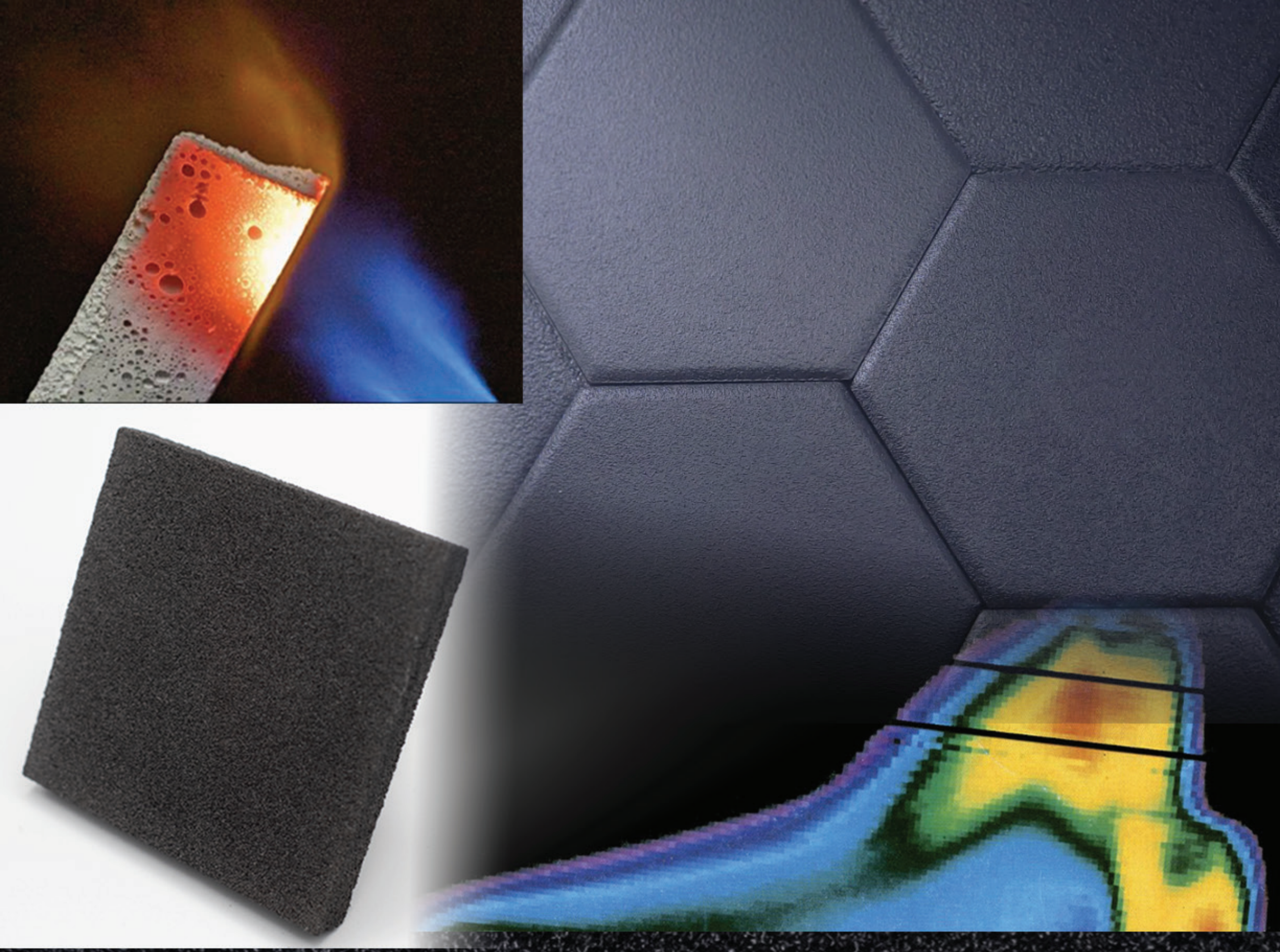


Aerospace Reentry Thermal Tile Applications with X-FOAM™

A Semplastics White Paper

Semplastics
269 Aulin Ave. Ste 1003
+1.512.663.3267
cris@x-materials.com
www.ceramic-foam.com

X-FOAM

Semplastics

Silica + alumina borosilicate composite tiles similar to FRCI-12 have dominated the re-entry thermal tile space for almost 50 years[1]. The Space Shuttle program FRCI-12 tiles were used from 1981 until 2011, replacing the silica HRSI tiles when each of those failed[2]. SpaceX and Dreamchaser use tiles based on this technology today. These micro-structured tiles have low density, low thermal conductivity, and high temperature tolerance. This combination of features has mostly justified their very high cost, typically over $1,000 per square foot.

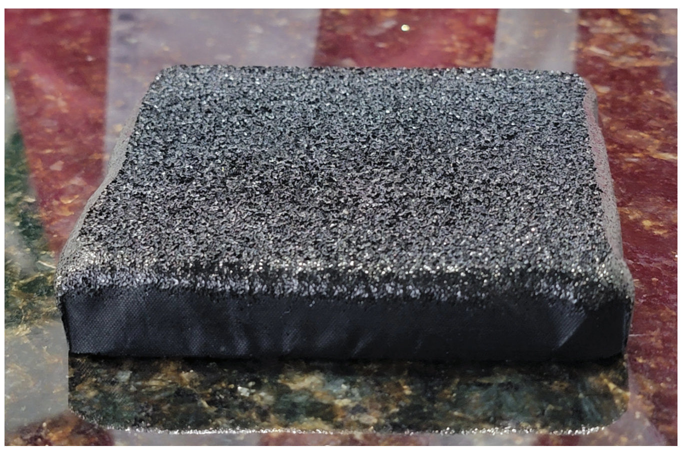
As the new space economy leaps forward in vehicle size and number of missions, these very high prices and higher demand for more cycles of reusability put increasing pressure on commercial and military designers to reduce costs and increase performance where possible. Incremental changes in performance and expense have been made over the last decade, but a novel material is the only way to boost the economic viability of high-volume re-entry vehicle thermal protection.

To this end, Semplastics has developed X-Foam, a new type of stiff silicon oxy-carbide amorphous ceramic foam that can match most or all of the functional parameters of these traditional tiles, but at a much lower price point. Below we will look at a technical feature-by-feature comparison of the Silica + Alumina Borosilicate tiles and X-Foam.

Technical specifications for the proprietary versions of these tiles used at Sierra Space, SpaceX, and other reusable orbital rocket companies are tightly held proprietary information. However, industry analysis confirms that the parameters of these newest tiles are in-family with the best of the Space Shuttle program tile, the FRCI-12 HRSI tile. This tile is alumina borosilicate (Nextel) fiber-reinforced silica composite, and its parameters are public and well-known. This white paper will compare X-Foam to the known specification of FRCI-12 HRSI, under the assumption that the tiles currently used by SpaceX, Sierra Space, and other companies are fairly similar, with only minor improvements.

What Is X-Foam?

X-Foam is designed and manufactured in America by Semplastics, an advanced materials company based in Oviedo, FL. X-Foam is based on Semplastics' polymer-derived ceramic technology. A proprietary Semplastics resin is combined with catalysts in a way that creates a homogenous foamed plastic. This plastic is cured to become solid, and then is pyrolyzed in an oxygen-free furnace. In this process, the foamed plastic is transformed into an amorphous silicon oxycarbide ceramic.



This black ceramic is hard and strong, and the foam cells are typically half open and half closed and smaller than a millimeter. Because the ceramic is amorphous and not crystalline, the material thermal conductivity is 10-20 times less than typical crystalline ceramics of the same type. The foam is extremely stiff, and can be machined to custom shapes after final firing. It does not crack during machining and holds a sharp edge. Semplastics can make this foam in many different densities and pore sizes.

Cost

In 2010, NASA estimated that each 6” x 6” x 1” tile cost $1,000 to procure in large quantities. Scaled to larger tiles, mean estimates of procurement cost was approximately $1,000-2,500 per square foot in 2010 dollars. This would be on the order of $3,000 per square foot in 2025 dollars. Using modern techniques, the cost could perhaps go back down to $1,500 per square foot.

Semplastics' vertical integration of resin components, green state manufacturing, and furnace processing combine with the novel foaming process to allow for significantly lower cost per tile. At moderate mass production quantities, a 6" x 6" x 1" X-Foam tile will cost less than $380, with a cost per square foot of around $1,100. Scaling up to full mass production can allow the price to fall even lower, on the order of $700/ft², a potential savings of over 50%.

More importantly, X-Foam can also perform the extreme environment insulation functions needed by tomorrow's re-entry vehicles. Below are detailed descriptions of how X-Foam compares to FRCI-12 and current state-of-the-art variants being used by commercial re-entry vehicles today, one important parameter at a time.

	FRCI-12	X-Foam
Cost	$1,500-$3,000/ft²	$700/ft²

Thermal Conductivity

The room-temperature thermal conductivity of FRCI-12 is 0.052 W/m·K[3], and this served over a hundred shuttle missions well for three decades. Whenever the older LI-900 tile failed, it was replaced by the newer FRCI-12 tile, and by the turn of the century, 5-10% of the 20,000 original shuttle tiles had been replaced with FRCI-12. This thermal conductivity was good enough to protect the aluminum skin of the orbiter from 1200°C+ temperatures during hypersonic re-entry.

X-Foam's thermal conductivity is measured to be 0.034 W/m·K. This low thermal conductivity at room temperature is enabled by the amorphous nature of the silicon oxycarbide (SiOC) and the high porosity of X-Foam. It is worth noting that this thermal conductivity is only 1.5 times higher than air at room temperature.

Phonons are the quantized units of vibrational energy that transmit thermal energy through a material. In crystalline materials, the ordered rows of atoms allow for easier transmittal of select vibrational frequencies, allowing heat to flow through a material in a faster, ordered manner. In amorphous materials, like the SiOC which comprises X-Foam, the material is an amorphous ceramic glass. This means that the atoms don't follow any regular long-range pattern, and thus no periodic vibrational channels exist to more easily transmit heat through the material.

	FRCI-12	X-Foam
Thermal Conductivity	0.052 W/m·K	0.034 W/m·K

The porosity of X-Foam is 90-95%, and this also greatly decreases the thermal conductivity. This combination of low inherent material thermal conductivity and high porosity lead to very high insulation properties in a material that also has structural stiffness and strength. Further testing is underway to measure the thermal conductivity of X-Foam across a wider temperature range.

Density

The density of FRCI-12 and similar tiles is 12lb./cu.ft., hence the '12' in its name. This translates to about 0.19g/cc. While the NASA patent describing the original formulation described variants with densities from 0.08 g/cc up to 0.48 g/cc[4], the most commonly used version on the Space Shuttle and currently has a density of approximately 0.19g/cc.

Due to FRCI-type tiles' friability, high water absorption, and low-emissivity white color, they are all coated with a high temperature black glass called Reaction-Cured Glass, or RCG. A typical bare FRCI-12 tile that is 6" x 6" will weight 112 grams. The RCG coating adds another 30 grams, bringing the effective density of the tile to 0.23g/cc.

X-Foam comes in a range of densities, but for the purpose of this white paper we will use our standard formulation, which has a density of 0.15g/cc.

Semplastics has the ability to tightly control X-Foam density during the manufacturing process, and can tune the density from 0.13g/cc to 0.35g/cc. Much of the material testing Semplastics has carried out on X-Foam is with the 0.15g/cc variant, but testing does show that strength and thermal conductivity scale strongly with density, creating interesting tradeoff opportunities. Structurally relevant versions of X-Foam are discussed below in the Stiffness and Strength section.

	FRCI-12	X-Foam
Density	0.19-0.23 g/cc	0.15 g/cc

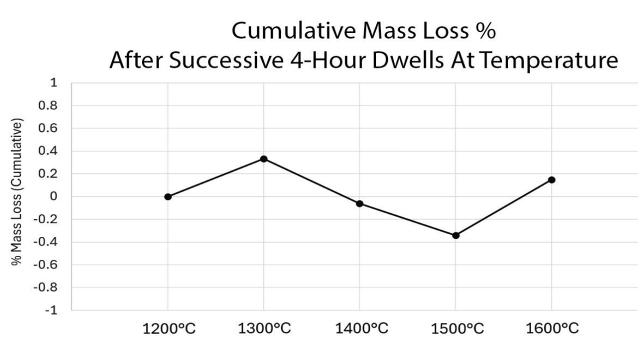
Operating Temperature

The maximum operating temperature of FRCI-type tiles is typically considered to be 1260°C for the Space Shuttle version. Elon Musk claimed on X that the SpaceX tiles were tested to as high as 1375°C (1650°K)[5], though this was only short-term testing, not operational re-use temperatures. Most industry experts assess that the long-term operational limit of RCG-coated silicon + aluminum borosilicate tiles is ~1300-1325°C. Each re-entry has peak heating time of 7-10 minutes, so a long-term reusability lifetime for a tile is on the order of 2-4 hours at peak temperature.

X-Foam has been tested in propane torch tests for short periods (1 minute, ~1,900°C surface impingement temperature) with no apparent degradation. Additionally, X-Foam has been tested at 1300°C for 4 hours in an oven in air and experienced no chemical changes measured via X-ray diffraction (XRD). The material stayed fully amorphous silicon oxycarbide and

showed no visual or mechanical signs of degradation. It also experienced a mass loss of only 0.3%.

Furnace testing was also completed at higher temperatures in air. Pieces of X-Foam were held at temperatures ranging from 1300°C to 1600°C in 100°C increments and held at each temperature for four hours. Starting at 1400°C, teh material began to slowly transform into silica glass (as measured by XRD), but it held its shape with reduced strength even through the highest temperature of 1600°C. The total mass change was only 0.15%, measured after 4 hours serially at each of the test temperatures. Changes in mass can be seen in the figure below.



While X-Foam is guaranteed to 1300°C, X-Foam will hold its shape as it slowly transforms into foamed silica (cristobalite) when above 1400°C.

	FRCI-12	X-Foam
Max Operating Temp.	1300-1325°C	1300°C

Another interesting aspect of X-Foam is that it is not friable and has extremely high emissivity, being a dark black color. It has no need for RCG glass coating, enabling easier processing and less weight per tile. Semplastics also has a process to close off the foamed surface with a smooth surface, a process that will be discussed further in the Waterproofing section below.

Stiffness and Strength

FRCI-12 material has a uniaxial normal compressive strength of 145psi, and a normal tensile strength of 76psi on average.[6] The material is anisotropic, and so its strength is different through different axes. Here we are looking normal to the surface of the tile, or "through the thickness" as it is described in the NASA reports on mechanical testing.

X-Foam shows isotropic compressive and tensile strengths because it is uniform in each direction. Its compressive strength (for the 0.15g/cc version) is 250 psi and the Flexure strength (as measured in a 3-point test) is 170 psi.

The X-Foam is more mechanically strong than typical FRCI-like tiles, and thus requires less lateral support. However, it is not strong enough to be a significant structural element. Denser versions of X-Foam, however, do exhibit significant and potentially useful strengths of over 1,000 psi.

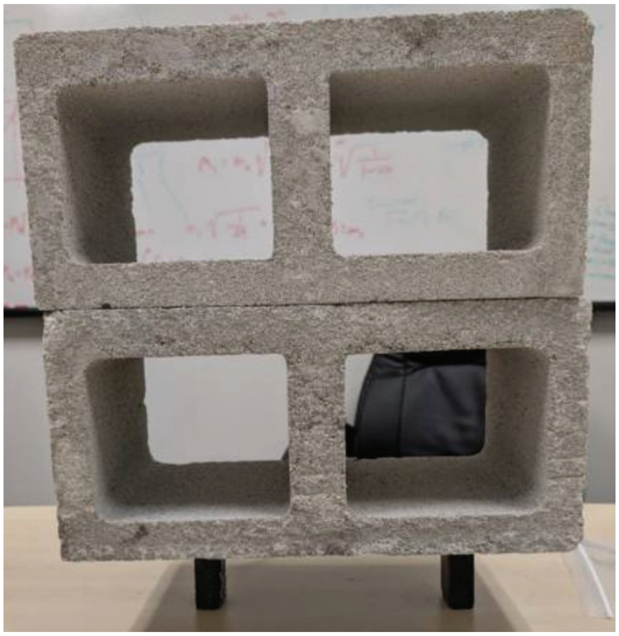
	FRCI-12	X-Foam
Compressive Strength	145 psi	250 psi
Tensile/Flex Strength	76 psi (Tensile)	170 psi (Flex)

Vacuum Stability

There is no recorded vacuum stability testing by NASA or others of FRCI-like tiles, as they are outward-facing. Given their chemical makeup, it is likely the only outgassing that would occur in vacuum would be based solely on any water or humidity that had been absorbed.

ASTM E595 vacuum testing has been performed on X-Foam, and it passed the standard easily. X-Foam is completely chemically stable across its operation temperature range and no solvents or components were measured to volatize during that ASTM test.

Outgassing is not a major concern for outward-facing tiles, but it is important for use cases that include encapsulation or use as insulation around avionics. X-Foam is potentially useful in both cases.



Machinability

FRCI-like tiles can be cut like soft chalk due to their high porosity. But while they are very easy to cut, the edges left are very friable[7]. Chips and cracks on edges and corners are quite common. Further, during machining, a very fine silica dust is produced that is easy to inhale. So while the tiles are easy to cut, they are difficult to shape—leading to an almost artisanal process.

X-Foam is also very easy to cut, but is much stiffer. Edges hold very strongly, even with very small holes, thin cuts, and sharp corners. Normal wood-working machines such as band saws, drills, and even hacksaws can be used to cut X-Foam reliably and cleanly. Lathes and CNC machines cut X-Foam exceptionally well, requiring no lubrication or cooling. The particles produced are fairly large and chemically inert. They are dark, glassy particles on the order of 50-200 microns in size. Masks and eye protection are recommended to protect against these sand-like particles, but no special precautions are needed for collection or disposal of waste material. X-Foam lends itself very easily to high volume, very repeatable machining.

Waterproofing

As tiles sit outdoors on the side of spaceships, they are subject to rain, condensation, and high humidity. The RCG coating on FRCI-like tiles is a fairly good rain shield in its pristine state. But the Coefficient of Thermal Expansion (CTE) mismatch, thermal stresses, and high vibration from launch create many small cracks in this outer glassy coating. This allows moisture to seep into the FRCI substrate, and this substrate is very hydrophilic, absorbing water readily. Because of this, the Space Shuttle program injected waterproofing through the glass into the FRCI substrate . But because those silanes burn away at about 1050°C, these injections had to be repeated for every flight. This costly operation is infeasible for rapid reuse goals of modern commercial flights. Newer FRCI formulations and coatings help reduce this problem somewhat, but waterproofing issues remain.

When X-Foam's surface is machined and the foam structure is fully open, it also absorbs water, though not as readily as FRCI. However, X-Foam can also be made in its green state with a thin outer seal over all surfaces that is glassy and made from the exact same material as the bulk foam. This seal is waterproof, allowing no water to seep into the foam. Because it is inherently part of the foam piece and made of the same material, minimal CTE mismatch occurs, and it does not easily crack or delaminate. It is also much thinner than RCG, on the order of 10 microns, and so the extra weight of this non-foamed silicon oxycarbide layer is negligible. This coating protects the tiles from moisture on the launch pad and generally requires no refurbishment before the next mission.

Summary Conclusion

X-Foam offers a new and important alternative to silica + alumina borosilicate FRCI-style tiles for aerospace thermal protection. The weight, thermal insulation, and maximum operating temperature of X-Foam are all comparable to the FRCI tiles, and the stiffness, machinability, emissivity, and waterproofing features are superior. Most importantly, the X-Foam material is much less expensive than FRCI-type tiles, offering material savings of better than 50% and machining, handling, installation, and refurbishment savings on top of this. As a new aerospace material, some further testing needs to be performed with partners, such as

Arcjet testing, thermal conductivity measurements above 1,000°C, and ionization tests. The material properties of the silicon oxycarbide material of which the foam is comprised and other tests indicate a high confidence that very positive results will come from these tests.

The specifications and other test results for X-Foam are shown below.

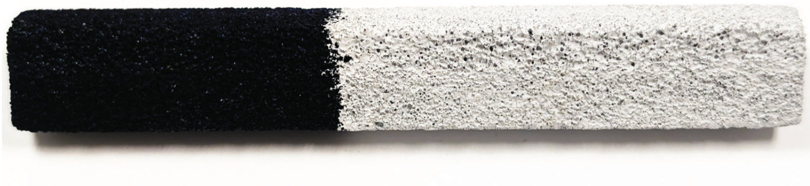
Parameter	Semplastics X-Foam (SI)	Semplastics X-Foam (Imperial)
Density	0.15 g/cc	9.4 lb/cu.ft.
Max Operational Temp. (in air)	1300°C	2370°F
Thermal Conductivity	0.034-0.075 W/m·K	0.019-0.043 BTU/h· ft· °F
Specific Heat Capacity (25°C)	850 J/kg·°C	0.20 BTU/lb·°F
Heat Capacity per Volume	0.13 MJ/m³·K	1.9 BTU/ft³·°F
Coefficient of Thermal Expansion	3.2×10^{-6} /°C	1.8×10^{-6} /°F
Compressive Strength	2-14 MPa	300-2000 PSI
Pore Size (tunable)	80-1200µm	80-1200µm
Pores Per Inch (PPI, tunable)	30-250	30-250
Machinability	Easy	Easy

Aerospace Reentry Thermal Tile Applications with X-FOAM™

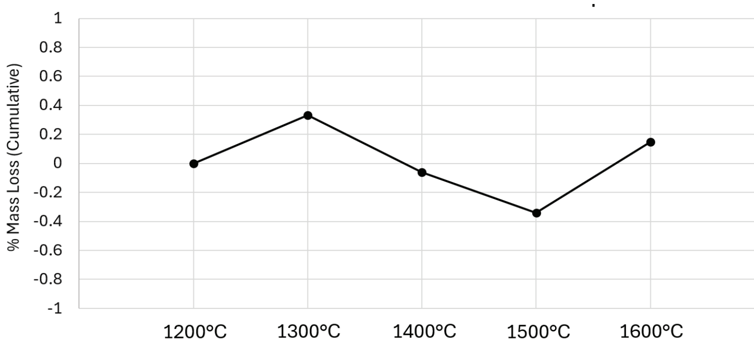
X-Foam is available in a range of densities. Unless otherwise noted, all data shown below is for the 0.15g/cc version.

Density (g/cc)	Pores Per Inch (PPI)	Compressive Strength (PSI)	Flexural Strength (PSI)
0.15	30-120	300	150
0.22	60-150	740	270
0.28	100-200	1330	360
0.35	140-250	2000	500

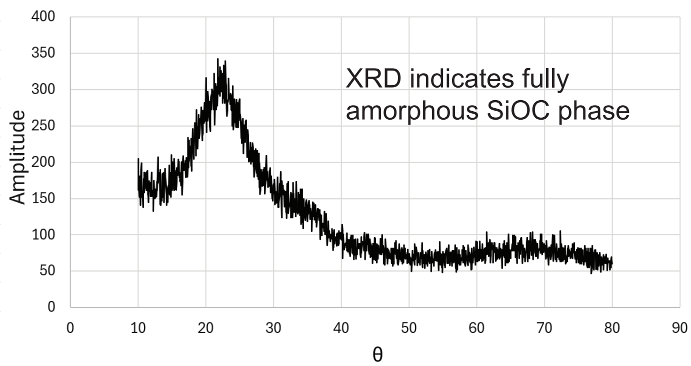
Semplastics can grow a thin, 100µm bonded layer of alumina on the surface of X-Foam pieces upon request. It is resistant to cracking and delamination, even under temperature shocks of 1000°C per second.



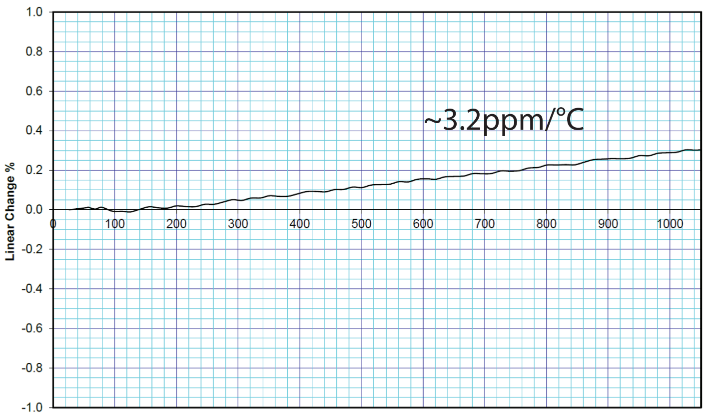
Cumulative Mass Loss % After Successive 4-Hour Dwells At Temperature



2-θ X-Ray Diffraction Measurement After 4-Hour Dwell at 1300°C



Thermal Expansion Test Data (% change vs °C)



Thermal Conductivity and Effusivity Test Data

#	k (W/mK)	Effusivity (Ws½/m²K)	R^2	1/m	Temperature (°C)
1	0.0376	70.6	0.9997	50.8	24.5
2	0.0374	69.0	0.9997	50.7	24.5
3	0.0376	70.6	0.9997	50.8	24.5
4	0.0376	70.9	0.9997	50.8	24.5
5	0.0377	71.1	0.9997	50.8	24.5

ASTM E595 Vacuum Outgas Test Data

SN	%TML	Average % TML	%CVCM	Average %CVCM
Replicate #1	0.01		0.00	
Replicate #2	0.01	**0.01**	0.00	**0.00**
Replicate #3	0.01	**Pass**	0.00	**Pass**

References

1. Review of Lightweight, High-Temperature Thermal Insulation Materials for Aerospace. Materials (Basel). 2025 May 20; Zhang Q, Huang H, Lei C, Liu Y, Li W. 18(10):2383. doi: 10.3390/ma18102383
2. "Orbiter Thermal Protection System" NASA Facts Sheet FS-2008-02-042-KSC https://www3.nasa.gov/centers/kennedy/pdf/167473main_TPS-08.pdf
3. https://tpsx.arc.nasa.gov/Material?id=1 for LI-900; FRCI-12 was 10% more thermally conductive than LI-900 per this report: https://ntrs.nasa.gov/api/citations/19830003890/downloads/19830003890.pdf
4. Patent US4148962A - Fibrous refractory composite insulation, NASA, 1978
5. https://x.com/elonmusk/status/1107384308459659264
6. "Mechanical Properties of Thermal Protection System Materials" June 05; Yee M, Hofer J, Bronowski D, Hardy R, Sandia National Labs, page 41
7. Fibrous Ceramic Insulation, 1983, Goldstein, H. E., NASA Ames Research Center, NASA Report no. 19830003890.
8. "Orbiter Thermal Protection System" NASA Facts Sheet (ibid.), pages 4-5

For more information or
samples, contact us:

X-MAT
269 Aulin Ave. Ste 1003
Cris DiRuggiero
+1.512.663.3267
cris@x-materials.com