AeroZero® Thermal Protection Systems (AZ-TPS) for Aerospace and Defense Transient Thermal Events (TTE)

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Executive Summary

- AeroZero® TPS (AZ-TPS) are thin (often <200 um), lightweight thermal protection systems that significantly increase the working temperature of plastic and metal aerospace parts.
- AZ-TPS protected PEEK from up to 300 °C (572 °F) constant temperature heat exposure in this analysis by reducing the PEEK temperature more than 220 °C (>400 °F).
- Extended recovery time between transient thermal events significantly further extends the protection provided by AZ-TPS.
- AZ-TPS and AeroZero film have achieved a UL94 VTM-0 classification, the highest-level flame retardancy rating that can be obtained for thin films.

Background

AeroZero® is a thin, polyimide aerogel film that is used as the primary insulator in AeroZero Thermal Protection Systems (AZ-TPS) in aerospace and defense applications. AeroZero is a flexible, durable film with 85% porosity produced at 165 microns (0.0065 in, 6.5 mil) thickness and provides the thermal insulation, RF transparency, dielectric properties, and lightweight benefits of an aerogel with the ease of use and mechanical strength of a plastic film. AeroZero is an aromatic polyimide aerogel, and polyimides are widely accepted and used in aerospace and defense applications due to their exceedingly high thermal stability, excellent chemical resistance, and robust mechanical properties.

The unique combination of low thermal conductivity and diffusivity, high heat tolerance, ultra-low dielectric properties, high strength-to-density ratio – all in a very thin profiles combine to make AZ-TPS preferred options for demanding aerospace and defense thermal management applications, especially those with Transient Thermal Events (TTE). As a result, AZ-TPS have become essential solutions for product developers with challenging temperature control in limited spaces.

AeroZero film is manufactured using Blueshift's highly efficient, state-of-the-art polyimide aerogel production equipment, SP-1, which is the first in the world and incorporates emission controls and in-line solvent recycling. AeroZero film is combined with functional adhesives and protective films such as polymer films and metal foils to produce AZ-TPS.

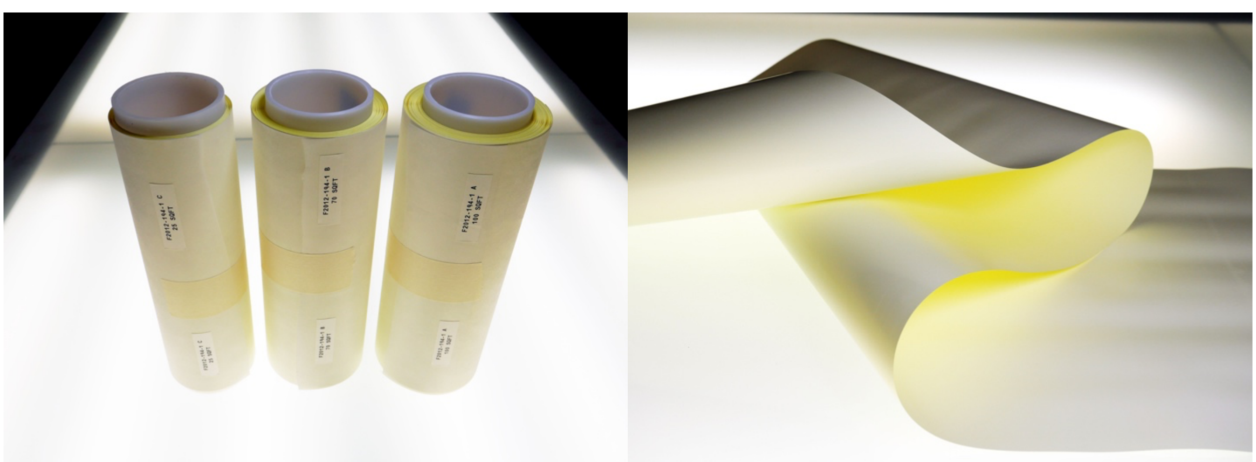

Figure 1. Left: Rolls of AeroZero polyimide aerogel film produced in continuous rolls in Massachusetts, USA. **Right**: Closeup of AeroZero film unrolled.

AZ-TPS are installed in aerospace and defense systems when challenging temperature or space restrictions exist that impede the use of legacy insulators. AZ-TPS are ideal for hot spot elimination and control of heat flow within confined spaces. AZ-TPS are the first Thermal Protection Systems (TPS) in the world that are manufactured in continuous rolls from polymer aerogels, and cut to shape in Blueshift's fabrication plant in central Massachusetts, USA. They are designed for high heat and tight space applications, most of them having less than 1 mm of available head space.

AZ-TPS consists of one or more layers of AeroZero with thickness 165 microns bonded with a 25 micron thick layer of silicone pressure sensitive adhesive (PSA). AZ-TPS Type 1 (single layer AeroZero) and AeroZero film both received a UL94 VTM-0 classification, the highest-level flame retardancy rating that can be obtained for a thin film.

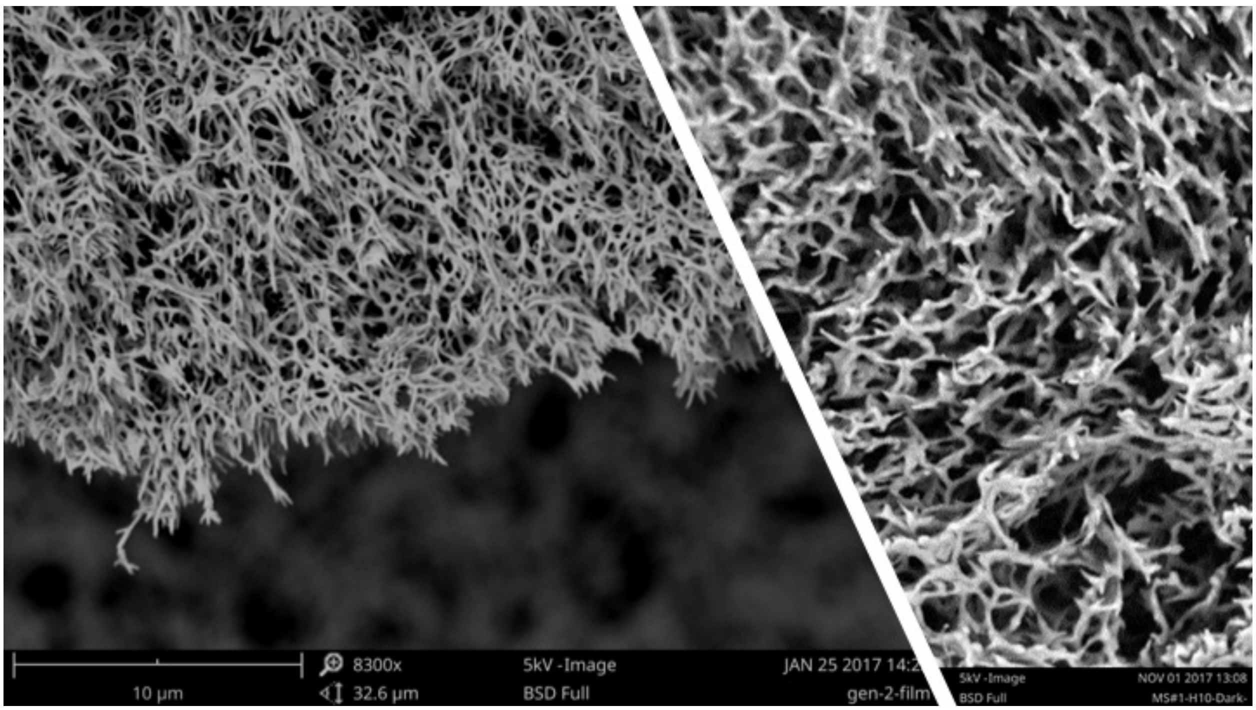

Figure 2. SEM image showing nanoporous structure.

Thermal Properties Defined

Thermal Conductivity:[1] The thermal conductivity, λ, of a material is a measure of its ability to conduct heat under steady state conditions. Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity. For example, metals typically have relatively high thermal conductivity and are very efficient at conducting heat, while the opposite is true for insulating materials like engineering plastics and foams. Correspondingly, materials of high thermal conductivity are widely used in heat sink applications, and materials of low thermal conductivity are used as thermal insulation. The reciprocal of thermal conductivity is thermal resistivity.

For simple applications, Fourier's law of thermal conduction (Eqn 1) shows that local heat flux, $\boldsymbol{q}$, is equal to the product of thermal conductivity, **λ**, and the negative local temperature gradient ($\boldsymbol{T_2 - T_1}$)

in one direction, $\boldsymbol{x}$. The heat flux is the amount of energy that flows through a unit area per unit time.

Eqn. 1. Fourier's Law of Thermal Conduction, describing thermal conductivity, λ:

$$q = -\lambda \frac{T_2 - T_1}{L}$$

The thermal conductivity is often treated as a constant, though this is not always true. While the thermal conductivity of a material generally varies with temperature, the variation can be small over a significant range of temperatures for some common materials. In anisotropic materials, the thermal conductivity typically varies with orientation.

Thermal Diffusivity:[2,3] The thermal diffusivity, α, of a material is the thermal conductivity divided by density and specific heat capacity at constant pressure (Eqn. 2). It measures the rate of heat transfer of a material by conduction during changes of temperature. The higher the thermal diffusivity, the faster the heat propagation, because the substance conducts heat quickly relative to its specific heat capacity or 'thermal bulk'.

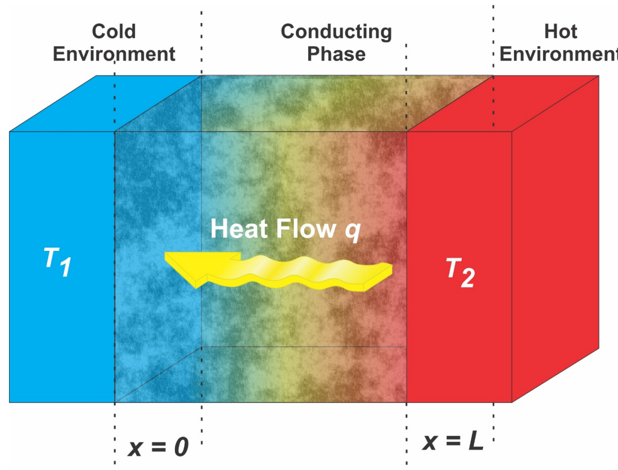

Figure 3. Heat flow from hot to cold environments.

A very effective method used for measuring thermal diffusivity of high thermally conductive solids is the flash method. This transient technique features short measurement times, is non-destructive, and provides values with excellent accuracy and reproducibility. The flash method involves uniform irradiation of a small, disc-shaped specimen over its front face with a very short pulse of energy.

Eqn. 2. Definition of Thermal Diffusivity, **α,** where α is the thermal diffusivity, λ is the thermal conductivity, ρ is the density, and c_p is the specific heat capacity.[2,3]

$$\propto = \frac{\lambda}{\rho \cdot c_p}$$

In the flash method, the time-temperature history of the rear face of the sample is recorded through high-speed data acquisition from an optical sensor with a very fast thermal response. Based on this time-dependent thermogram of the rear face, the sample's thermal diffusivity, **α**, is determined from the thickness (L) of the sample and the time the thermogram takes to reach half of the maximal temperature increase ($t_{1/2}$).

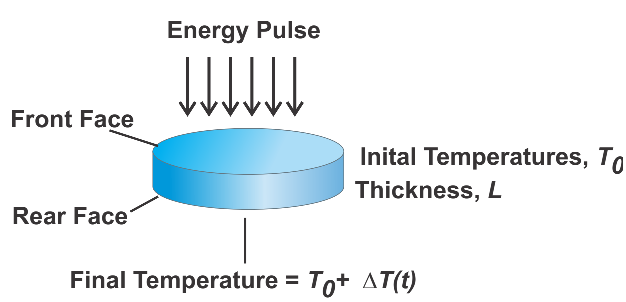

Figure 4. Flash method for directly measuring thermal diffusivity.[2,3]

Specific Heat Capacity:[4] In thermodynamics, the **specific heat capacity, c_p**, of a substance is the heat capacity of a sample of the substance divided by the mass of the sample. Informally, it is the amount of energy that must be added, in the form of heat, to one unit of mass of the substance in order to cause an increase of one unit in temperature.

How Does AeroZero® Compare?

A powerful tool for helping in materials selection is offered by the Ashby plot.[5] This is a scatter plot displaying two or more properties of materials or classes of materials. These plots are convenient because they provide useful information not only on which material displays the highest (or the lowest) property, but also the ratio between the two properties.

In the example Ashby plot below, the thermal conductivity and thermal diffusivity of several classes of materials are plotted. For applications requiring thermal insulation, materials having especially low values for both properties are most desirable. Various polymers, elastomers and foamed materials generally provide these properties, with AeroZero providing an ideal combination of both properties.

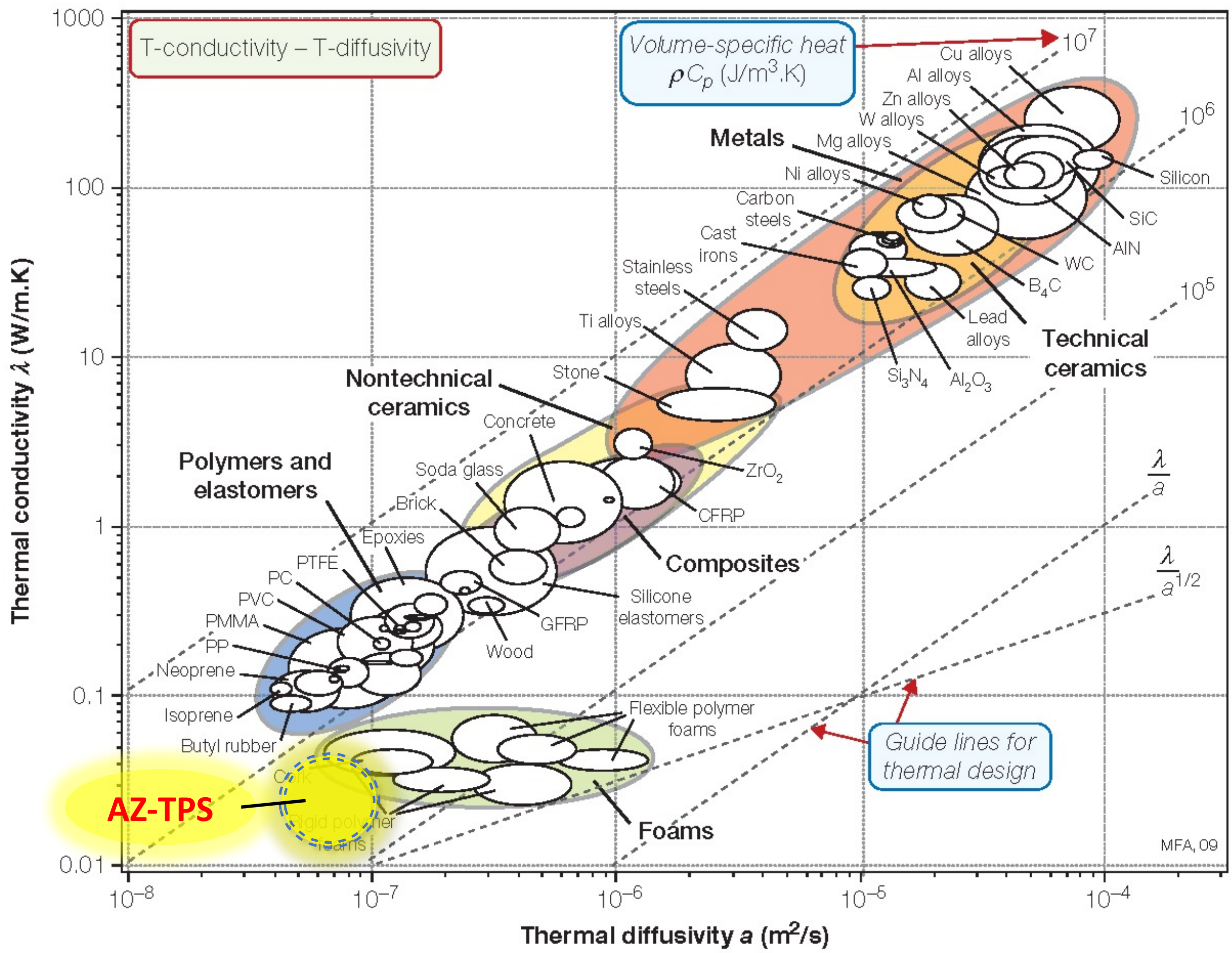

Figure 5. AeroZero thermal properties plotted on the Ashby Thermal Conductivity-Thermal Diffusivity Chart[6]

In another representative Ashby plot, the thermal expansion and thermal conductivity of several classes of materials are plotted. Similarly, for applications requiring dimensional stability while also providing superior thermal protection, AeroZero is a preferred option.

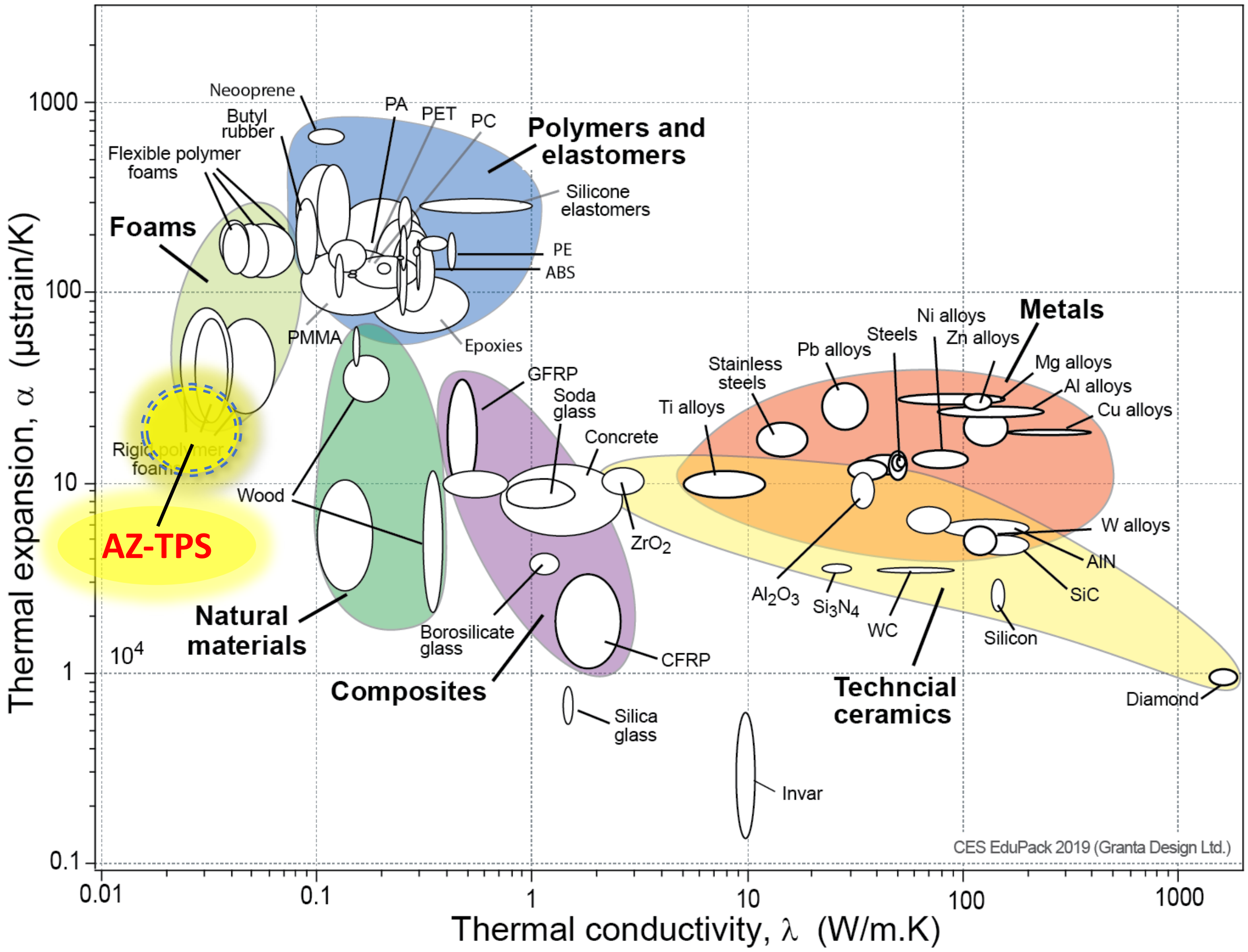

Figure 6. AeroZero thermal properties plotted on an Ashby Thermal Expansion-Thermal Diffusivity Chart[7]

Model Case Studies

Case 1: AZ-TPS Thermal Protection of PEEK – Constant 300 °C Heating. An infinitely thick polyetheretherketone (PEEK) substrate is protected by AZ-TPS consisting of one, two, or three layers of AeroZero, each layer with a thickness of 165 microns. The AeroZero film(s) are bonded to each other with a 25 micron layer of silicone pressure sensitive adhesive (PSA), and also bonded to the PEEK substrate with a 25 micron thick layer of silicone PSA. While the sample is held at 20 °C, a 30 second thermal load of 300 °C is applied to the sample from a contact heat source.

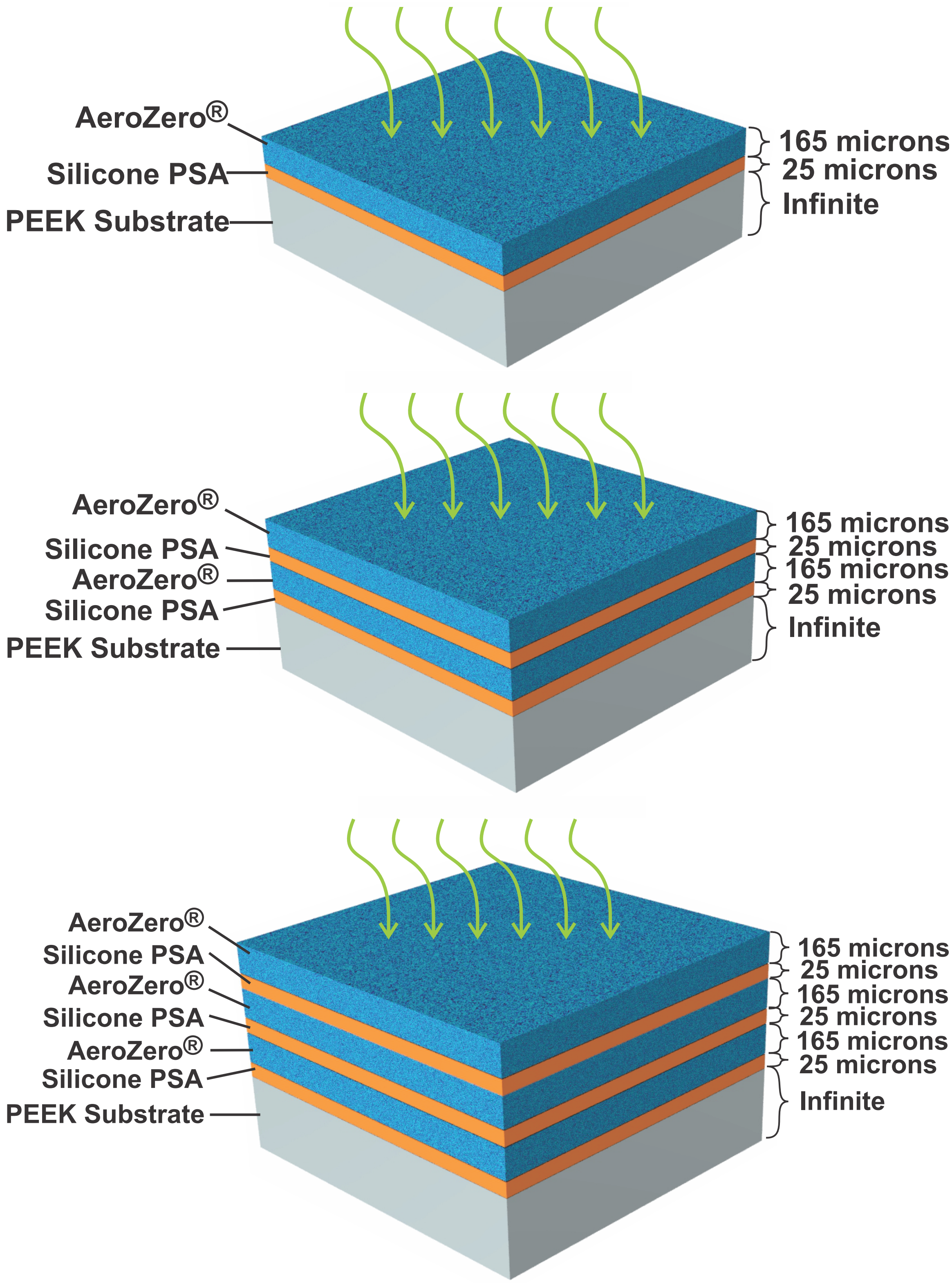

Figure 7. **TOP:** PEEK substrate protected by AZ-TPS Type 1 (One Layer AeroZero). **MIDDLE:** PEEK substrate protected by AZ-TPS Type 2 (Two Layers AeroZero). **BOTTOM**: PEEK substrate protected by AZ-TPS Type 3 (Three Layers AeroZero). Temperature rise is measured at the PSA/PEEK interface.

The temperature at the PEEK surface (the PSA/PEEK interface) is monitored to determine the rate and extent of temperature rise. The thermal load is uniformly applied at the top of the layered build. The resultant temperature is plotted as a function of time, and shown in Figure 8.

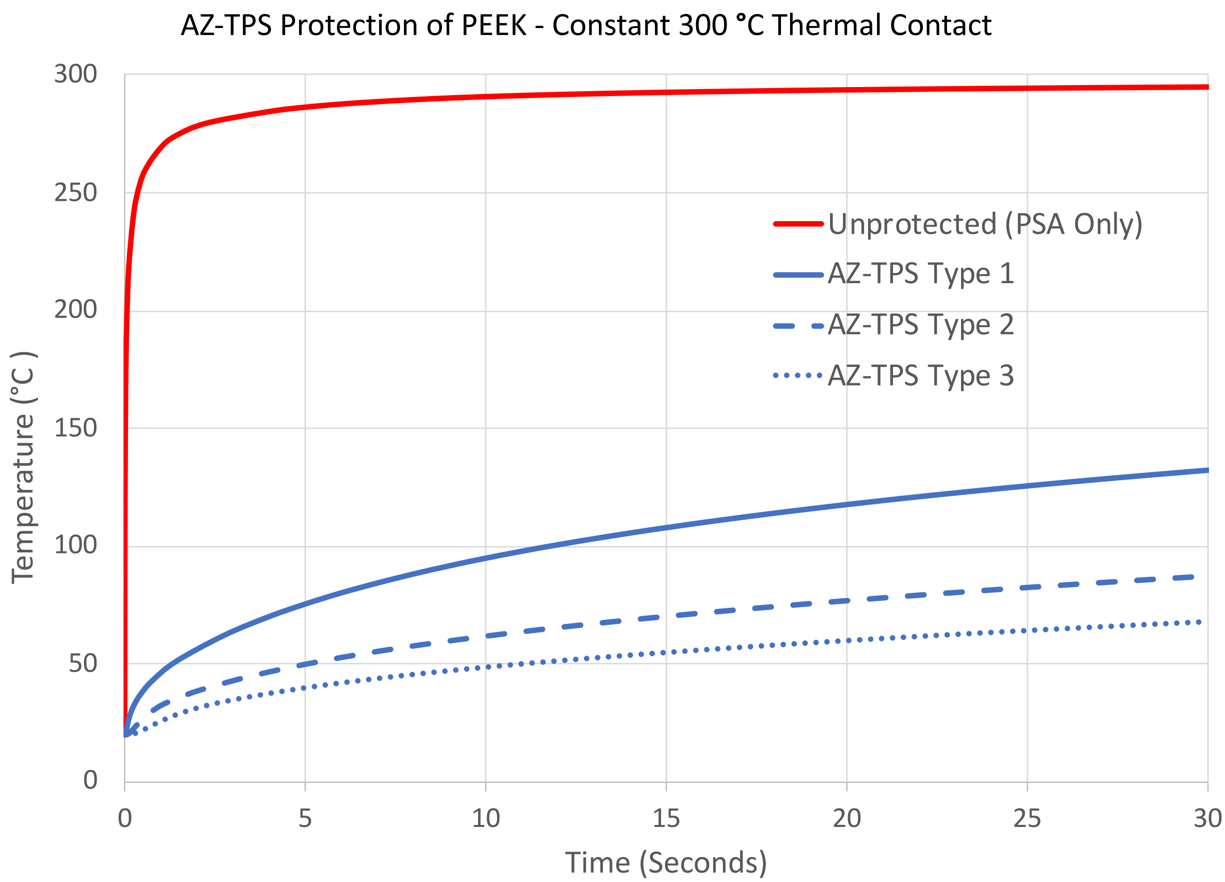

Figure 8. Temperature as a function of time for PEEK substrate protected by AZ-TPS Types 1, 2, and 3 and PSA only (upper line).

With the AZ-TPS Type 1 in place, a maximum temperature of 132 °C (270 °F) is reached at the PEEK surface after 30 seconds of thermal exposure, vs 295 °C (563 °F) with PSA only, a difference of 162 °C (293 °F). The temperature was further reduced with Type 2 and Type 3 AZ-TPS. Note that AeroZero reduces both the rate of heating as well as lowers maximum temperatures after the thermal load is applied.

Table 1: Maximum temperature PEEK substrate experiences when protected by AZ-TPS and exposed to 300 °C for 30 seconds.

Configuration	Max Temp (°C)	Temperature Decrease (°C)	Max Temp (°F)	Temperature Decrease (°F)
Unprotected (PSA Only)	295	---	563	---
Type 1 (1 Layer AeroZero)	132	163	270	293
Type 2 (2 Layers AeroZero)	87	208	189	374
Type 3 (3 Layers AeroZero)	68	227	154	409

Case 2: AZ-TPS Thermal Protection of PEEK – Cyclic Heating 300 and 500 °C, 5 s Recovery. For the same configuration as Case 1, a series of 10 thermal pulse cycles were applied, each lasting 5 seconds at either 300 or 500 °C, then resting for 5 seconds before the next pulse. Again, the temperature at the topmost surface of the PEEK is monitored throughout the thermal pulses to determine the rate and extent of temperature rise, and shown in Figure 9.

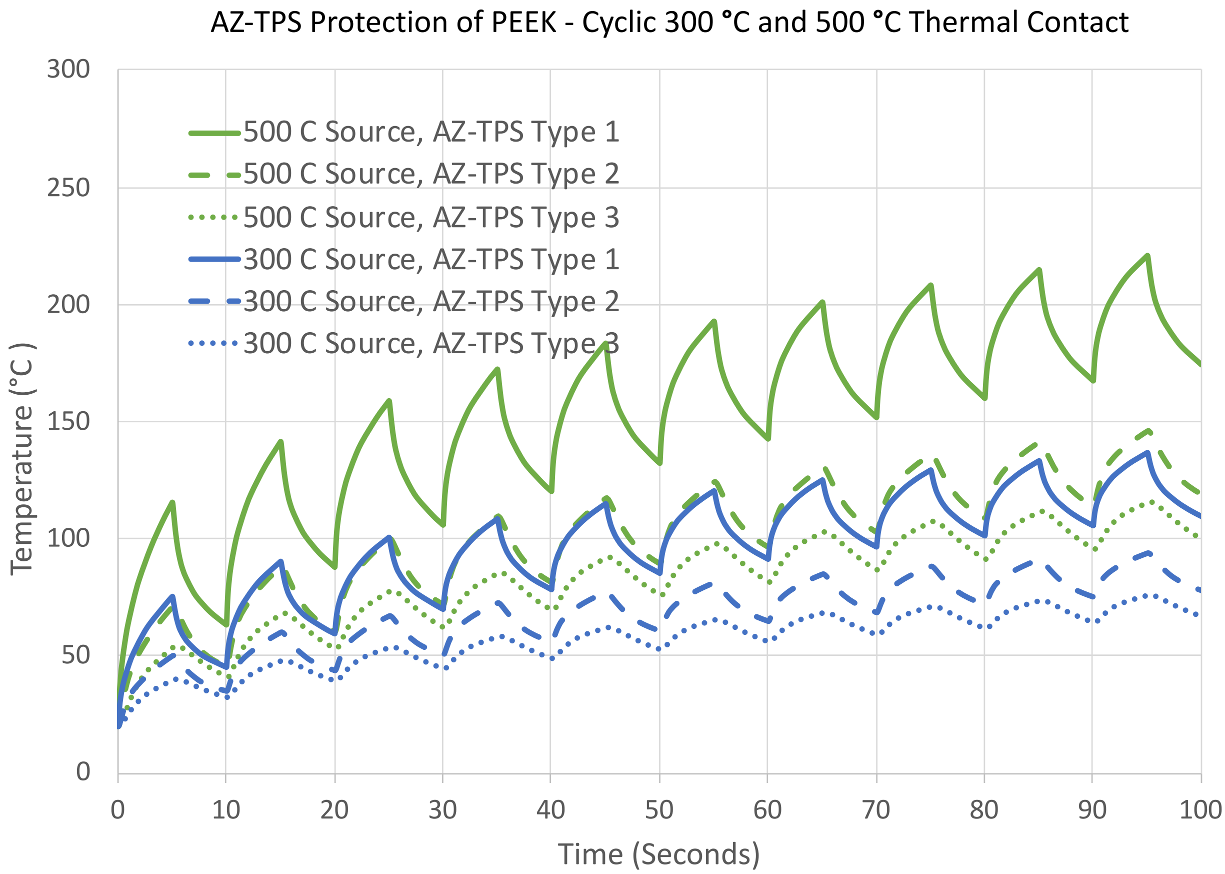

Figure 9. Temperature as a function of time for PEEK substrate protected by AZ-TPS Types 1, 2, and 3 subjected to cyclic 300 °C and 500 °C pulse loads with 5 seconds recovery time between pulses.

During repeated heating / cooling thermal cycles and transient thermal events, the AZ-TPS protective layer provides continued thermal protection of the substrate. While a gradual temperature increase occurs at the PEEK surface, the AZ-TPS maintains the temperature significantly below the applied thermal load, even after 10 cycles. For a 500 °C (932 °F) applied load, the maximum temperature reached after 10 cycles is only 221 °C (429 °F) for Type 1, while for a 300 °C (572 °F) load, the maximum temperature reached for Type 1 is only 137 °C (279 °F). The temperature was further reduced with Type 2 and Type 3 AZ-TPS.

Table 2: Maximum temperature PEEK substrate experiences when protected by AZ-TPS and exposed to 10 cycles of 5-second **300 °C** thermal loads with 5 seconds delay between pulses.

Configuration	Max Temp (°C)	Temperature Decrease (°C)	Max Temp (°F)	Temperature Decrease (°F)
300 °C, Unprotected	300	---	572	---
300 °C, Type 1 (1 Layer AZ)	137	163	279	293
300 °C, Type 2 (2 Layers AZ)	94	206	201	299
300 °C, Type 3 (3 Layers AZ)	76	224	169	331

Table 3: Maximum temperature PEEK substrate experiences when protected by AZ-TPS and exposed to 10 cycles of 5-second **500 °C** thermal loads with 5 seconds delay between pulses.

Configuration	Max Temp (°C)	Temperature Decrease (°C)	Max Temp (°F)	Temperature Decrease (°F)
500 °C, Unprotected	500	---	932	---
500 °C, Type 1 (1 Layer AZ)	221	279	430	502
500 °C, Type 2 (2 Layers AZ)	146	354	295	637
500 °C, Type 3 (3 Layers AZ)	116	384	241	691

Case 3: AZ-TPS Thermal Protection of PEEK, Cyclic Heating 500 °C, 30 s Recovery. For the same layer configuration as Cases 1 and 2, a series of 3 thermal pulse cycles is applied, each lasting 5 seconds at 500 °C, then resting for an extended period of 30 seconds before the next pulse (vs 5 seconds in Case 2). As in Cases 1 and 2, the temperature at the topmost surface of the PEEK substrate is monitored throughout the thermal pulses to determine the rate and extent of temperature rise. The results are plotted in Figure 10.

During repeated heating / cooling thermal cycles and transient thermal events, AZ-TPS provides continued thermal protection of the substrate. While a relatively small increase in maximum temperature occurs between cycles at the PEEK/PSA interface, in part due to the extended recovery time between cycles, the AZ-TPS maintains the temperature significantly below the thermal load. For a 500 °C (932 °F) load, the maximum temperature reached after 3 cycles is only 156 °C (313 °F), an indication that a single layer of AeroZero is providing nominally 344 °C (619 °F) of protection from the initial thermal load.

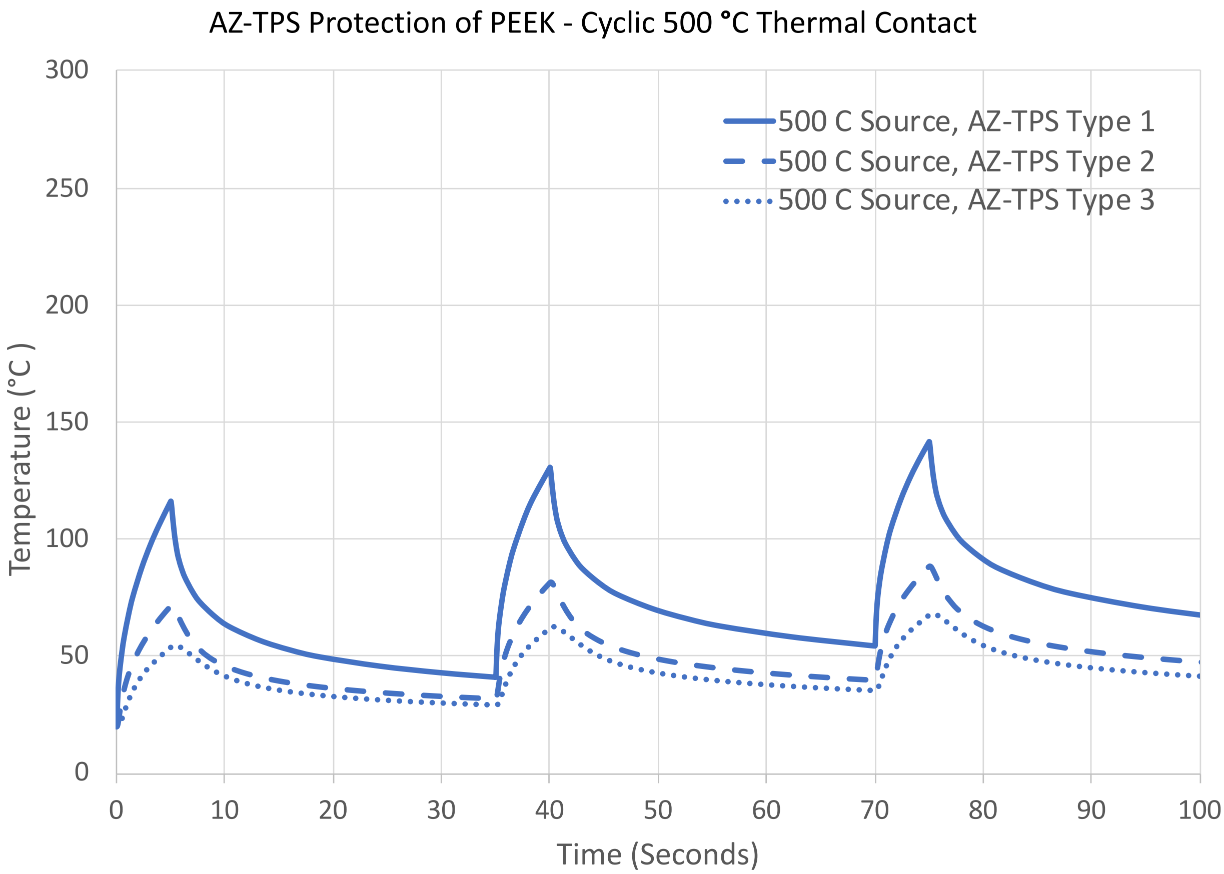

Figure 10. Temperature as a function of time for PEEK substrate protected by AZ-TPS Type 1 subjected to cyclic 500 °C pulse loads with 30 seconds recovery time between pulses.

Table 4: Maximum temperature PEEK substrate experiences when protected by AZ-TPS and exposed to 3 cycles of 5-second **500 °C** thermal loads with 30 seconds delay.

Configuration	Max Temp (°C)	Temperature Decrease (°C)	Max Temp (°F)	Temperature Decrease (°F)
500 °C, Unprotected	500	---	932	---
500 °C, Type 1 (1 Layer AZ)	141	359	286	646
500 °C, Type 2 (2 Layers AZ)	88	412	190	742
500 °C, Type 3 (3 Layers AZ)	67	433	153	779

Case 4 : AZ-TPS Thermal Protection of Aluminum – Constant 300 °C Heating. In this Case, the same configuration is used from Case 1, only the PEEK substrate is replaced with an infinitely thick aluminum block. While the sample is held at 20 °C, a 30 second thermal load of 300 °C is applied to the sample from a contact heat source.

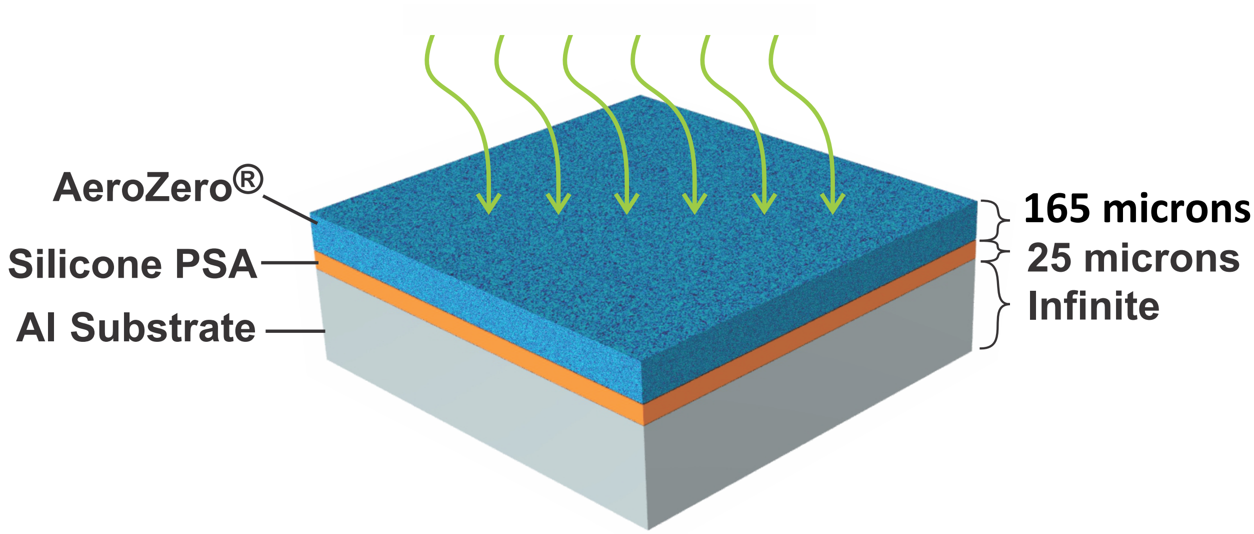

Figure 11. Representative architecture of Aluminum substrate protected by AZ-TPS.

As shown in Figure 12, when protected by AZ-TPS Type 1, a maximum temperature of 33 °C (91 °F) is reached at the PSA/Aluminum interface after 30 seconds of thermal exposure. Without the AZ-TPS present, the maximum temperature is 237 °C (458 °F), a difference of 204 °C (367 °F). As in the previous case, the structure with AZ-TPS exhibits a slower rate of heating as well as a lower maximum temperature after the thermal load is applied. The temperature was further reduced with Type 2 and Type 3 AZ-TPS.

Table 5: Maximum temperature Aluminum substrate experiences when protected by AZ-TPS and exposed to 300 °C for 30 seconds.

Configuration	Max Temp (°C)	Temperature Decrease (°C)	Max Temp (°F)	Temperature Decrease (°F)
Unprotected (PSA Only)	235	---	455	---
Type 1 (1 Layer AeroZero)	33	202	91	364
Type 2 (2 Layers AeroZero)	27	208	81	374
Type 3 (3 Layers AeroZero)	25	210	77	378

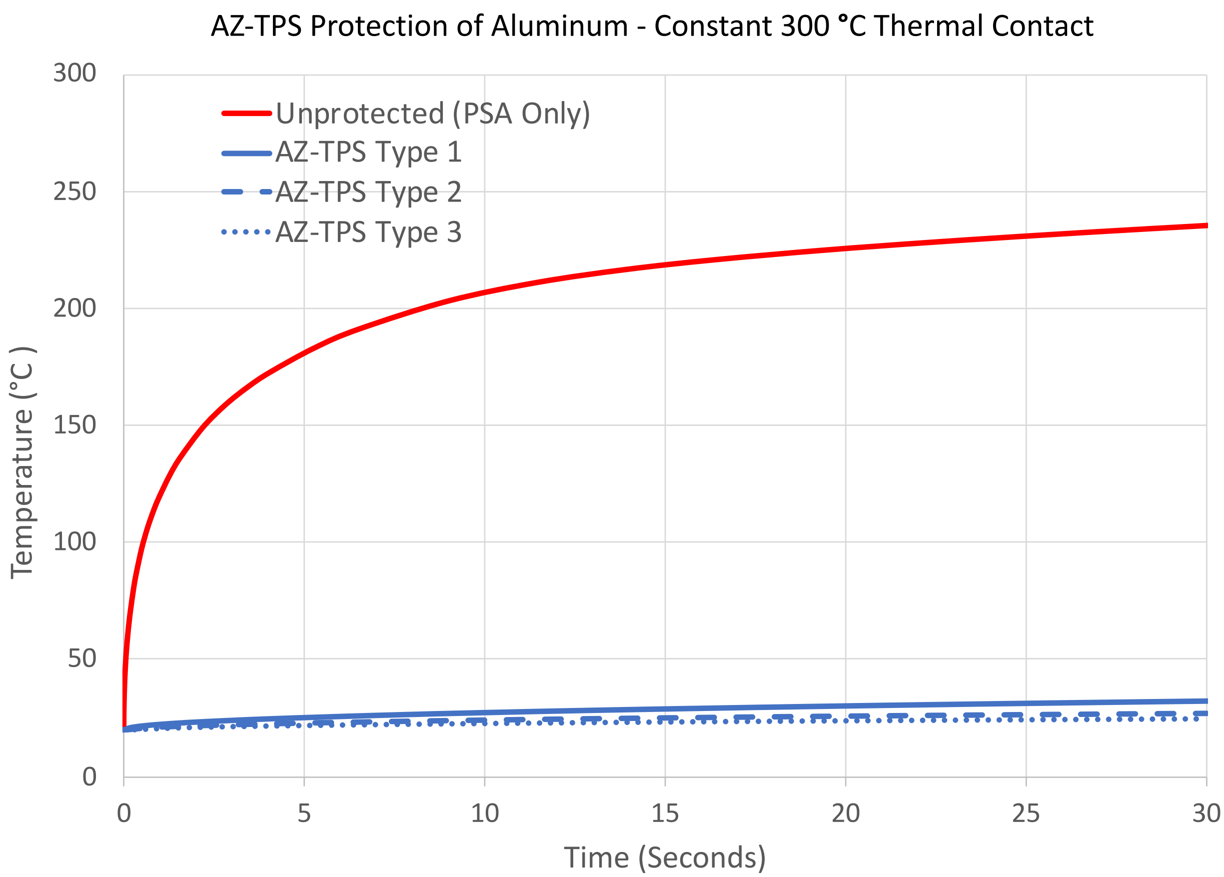

Figure 12. Temperature as a function of time for aluminum substrate protected by AZ-TPS subjected to 300 °C constant thermal load.

Key Summary Points

- AeroZero® TPS (AZ-TPS) provide excellent thermal protection of polymer and metal substrates when exposed to single transient thermal events.
- AZ-TPS provide extended thermal protection during multiple, transient thermal events at least as high as 500 °C (932 °F).
- Extended recovery time between transient thermal events significantly further extends the protection provided by AZ-TPS.
- AZ-TPS and AeroZero film have achieved a UL94 VTM-0 classification, the highest-level flame retardancy rating that can be obtained for thin films.

References

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