# BOYD CORPORATION

## Discussion of SOLIMIDE® Foams


## White Paper

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## Discussion of SOLIMIDE® Foams

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## Introduction

There are a myriad of foams available on the market for thousands of different applications; every foam has different physical characteristics that define how that foam will perform in any given application. When selecting the right foam, the first characteristic to define is the physical function of the foam. Does the foam need to cushion a specific part from shock or jolt, insulate to contain heat or cool air, or control sound?

Raw physical polymer properties of a given foam determine which particular foam is best suited for specific applications or environments. Close-cell foams are used in applications that require moisture isolation or blocking. Open-cell foams are ideal for enhanced absorption as well as filtration of dust particles while allowing the passage of gases. Silicone foams are used in very high temperature applications. Polyurethane foams are ideal when the foam needs to compress and rebound to its original shape repetitively.

Since cellular polymers first became generally available, it has been recognized that in a fire condition, they behave quite differently from conventional solid polymers. Cellular polymers usually ignite and burn quite rapidly because of the high surface area resulting from their cellular structure, readily available access to oxygen and low thermal inertia.

SOLIMIDE® Foam, the trade name for polyimide foam, occupies a unique portion of the foam spectrum. Polyimides are polymers that usually consist of aromatic rings coupled by imide linkages. They are thermally stable in inert atmospheres at temperatures up to 500°C. Polyimide foams are derived from polyimide resins and have demonstrated excellent long term thermal stability for a variety of high temperature applications. This proprietary foam was developed for NASA in response to the need for a flame resistant, thermally insulating material that could handle the extreme hot and cold temperature conditions that spacecrafts encounter. SOLIMIDE® Foams' resistance to heat flow make it ideal as a thermal insulator and its very-low density make it ideal for this weight-sensitive application. Following in NASA's footsteps, additional weight sensitive market segments, such as aerospace, naval and transportation, have sought similar performance and property characteristics. Add self-extinguishing and non-toxic generating properties and this makes SOLIMIDE® Foams a good fit for any vehicular application such as watercraft, passenger automotive, commercial vehicle, RV, aircraft and spacecraft.

## Thermal Properties

SOLIMIDE® Foam combines unique performance characteristics across a number of thermal specifications:

- Wide operating temperature range: from cryogenic (at which it retains its room temperature flexibility) up to 400°F (204°C) for most grades, and up to 575°F (300°C) for the specialized high-temperature HT-340 grade.
- Excellent insulation properties with low thermal conductivity numbers: 0.29 - 0.34 BTU-in/hr-ft²-F° (0.041 - 0.049 W/mK) at mean room temperature.
- It will char when exposed to flame, immediately self extinguish, and not retain a flame where most cellular products will ignite.
- Generates almost zero toxins when exposed to flame and has miniscule amounts of out gassing at room temperature.
- Extremely low formaldehyde off-gassing.
- Rated to Underwriter Laboratories UL94 V-0 Vertical Burn Test and passes several Federal Naval and Aviation Regulations.

Because the use of SOLIMIDE® Foam was increasing in fire-sensitive applications, studies of its fire safety became greatly important. Cone calorimeter testing for ignition, flaming combustion and smoldering combustion was conducted on SOLIMIDE® Foams' AC-500 and AC-530 products to support fire safety in these sensitive applications.

## Ignition: To set on fire

Because ignition is the initiation of fire, it is important to know how materials ignite and how to use this knowledge to reduce chances of ignition. This is especially critical for assessing fire hazards in fire sensitive applications, like space, water and air transportation. Table 1 shows average ignition characteristics of SOLIMIDE® Foam. It is important to note that neither material ignited until exposed to approximately 50 kW/m² incident heat flux, establishing the minimum incident heat flux (MIF), which is significantly higher than that of competing materials. The MIF of standard polyurethane foam (with density from 54 - 693 kg/m³) is less than 15 kW/m². SOLIMIDE® Foams' MIF is also much higher than most solid polymers, despite its extreme low density. It is also important to note the 50 kW/m² is the typical heat flux radiated from developed fire environments, meaning SOLIMIDE® can easily operate within extremely high temperature environments, up to the level of an active, developed fire.

| Incident Heat Flux (kW/m$^2$) | Time to Ignition (seconds) |
|---|---|
| AC-550; Spark Ignition; Minimum Heat Flux for Ignition: 48 kW/m$^2$ | |
| 75 | 2 |
| 65 | 6 |
| 55 | 117 |
| 50 | 167 |
| 48 | NI |
| 47 | NI |
| AC-530; Spark Ignition; Minimum Heat Flux for Ignition: 54 kW/m$^2$ | |
| 75 | 3 |
| 65 | 6 |
| 55 | 7 |
| 54 | 148 |
| 53 | NI |
| Note: NI: no ignition in 10 min. | |

Table 1: Ignition characteristics of SOLIMIDE® Foam (three tests, scores averaged)

Ignitability of foam materials strongly depends on foam thickness in addition to other characteristics. Table 1 illustrates thicker materials being resistant to ignition at high levels of incident heat flux. For foam materials, trapped air in the cellular structure may serve as a sort of heat sink; the thicker the foam, the larger the heat sink. This may explain the pronounced effect of foam thickness on ignitability of SOLIMIDE® Foam.

The decomposition temperature of SOLIMIDE® Foam is high and decomposition products do not readily burn. It was observed that SOLIMIDE® Foam smoldered and charred at the beginning of heat exposure higher than MIF, then ignited, but immediately returned to smoldering when the heat flux moved to lower than MIF. SOLIMIDE® Foam will not drive continual burning in an emergency situation.

Figure 1 shows the effect of incident heat flux and ignition mode on the time to ignition of AC-550.

## FLAMING COMBUSTION: ACTIVE BURNING DUE TO HEAT EXPOSURE, THE VISIBLE GASEOUS PART (FLAMES) OF A FIRE

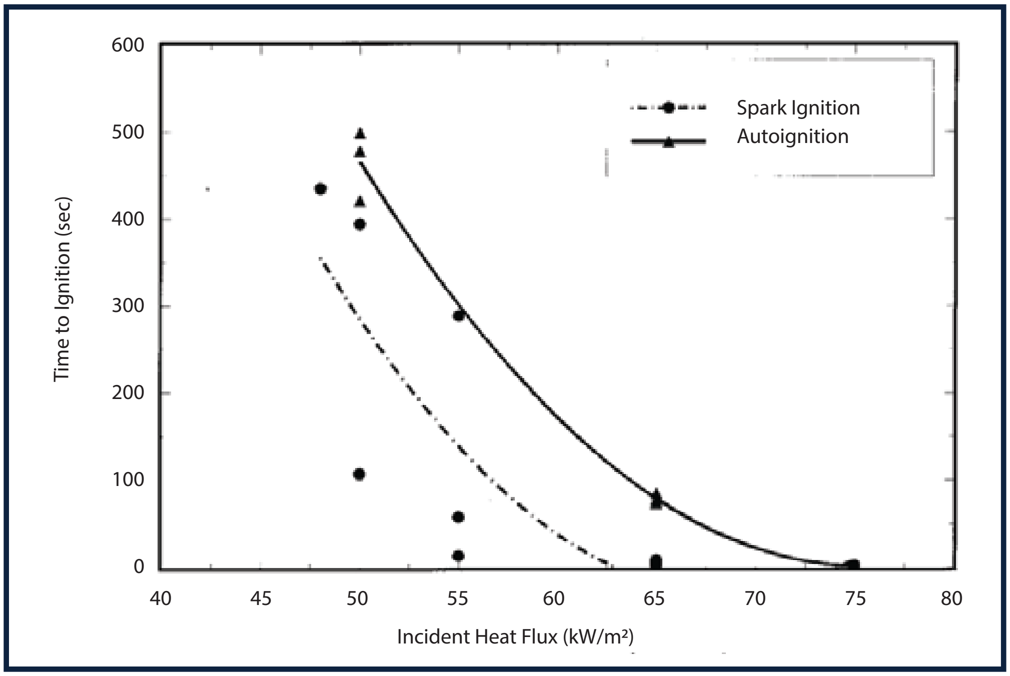

Figure 1: Effect of incident heat flux on the spark ignition and auto ignition of AC-550.

Cone calorimeter testing simulates the burning of a material initiated by an adjacent fire environment. 50 kW/m² incident heat flux typically radiates from a developed-fire environment. AC-530 at 2.5cm was tested at 50 kW/mk² and showed a comparatively low heat release rate, mass loss rate, total heat released, smoke production rate and carbon monoxide (CO) production rate. To investigate higher heat environments, testing was conducted on AC-550 and AC-530 foams at 55, 65 and 75 kW/m². Figures 2 and 3 show both of the heat release rate curves. The effect of incident heat flux on the peak heat release rate can be seen in Figure 4. Both foams exhibited very low peak heat release rates, even at the highest incident heat flux.

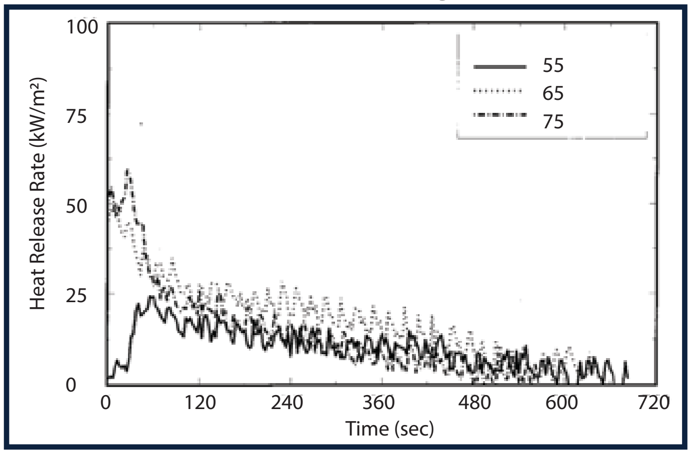

Figure 2: Heat release rate curves of AC-550

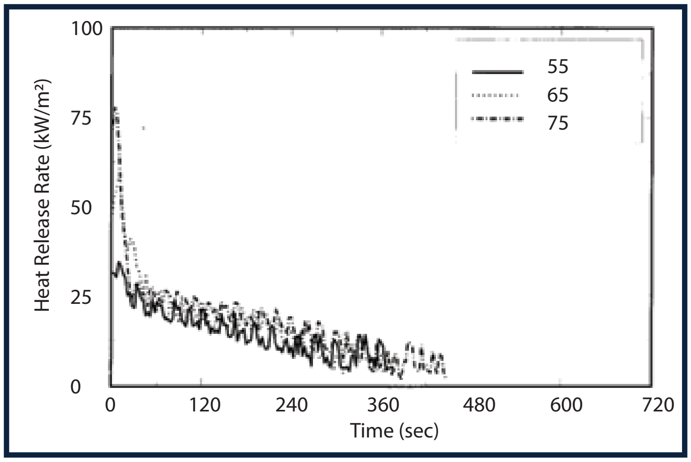

Figure 3: Heat release rate curves of AC-530

The net heat of combustion is the amount of heat generated from a combusted material. The net heat of combustion of polyimide foams (about 23.15 MJ/kg) is similar to that of polyurethane foams and silicone foams at optimal densities, however, their practical application densities are quite different. Because it is difficult to manufacture a low density silicone foam with a useful mechanical strength, the practical application density of silicone foam is limited to about 160 kg/m³ or above. The practical application density of polyurethane foams can be as low as 22 kg/m³. The net heat of combustion of silicone foam at applicable density generates 3936 MJ/m³ while polyurethane foam at applicable density generates 510 MJ/m³. SOLIMIDE® Foam is far superior in heat of combustion performance while significantly less dense (6 - 8 kg/m³) and lighter weight.

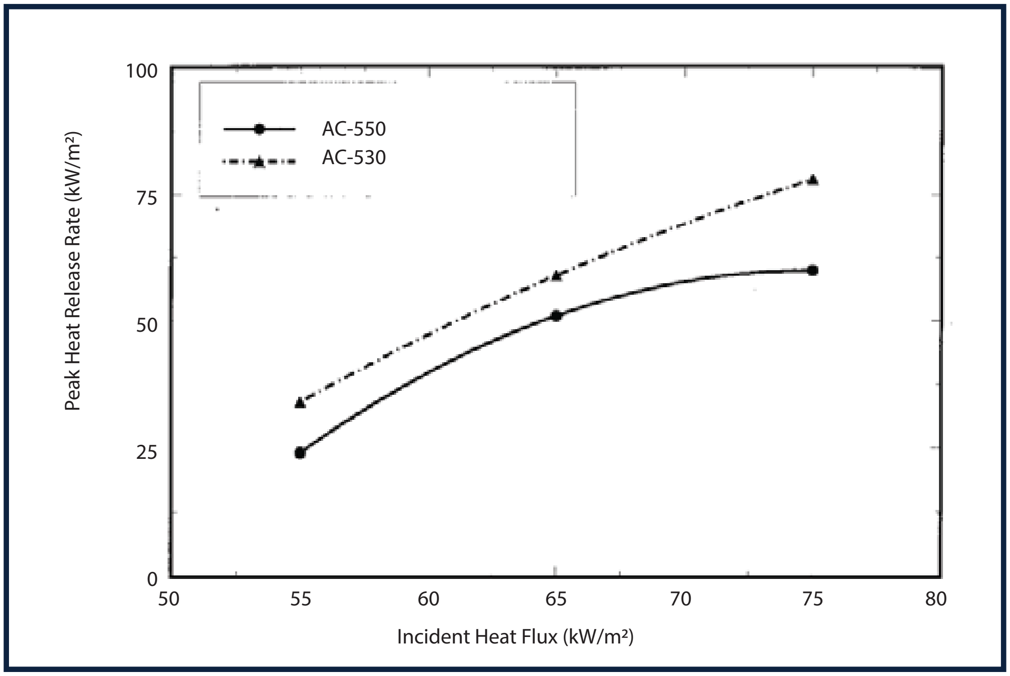


Figure 4: Effect of incident heat flux on the peak heat release rates of AC-550 and AC-530

Figures 5 and 6 show the (CO) yield curves of AC-550 and AC-530 in flaming combustion. Peak CO concentrations were generally lower than 0.01%, or 100 ppm, far below CO levels considered to be dangerous to human health. In the event SOLIMIDE® Foams flames, it will not produce CO at levels detrimental to human safety.

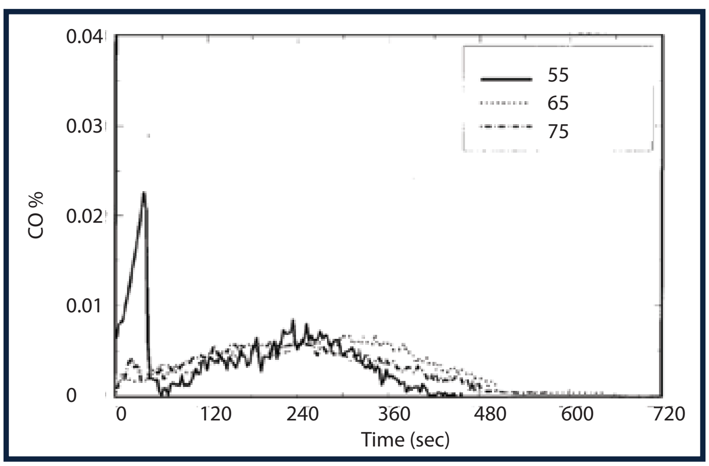


Figure 5: CO concentrations of AC-550

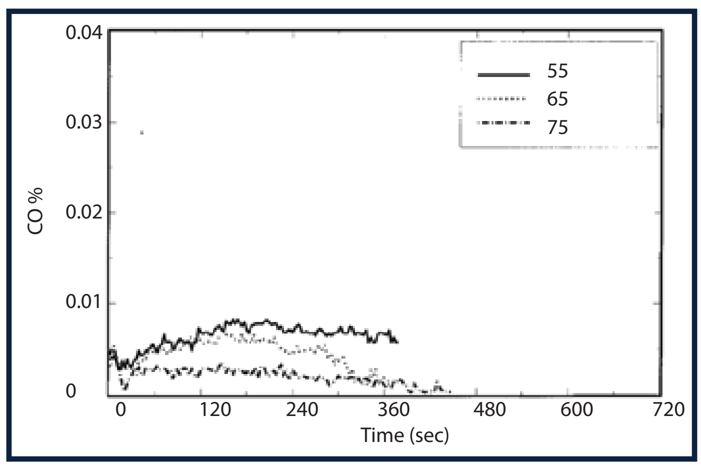


Figure 6: CO concentrations of AC-530

## SMOLDERING COMBUSTION: LOWER TEMPERATURE, FLAMELESS FORM OF COMBUSTION ON THE SURFACE OF A MATERIAL

Smoldering combustion of AC-550 was studied at heat fluxes lower than 50 kW/m² because the ignition study showed that MIF (ignition temperature) was 50 kW/m². Figure 7 shows weight loss curves of AC-550 when exposed to different heat fluxes. Test samples showed only slight charring with no significant change in physical structure, indicating that SOLIMIDE® Foams exhibited high thermal stability with only a small portion thermally decomposing.

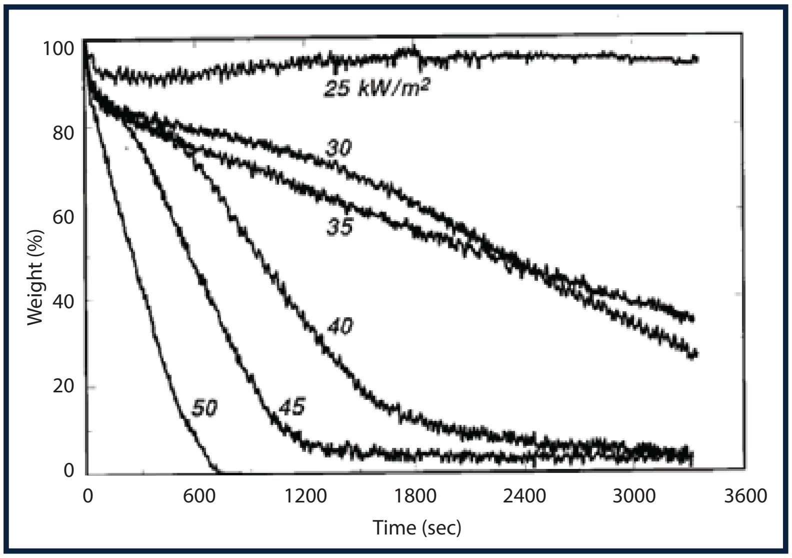


Figure 7: Weight loss curves of the smoldering combustion of AC-550, at various incident heat fluxes

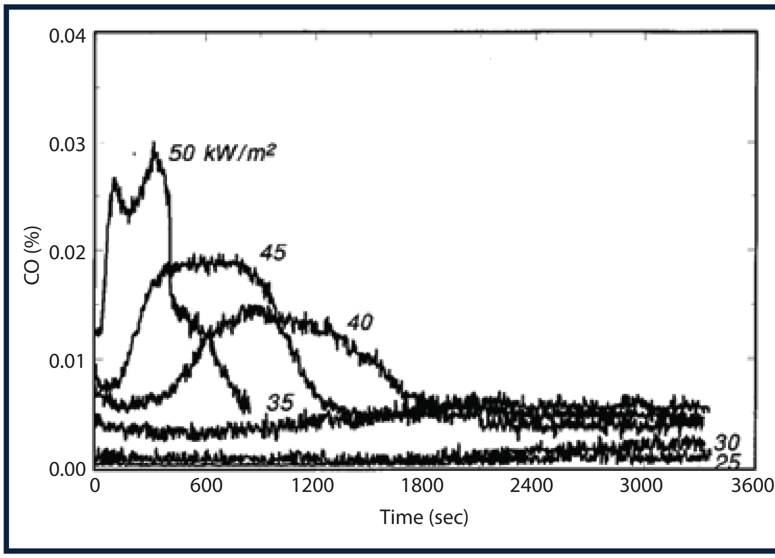


Figure 8: CO yield curves of the smoldering combustion of AC-550 at various incident heat fluxes

Comparing this to polyurethane foams with a MIF lower than 15 kW/m² that will burn readily at 25 kW/m², SOLIMIDE® Foams can withstand smoldering environments at much higher heat levels. This difference is mainly due to the thermal stability of the foam structures. SOLIMIDE® Foams experienced more significant charring at a heat flux of 30 kW/m², burned but did not transfer from smoldering to flaming combustion at 45 kW/m², and smoldered, charred and consumed 75% of its weight before flaming combustion occurred at 50 kW/m² heat flux. A critical external heat flux is needed to initiate the transition from smoldering to flaming combustion of SOLIMIDE® Foams. Figure 9 shows the weight loss curves of AC-550 when exposed to various incident heat fluxes.

Smoldering combustion generally generates higher concentrations of toxic compounds than flaming combustion. Figure 8 shows that the CO yield curves of smoldering combustion at various incident heat fluxes. At heat fluxes of 35 kW/m² or less, peak CO concentrations were generally lower than 0.005%, or 50 ppm. Average CO concentration of smoldering combustion at 45 kW/m² was 0.008%, or 80 ppm. SOLIMIDE® Foams can withstand high heat smoldering environments and still remain below the CO yield threshold considered safe for human exposure.

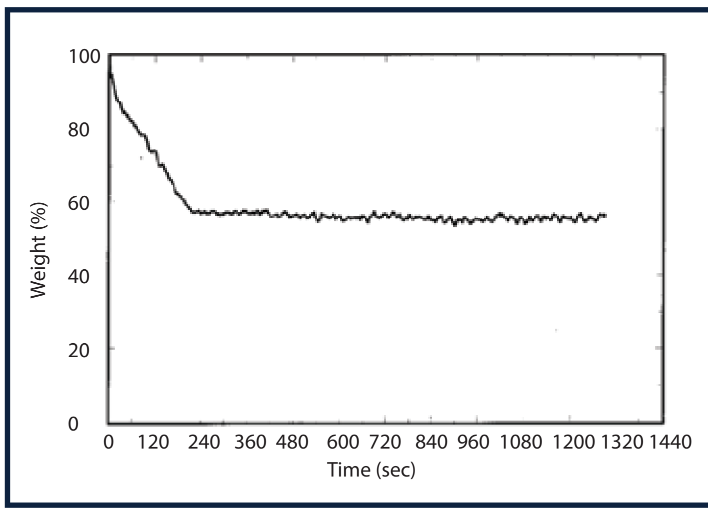


Figure 9: Weight loss curve of the smoldering combustion of AC-550, at 50 kW/m². The heater was turned off three minutes after the sample was exposed to the heat.

For a smoldering combustion environment, it important to know if combustion can be self-sustaining after removal of the external heat source. AC-550 was exposed to a heat flux of 50 kW/m² for three minutes and then the heater was turned off. Sample weight and CO yield were monitored, shown in Figure 9 and 10. The sample lost about 44% of its weight during exposure to the heat flux, then remained constant after the heat flux was removed. Similarly, CO concentration dropped to zero after the heat flux was removed, suggesting that the smoldering combustion of SOLIMIDE® Foam is not self-sustaining when a heat flux is removed.

SOLIMIDE® Foam exhibits high ignition resistance due to its thermal stability. Minimum heat flux for ignition of flaming combustion is much higher than most solid polymers (ignition environments). It also has very low flammability properties, even in extraordinarily high incident heat fluxes (flaming combustion). SOLIMIDE® Foam does not experience significant smoldering unless in incredibly high incident heat fluxes and will not self sustain once the heat source is removed (smoldering combustion).

Due to these inherent properties, SOLIMIDE® Foam is used as insulation in sensitive test equipment that measures airborne particulate and is the foam of choice inside the International Space Station. SOLIMIDE® Foam is an insulation component of nearly 100% of the commercial aircraft flying overhead today.

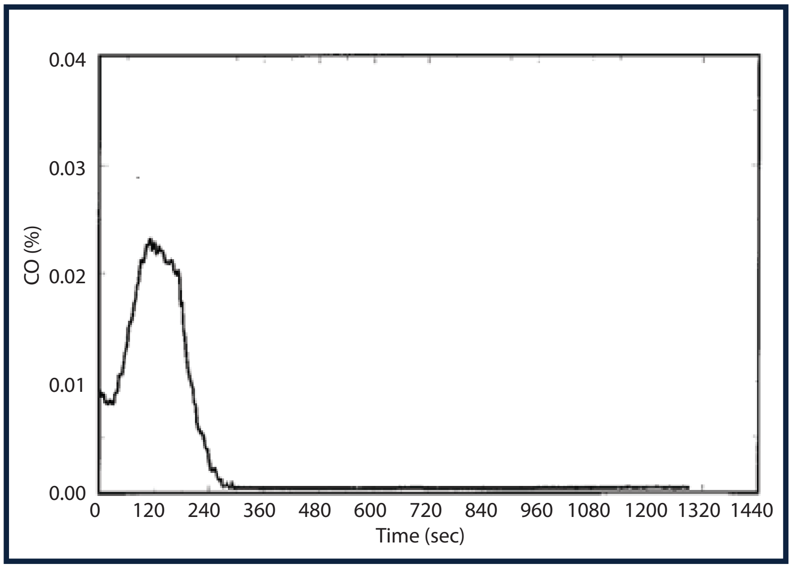


Figure 10: CO yield curve of the smoldering combustion of AC-550, at 50 kW/m². The heater was turned off three minutes after the sample was exposed to the heat.

## MECHANICAL PROPERTIES

SOLIMIDE® Foams' mechanical characteristics further contribute to its unique position in the foam spectrum and complement its thermal performance characteristics, driving utilization in transportation-related industries.

One of the unique attributes of SOLIMIDE® Foam is that is has a very low density range (between 0.34 - 0.55 pounds per cubic foot (PCF) (5.4 - 8.8 kg/m³)). One of the advantages of this solution is that the amount of fuel required can be substantially reduced because of the weight advantages of the foam, therefore increasing fire safety by removing combustible fuel. SOLIMIDE® Foam has a superior advantage because of its extreme low weight.

SOLIMIDE® Foam retains its physical form over time; it will not distort nor does it degrade over time due to vibration, humidity or exposure to continuous high temperatures -- making it ideal for applications with long life cycles.

SOLIMIDE® Foam is a fiber-free product, supporting clean manufacturing and processing environments.

## WHY IS SOLIMIDE FOAM UNIQUE IN THE FOAM SPECTRUM

SOLIMIDE® Foams have passed rigid federal smoke and toxicity tests in Aerospace, Naval and Railway applications. In the case of a survivable emergency aerospace landing with fire, the foam is part of an insulation system that resists post-crash fuel fire for up to five minutes, reducing fire hazard and expanding crucial time to escape as compared to alternative insulation systems that will combust quickly and with great heat. It is used as insulation in aircraft Environmental Control Systems (ECS) for its low weight and thermal performance, and in higher temperature bleed ducts and systems. In naval and rail applications, SOLIMIDE® Foam is used throughout as wall, ceiling and ducting insulation due to its low smoke and toxicity generating properties. Self-extinguishing properties add additional incentive to utilize SOLIMIDE® Foam, ensuring that foam insulation does not ignite and contribute additional danger to possible emergency situations in the event of an onboard fire.

Silicone foam or silicone sponge is often used in high temperature environments. This solution is rather dense and not ideal for weight-critical applications. The lightest silicone foam has a density of 12 PCF (192 kg/m³). The average SOLIMIDE® Foam density is 0.43 PCF, nearly 28 times less dense than silicone foam, with the added benefit of having lower thermal conductivity values.

Most foams at cryogenic temperatures become very rigid and will crack if bent. Some foams become so brittle when frozen that they shatter if dropped. SOLIMIDE® Foam retains its flexibility even in extreme cold conditions.

SOLIMIDE® Foam is dimensionally stable and easily accepts adhesives, meaning it is easy to assemble, improves manufacturing efficiency, and can be mounted in a vertical position without distorting or drooping. Fiberglass, a prime competing solution in high heat environments, in most cases must be attached with mechanical fasteners due to weight and dimensional stability. Attaching with mechanical fasteners adds cost and complexity to any vertical mount. Additionally, fiberglass can distort and degrade over time, requiring additional repair or replacement costs throughout the lifetime of a product.

## SOLIMIDE® FOAM CASE STUDIES

- SOLIMIDE® Foam was used in a home heating unit where vertical panels of foam could quickly be installed, replacing droopy fiberglass blankets and reducing weight in the system, assembly time and cost.
- SOLIMIDE® Foam was used in both oven-surround and refrigeration applications on an aircraft, solving both weight and thermal resistance problems in a cleaner, non-fibrous formulation as compared to conventional insulation materials.
- A ruggedized laptop application experienced display distortion due to temperature fluctuations between internal components during cold weather use. SOLIMIDE® Foam provided the thermal resistance needed to stop this distortion problem, promoting stable and reliable performance.
- Strips of SOLIMIDE® Foam with adhesive were assembled in a laptop lid application to channel cool air and shield heat sensitive components from a heat sink, promoting efficient and stable device operation.
- A telecommunication fiber-optics networking equipment manufacturer needed a low outgassing insulation material for their control unit. SOLIMIDE® Foams' near zero outgassing made it the best fit for the application and additionally provided much needed durability against degradation over time in fluctuating temperature environments.
- A food processing company needed insulation featured throughout their processes to be replaced. SOLIMIDE® Foam effectively performed in extreme temperature cycles from cryogenic to room temperature back to cryogenic. SOLIMIDE® Foams' flexible foam laminated with film liner was able to replace the traditional foam used in this application that required a stainless steel liner for stability. In addition to excellent performance throughout temperature cycling, SOLIMIDE® Foams brought significant weight savings to their insulation systems.
- A halogen light manufacturer needed to protect an electronic circuit from the heat of a bulb with very tight dimensional space. SOLIMIDE® Foam provided the thermal resistivity performance level needed in a super thin format.
- A hospital neonatal heating appliance manufacturer used ceramic fiber insulation in their assemblies that required manufacturing crews to wear personal protective equipment during the manufacturing process. By replacing this fiber insulation with SOLIMIDE® Foam, the manufacturer eliminated the need for personal protective equipment, increased employee morale, and boosted thermal performance efficiency of the unit resulting in lower costs to run the unit by the end customer.
- A large mining equipment manufacturer was able to replace polyester and polyurethane cabin insulations with the more fire retardant SOLIMIDE® Foam resulting in the double benefit of improved cabin acoustics and fire safety.

## HOW BOYD CORPORATION CAN HELP YOUR COMPANY SOLVE YOUR THERMAL INSULATION NEEDS

Boyd's testing database contains all SOLIMIDE® Foam grades with data from many common ASTM, ISO, UL and customer testing specifications. Combine this specification history with chemists and a long-tenured engineering group, Boyd Corporation's SOLIMIDE® Foams team can aid your company in troubleshooting, design, and execution of any thermal insulation solution for nearly any thermal challenge you encounter. Boyd takes pride in turning rapid prototypes, using water jet cutters, 3-axis CNC routers, CNC knife-cutters and CNC punch presses allowing Boyd to quickly product proof-of-concept solutions to assist you in selecting the best design and grade of SOLIMIDE® Foam for your application.

## CONCLUSION

SOLIMIDE® Foam is an excellent choice for any insulation needs requiring high temperature resistance, extreme temperature fluctuations, low weight, self-extinguishing properties and low smoke and toxicity generation. Combine these performance characteristics with the fact that SOLIMIDE® Foams are easy to use and assemble, and you can experience benefits spanning improved performance, increased safety, and improved margins through manufacturing efficiency savings.

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## Boyd Corporation

With decades of experience and a wholly-owned global footprint, Boyd provides best-cost, engineered, specialty material-based energy management and sealing solutions through comprehensive technical materials and design expertise, world-class manufacturing quality and service reliability, and unparalleled supply chain management.

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