening of the structure.
- Care should be exercised to prevent the foam from bending (due to temperature gradients) or sagging (due to excessive softening).
- Assembly should be cooled in the tool for 50 seconds under pressure before handling.

Sandwich Panel Assembly

PPSU foam is often used as a core material in laminates or sandwiches. Simple laminates can be prepared either by thermal bonding or by using conventional wet, film or web adhesives. Laminates have been prepared by vacuum forming, pressing, and other methods. Skins can be made from consolidated thermoplastic prepregs or from thermoset prepregs. When using thermoset laminates (phenolic or epoxy based) the matrix resin acts as an adhesive. In this case, thermal curing under vacuum bag, press, or autoclave will glue the skin to the foam core. Using thermoplastic skins typically requires the use of an adhesive layer.

When forming laminates, final application strength, fabrication method, flammability, and environmental requirements must be taken into account. Skins should be chosen such that parts can be fabricated in an efficient manner and meet all end-use requirements.

Laminates Made Using Thermoplastic Skins

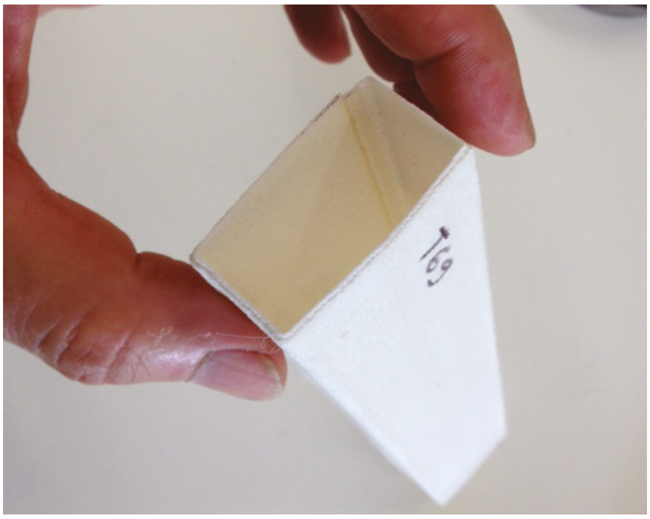
TegraCore™ PPSU foam has been successfully laminated with consolidated polyetherimide (PEI)-based and polycarbonate (PC)-based Cetex™ glass reinforced prepregs, consolidated carbon fiber reinforced polyethersulfone (PESU) prepregs and Aonix UltraMaterials™ prepreg.

Thermal bonding for laminate and sandwich assembly can be accomplished using lower temperature polymers, such as thin polymer films made from PC, acrylonitrile butadiene styrene (ABS), ethylene vinyl acetate (EVA), or polysulfone (PSU). PSU films with thicknesses of 80 to 250 microns have been used for bonding PPSU foam to itself and for bonding PPSU foam to Radel® PPSU sheet and Radel® PPSU-based prepreg with glass and carbon reinforcement.

This process can be performed under vacuum bag in an oven or under a hot press. In optimum processing conditions, the assembly is heated to 210 to 215 °C (410 to 419 °F) under a pressure of 0.1 to 0.3 bar (1.5 to 4.4 psi) for 10 minutes. The assembly is then cooled under pressure to < 190 °C (374 °F) before handling. This method can be used for the fabrication of flat panels, and the processing temperatures allow for thermoforming and lamination in a single step (Figures 16 and 17). Udel® PSU film is supplied by Solvay Ajedium™ Films.

Figure 16: TegraCore™ PPSU foam core with a 15-mm (0.6-inch) thickness shaped over a 40-mm (1.6-inch) radius jig and laminated to PPSU carbon fiber prepreg using Udel® PSU film in a single process step

Figure 17: TegraCore™ PPSU foam board with a 1-mm (0.04-inch) thickness shaped into a rectangular pipe using Udel® PSU film as a tie layer



Commercial web adhesives made from polyester, such as those from Bostik, can also be used to create robust sandwiches. The success of these and the previously described lower-temperature adhesives depends strongly on the chemistry of the substrate to which the foam will be bonded. Often PPSU foam can be bonded using these adhesives at temperatures lower than those that would soften the foam. Temperatures ranging from 150 to 180 °C (302 to 356 °F) can be used to bond these materials with minimal effect on the properties of the foam core. Higher temperatures may cause severe deformation to the foam, while lower temperatures may reduce adhesion. Care should be taken to know the softening temperature of the polymer film. Manufacturer's instructions for web adhesives should be followed carefully.

Lamination Using Phenolic-based Glass or Carbon-mat Prepregs

TegraCore™ PPSU foam can be successfully laminated to phenolic-based prepregs due to the foam's smooth surface, small cell size and its favorable compressive properties at elevated temperatures. Depending on part geometry and foam thickness, the PPSU foam may need to be pre-shaped (see Thermoforming section) or it can be cold formed together with the prepreg.

The Safety Data Sheets for the prepregs should be reviewed carefully to ensure safe working conditions when handling phenolic prepregs. Plastic gloves should be used and the workplace should be well ventilated. Steps for laminating TegraCore™ PPSU foam with phenolic prepregs are detailed below.

- Remove a large section of cooled prepreg from the freezer and condition to room temperature, which may take several hours.
- Cut the prepreg into the correct size using scissors or a knife.
- Remove one side of the protective film and drape the prepreg over the PPSU foam board from one end to the other. A plastic plate can be used to gently press the prepreg on to the foam surface. For more complicated structures, a sharp PTFE chisel-shaped tool can be used to press the prepreg into the details of the foam core.
- Remove the top protective layer.
- If needed, a second layer of prepreg can be placed over the first prepreg surface. Depending on the requirements, the second layer can be oriented in the same direction as the first layer or at a relative angle of 90° or 45°.
- Cover the wet prepreg with an ETFE release film (with or without perforation).
- Turn the part and repeat with the other surface, covering the second side with an ETFE release film as well.
- A polyester breather/bleeder is used to distribute the pressure resulting from the vacuum bag (see next step) over the complete surface. A bleeder will absorb the excess resin in case a perforated ETFE layer is used.
- Cover the part with a vacuum bag. Depending on the thickness of the foam and the geometry of the part, a tool may be needed to guarantee tolerances. In some cases, mainly when using thicker foam, the foam core is dimensionally stable enough for curing without fixation to a tool.

- Curing phenolic prepreg to TegraCore™ PPSU foam can be achieved in an oven under vacuum bag in a hot press or in an autoclave. In oven vacuum bagging, curing begins with a dwelling temperature of 80 °C (176 °F) for 15 min, and then 150 °C (302 °F) for 15 minutes followed by 30 to 60 minutes at 0.3 MPa (44 psi) pressure. Relationships between maximum pressure, time, and temperature are discussed below.
- After curing, remove the parts from the oven, allow them to cool under vacuum in the vacuum bag, and then demold.

Favorable results have been obtained using the glass fiber reinforced MTM 82S-C line of phenolic prepregs, supplied by Solvay Composites Materials, which have good mechanical strength, excellent peel strength, and superior impact properties. The resulting sandwich panels and parts meet FAR 25.853 flammability requirements.

EcoTechnilin's FibriPreg skin has also been successfully laminated to a TegraCore™ PPSU foam core. FibriPreg is made from a flax- and sugar-based bioresin and reinforced with woven basalt fiber. These sandwich panels also meet the FAR 25.853 flammability requirements.

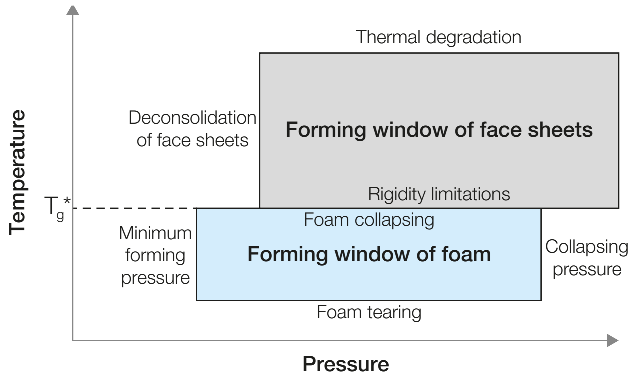
Laminates made from TegraCore™ PPSU foam perform better in peel strength tests than Nomex® Honeycomb material. For example, the peel strengths of laminates made from TegraCore™ PPSU foam and Nomex® Honeycomb laminates with Cycom® 2265/7781 phenolic prepreg were compared using the BMS 8-222 test protocol. Average peel strengths of 3.3 mm·kg_f/mm (7.3 in·lb_f/in) of width were measured for TegraCore™ PPSU foam-based laminates as compared to 2 mm·kg_f/mm (4.33 in·lb_f/inch) of width for the Honeycomb material. The higher peel strength values for the PPSU foam are a result of the increased contact area of the foam core with the skin.

Cold Forming Sandwich Panels with Thermoplastic Skins

It is possible to cold form sandwich panels made from TegraCore™ PPSU foam using either single- or multiple-step processing. The chosen process will depend on the composition of the reinforcing skins, the thickness and complexity of the final part, and the adhesive system. Several design and processing factors should be taken into consideration.

Processing requirements for the skin may indicate higher pressure and temperature than is suitable for PPSU foam due to the fact that the skin is a solid form. Processing requirements for the foam will likely be lower due to the morphology of the foam. Figure 18 shows the typical processing window for foam core materials and solid skins. A minimum pressure is required to form the foam as well as to maintain good contact and adhesion to the face sheets. Too much pressure can cause the foam to collapse. A minimum temperature is also required to form the foam and to prevent spring back and tearing. Typically, a higher temperature will be required to allow the solid skin to form. However, if the temperature is too high, it can cause the foam to collapse.

Figure 18: Typical processing windows for PPSU foam core and solid skins



Glass transition temperature

It is possible to creep form thermoplastic skins and PPSU foam core together in the same step if the processing windows overlap or if the creep properties at skin temperature can be leveraged to cause appropriate deformation. This is particularly true in simple geometries that require only a modest draw or deformation.

Compression Retention of TegraCore™ PPSU Foam Under Pressure, Temperature and Time

Understanding the viscoelastic behavior of PPSU foam is essential when designing high-temperature forming processes. PPSU foam exhibits a viscoelastic behavior under mechanical stress. Most of the deformation is elastic well below the yield point of the foam. As the yield point is approached, plastic deformation increases. Above the yield point, plastic deformation is dominant.

Creep behavior of PPSU foam must also be considered. Below 200 °C (392 °F), TegraCore™ PPSU Foam exhibits excellent resistance to creep. At temperatures that approach the glass transition temperature (T_g) of PPSU, significant creep will occur over time when the foam is under pressure. For every process where pressure, temperature and time are required, it is necessary to measure the resulting loss of thickness due to processing conditions. Loss of thickness can be mitigated by adding more foam thickness. Using shims between the pressing plates will minimize thickness loss. Table 3 gives the maximum processing pressure at a given temperature for a 1-hour maximum cycle time. At these conditions, PPSU foam thickness loss is limited to < 1 mm (0.04 inch).

Table 3: Maximum processing pressures at various temperatures used to limit thickness loss of TegraCore™ PPSU foam

Temperature [°C (°F)]	Maximum Processing Pressure [MPa (psi)]
215 (419)	0.05 (7.3)
200 (392)	0.20 (29)
180 (356)	0.30 (44)
150 (302)	0.40 (58)

Using Inserts with TegraCore™ PPSU Foam Sandwich Panels

It is common to use wall panel or floating inserts to attach composite panels to each other and to supporting structures. These inserts assist in distributing the loads transmitted from one panel to another. Inserts also allow the use of a variety of joining methods. Inserts are typically potted into the panel and can be used as through inserts or in blind holes. For airplane cabin interiors, inserts can be used in floor panels, sidewall panels, stowage bins, galleys, lavatories, and more.

Preliminary testing was conducted to explore the compatibility of common inserts with sandwich panels formed from TegraCore™ PPSU foam. Sandwich panels were prepared using 1-mm (0.6-inch) thick PPSU foam and two layers of Cytec MTM82S phenolic prepregs. Inserts were potted with Scotch-Weld™ 9323 A/B, which is a 60 °C (140 °F) curing epoxy adhesive system. Three different inserts were tested. In each case, the panel was prepared with an undercut that was 3.15 mm (0.12 inch) larger than the insert diameter in order to increase the contact of the potting compound with the sandwich panel skins. Test results are shown in Table 4.

Table 4: Pull-out force required to remove inserts from sandwich structure of TegraCore™ PPSU foam core with glass fiber reinforced phenolic panels (2 plies)

Variable	Diameter [mm (inch)]	Height [mm (inch)]	Pull-out Force [N (lb_f)]
M6 Floating Nut	18.90 (0.74)	14.40 (0.57)	1,351 (304)
M5 Floating Nut	14.00 (0.55)	8.80 (0.35)	550 (124)
M5 Fixed Nut	14.10 (0.56)	6.40 (0.25)	590 (133)

The potting compound was observed to adhere well to both the foam and the phenolic skins. The strength and failure mechanism was different for each insert. The pull-out caused cracking of the prepreg followed by cracking of the epoxy casting, allowing the insert to be pulled out. In the case of the M6 insert, a 45° rupture in the foam and a 45° deformation in the skin occurred. In the case of the M5 fixed nut insert, the insert sheared off the epoxy potting compound, creating a crack in the prepreg. In this case, it is likely that extending the potting compound to fill the entire space under the insert would increase the strength. Due to the small, closed cells of PPSU foam, the hole machined in the foam prior to potting is well defined. This means that less potting agent is needed as compared to honeycomb cores.

Compatibility of TegraCore™ PPSU Foam with Infusion Resins

TegraCore™ PPSU foam has been evaluated for compatibility with various resin transfer molding resins. Its compatibility with the resin formulation depends on the curing temperature and the chemical makeup of the resin. Resin systems with amine hardeners can be aggressive to PPSU foam. Resin systems that require high-temperature cures under pressure may result in deformation of the foam.

The following procedure was followed using Hexcel's VRM-34 infusion system

- VRM 34 epoxy and hardener were mixed at 100 parts to 42 parts respectively
- Test specimens measuring 13 × 13 × 13 mm (0.5 × 0.5 × 0.5 inch) were cut from PPSU foam
- Foam cubes were submerged in a vial filled with the VRM 34 mixture and then placed in a 70 °C (158 °F) oven for 24 hours
- Specimens were cut in half to evaluate epoxy resin penetration

Test Results

- Foam did not dissolve in the VRM 34 system
- Penetration ranged from 0.1 to 1.0 mm (4 to 40 mils)

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