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LAST-A-FOAM® FR-3700 Series Foam: Crash & Fire Protection for Nuclear Transportation Containers

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Abstract

General Plastics Manufacturing Company's LAST-A-FOAM® FR-3700 series foam has a history of successful use for radioactive material shipping containers. The LAST-A-FOAM® FR-3700 formulation is specially designed to allow predictable impact-absorption performance under dynamic loading, while also providing an intumescent char layer that insulates and protects hazardous materials, even when exposed to pool-fire conditions.

In this study, General Plastics attempts to simulate a severely damaged nuclear transportation container in which the foam has been crushed and contained within the container as a single, highly compressed mass. A series of differing densities of FR-3700 series foams were subjected to crush strengths exceeding 50%, then subjected to thermal attack using an oil burner test apparatus. Thermal transfer through the foam, intumescence, burn distance, and plastics memory were monitored and will be discussed.

Migration of heat through the foam was found to be extremely low, the effects of intumescence on burn length and protection of the foam beneath the intumescent char layer performed as expected, and burn distance compared to flame exposure time was minimal. For specimens that were crushed prior to thermal testing, the final solid foam length, after removing the intumescent char layer, was slightly longer than the length before thermal testing. The heat cycle relieved stresses in the crushed foam causing expansion of the foam.

The information presented in this paper will help designers of radioactive material shipping containers understand the value of time that LAST-A-FOAM® FR-3700 series foam offers. The slow rate of heat transfer through the LAST-A-FOAM® FR-3700 formulation provides first responders sufficient time to respond to a radioactive material shipping container accident that includes an accidental fire.

Introduction

LAST-A-FOAM® FR-3700 has a 45-year history of successful use for radioactive materials shipping containers. The regulations governing radioactive materials shipping containers often require the shipping container to endure energy absorption accident conditions of 9 meter (30 feet) free drops and exposure to a 800 ºC (1,475 ºF), 30-minute pool fire. LAST-A-FOAM® FR-3700 is a unique material that can serve the dual purpose of assisting the radioactive materials shipping container design in mitigating both mechanical and thermal energy. This paper builds on previous studies published by General Plastics Manufacturing Company (1-7).

Test Method

Dynamic Compressive Testing

Dynamic compression tests at strain rates of 64 sec^{-1}, 103 sec^{-1}, and 180 sec^{-1} were conducted in the General Plastics test laboratory utilizing a 10 meter guided drop tower, designed by General Plastics (see Fig. 1). The impact mass includes stackable weights, a shuttle guide and a lifting plate, secured together with threaded rod. Two primary weights of approximately 133 kg and additional steel rounds of various weights can be assembled to produce a maximum weight of approximately 350 kg. Attached to the shuttle is a 7.6 cm wide fin that serves as a trigger for the timing lights. The shuttle and the entire mass are guided by two, 10 m long vertical stainless steel cables.

Figure 1 Dynamic Test Apparatus

The impact surface is a 5 cm thick, 32 cm X 32 cm square steel plate fastened to a larger 5 cm thick, 1.2 m X 1.2 m square steel base plate. This steel plate assembly is attached and nested into a 3,600 kg mass of concrete using six large threaded rods welded to a re-bar mesh encased in the concrete mass.

A 0-900 kg CAS digital scale was used to measure the suspended mass of each combination of weights used. A Kistler Instrument accelerometer is secured to the impact mass, just below the shuttle guide. Raw impact data is captured through Lab View for analysis. The impact mass assembly is secured to a hydraulic lift using a TR3 Sea Catch quick-release toggle that is released using a lanyard. An infrared timing light is attached to two plates through which the shuttle fin passes during the test, activating the timing light beam.

Drop heights of 15 cm to 109 cm were used, resulting in strain rates of 63 sec^{-1} to 180 sec^{-1} at the point of impact. All tests were conducted using specimens conditioned at 22 ºC. Adjustments to the mass were made as needed to achieve crush distances as strains as close to 70% as possible while ensuring strain rates above 60 sec^{-1} were maintained. Thin aluminum foil tubes are placed beside the test specimens and crushed simultaneously to record the maximum strain experienced by the foam specimen. The foil crushes with zero rebound, unlike the foam.

Static Compressive Testing

Static compressive testing was performed using an MTS Sintech 30/G Universal Testing Machine with a maximum load cell capacity of 150 kN. Testing was performed per ASTM D1621 at a rate of 2.5 mm/min until a final strain of 70% was achieved. Test specimen cross section was 25.8 cm^2, with the exception of the 30 pcf density foam sample, which had a specimen cross section of 6.45 cm^2. The 30 pcf density foam sample cross section needed to be reduced in order to achieve 70% strain. All conditioning and testing occurred at 22 ºC. Five test specimens were tested for each foam density.

Thermal Testing

For thermal testing, blocks of FR-3700 series foam, measuring 25.4 cm x 35.6 cm x 35.6 cm (10″ x 14″ x 14″) were cut from large, manufactured blocks for densities of 4, 6, 10, 18 and 30 pounds per cubic foot (pcf) density (64, 96, 160, 288, and 480 kg/m^3).

Fifteen (15) each thermocouples were attached radially at various depths through the back side of each block of foam. Three (3) each thermocouples were positioned at depths of 0, 4, 8, 12 and 16 cm. The thermocouple at 16 cm depth was the closest thermocouple to the flame surface. Zero (0) cm refers to the back side of the foam block and farthest from the flame surface.

The foam block was secured in a metal frame and flush against a one-inch ceramic board. A four-inch square opening allowed exposure of the flame to the foam surface. Thermocouples, attached to the back side of the foam were insulated with 4″ of ceramic wool and 1/2″ ceramic backer board to protect the thermocouples from transient heat. A 1/4″ ceramic blanket, with a 6″ cutout, was placed in front of the test unit to reduce transient heat from circulating around the foam block.
A Park oil burner, configured for FAA Seat Cushion Testing, using #2 diesel fuel, was used to produce an average 814 ºC flame with a heat flux of 9.38 $Watts/cm^2$ when positioned 25 cm from the foam test face. The burner was permitted to warm up for one minute prior to aligning the flame to the foam test face. The flame was applied directly to the foam test face for 30 minutes, then removed from the foam test face.

A temperature recorder monitored the temperature of each thermocouple throughout the duration of the 30-minute flame test, and continued to record temperatures for an additional 5 ½ hours, for a total of 6 hours, to monitor migration of heat through the foam test specimen, as well as cooling rates.

All pre-test and post-test foam weights were collected, the intumescent char length recorded, then removed and the remaining foam depth measured.

Intumescence Testing

FR-3710 foam specimens were cut to 2″ cubes, center-drilled parallel to the direction of rise, and skewered to a 1″ thick ceramic insulation board. All specimens were accurately measured and weighed prior to testing. Two specimens were tested in the as-cut condition. Two specimens were tested following compression to 50% of their original height. Compressed specimens were allowed to recover for two minutes, then accurately measured immediately prior to thermal testing. This approach simulates an impact incident, shortly followed by a post-crash fire. Standard muffle furnaces with inside dimensions of 6″ x 6″ x 6″ were used to expose the specimens to 800 ºC radiant heat for 90 seconds. The overall thickness of the foam specimen and intumescence were measured after removal from the muffle furnace. The intumescent char layer was removed and the solid foam thickness and weight were recorded.

Dynamic & Static Strength Test Results

When evaluating the stress-strain curves for the FR-3700 series foam, the Y-axis represents the load or force applied to the specimen, and the X-axis represents the strain or compression of the specimen under load. Whether the compression of the FR-3700 series foam specimens is dynamic or static, both modes of compression exhibit an initial yield point near 10%. A small change in stress is observed from 20%-40% strain, and the stress begins to increase around 50%, then exponentially increases around 65%-70% strain.

Dynamic stress is higher than static stress initially at 10% strains. On average, the compressive strength of FR-3700 series foam at the initial 10% yield point was approximately 60% higher for dynamic testing compared to static testing for all densities.

Although dynamic impacts and static loads have dramatically different modes of occurrence the stress-strain curve for either mode will exhibit similar properties. A dynamic impact undergoes a major transition within a matter of micro seconds, whereas, a static load is a slowly increasing load over a period of time.

Figures 2-4 present the dynamic and static compressive test results for FR-3706, FR-3718, and FR-3730. The dynamic and static stresses for FR-3706, FR-3718, and FR-3730 are very similar, but for strain rates approaching 60%-70% strain, the stress increases earlier for static testing. Most densities see a transition point between 50%-60% strain where the static test data tends to have a higher compressive strength compared to dynamic testing.

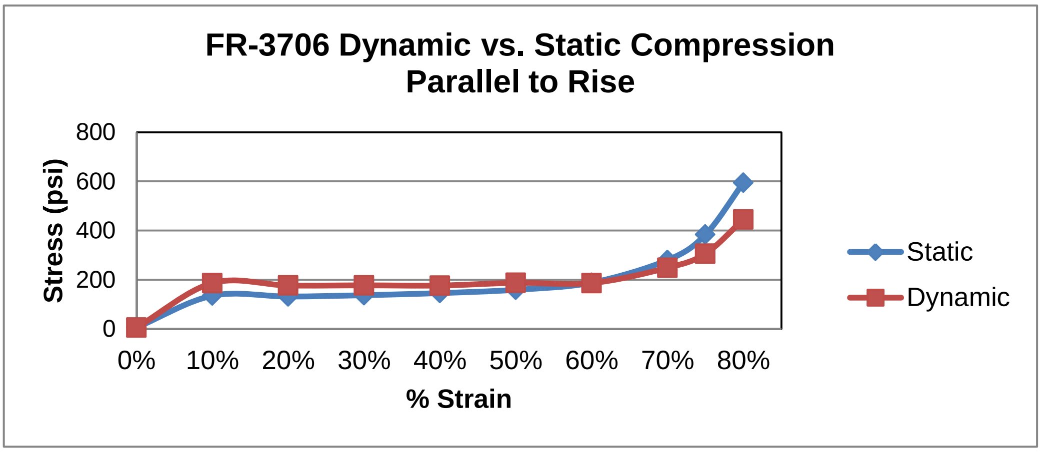

Figure 2 FR-3706 Dynamic and Static Test Result

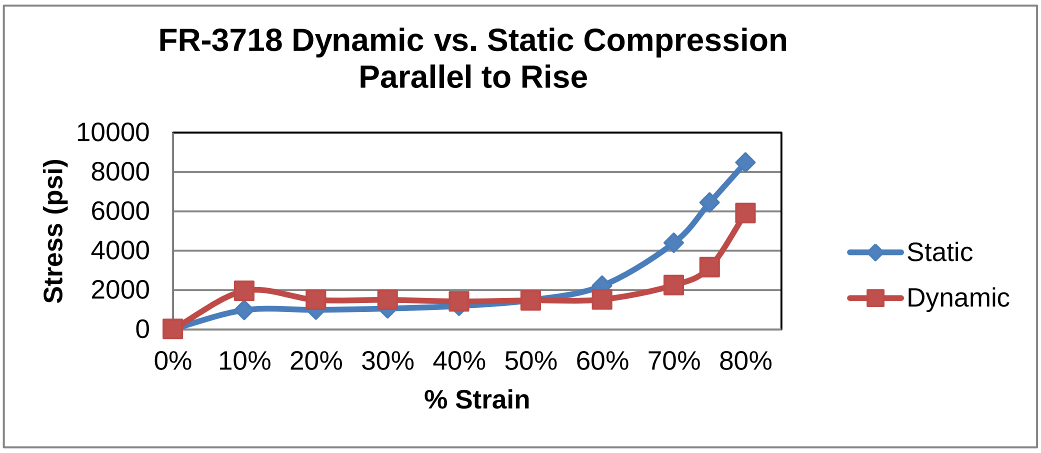

Figure 3 FR-3718 Dynamic and Static Test Result

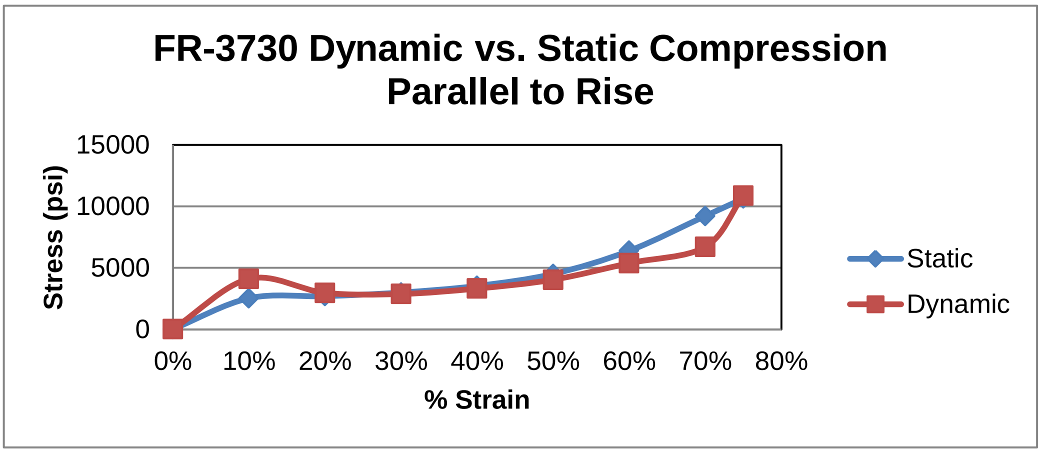

Figure 4 FR-3730 Dynamic and Static Test Result

Thermal Test Results

Figure 5 presents the test setup and oil burner configuration used for all thermal tests. Thermocouples were strategically placed at 0, 4, 8, 12, and 16 cm deep from the back face of each foam density sample, 0 cm being the back face of the foam, and 16 cm being the distance from the back face of the foam, and closest to the flame front.

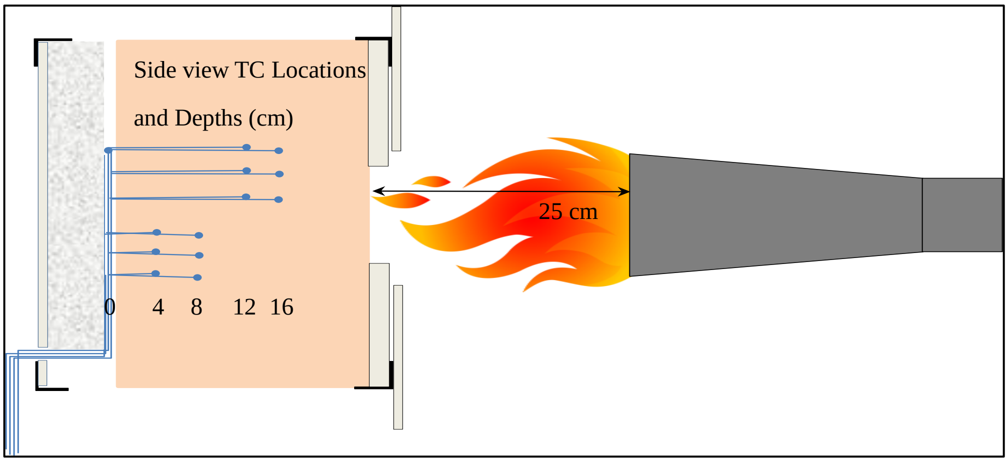

Figure 5 Test Setup and Oil Burner Configuration

Figures 6-8 present the temperature profiles at three separate depths (16 cm, 8 cm, and 0 cm) for each foam density. The lowest density specimen (FR-3704), experienced thermal degradation and charring to a depth reaching both thermocouples located at 16 and 12 cm from the back face of the test specimen. However, the insulating properties of the intumescent char plug are evidenced by the maximum temperature reading of approximately 400 ºC, or 50% of the 800 ºC flame temperature at the deepest thermocouple (16 cm). Exposed thermocouples (16 and 12 cm) were well protected by the intumescent char layer from any direct contact with the flame, keeping the foam temperature significantly lower than the measured flame temperature. Thermal degradation and charring never reached any of the thermocouples for the 18 pcf and 30 pcf density foam.

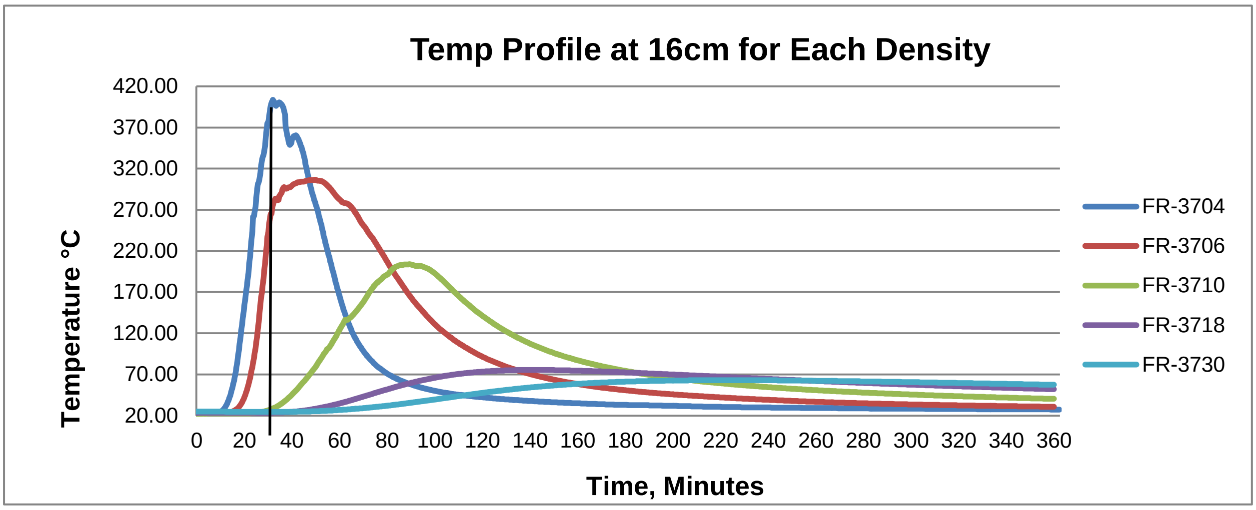

Figure 6 Temp Profile at 16cm

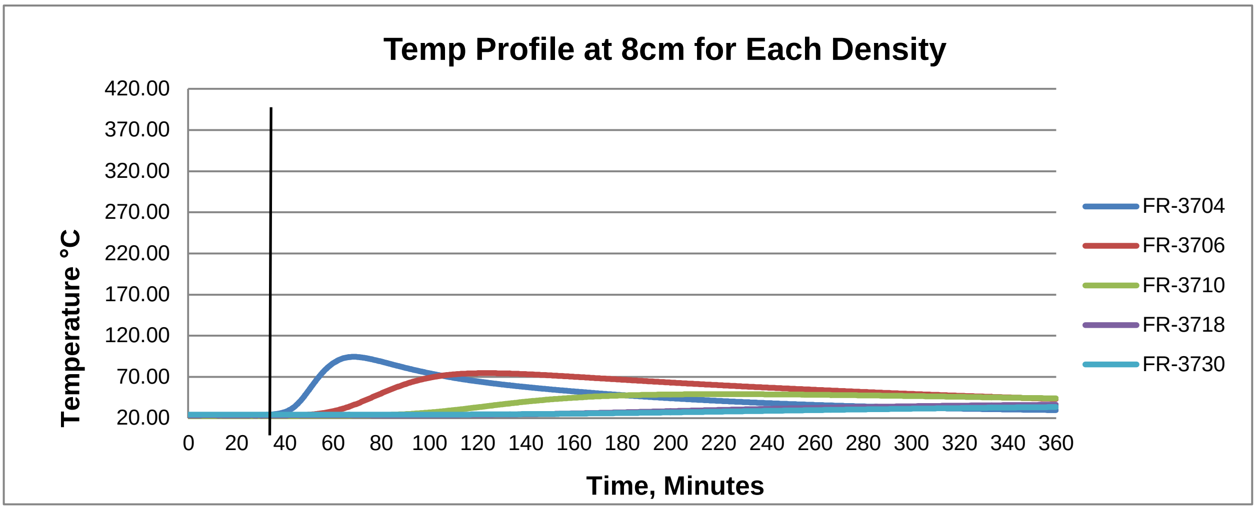

Figure 7 Temp Profile at 8cm

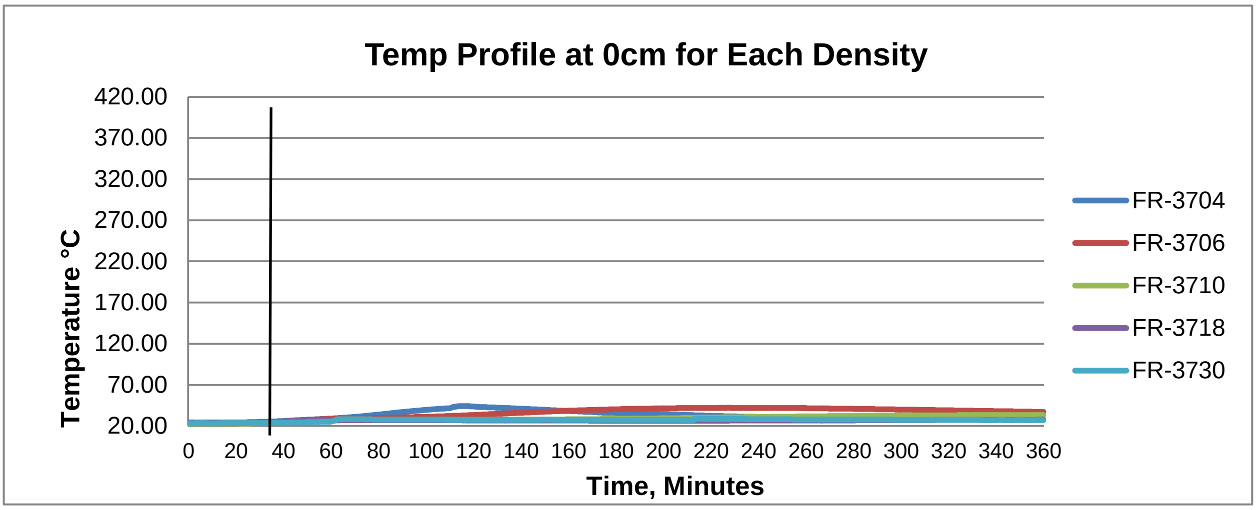

Figure 8 Temp Profile at 0cm

Thermal transfer of heat through the lower density foams (4 pcf and 6 pcf densities) is likely due to further progression of the flame into the foam thickness, while the higher density foams (10 pcf, 18, pcf, and 30 pcf densities) exhibit higher heat transfer which is most likely due to lower insulating properties with higher thermal conductivity. Thermal conductivity increases with increased foam density, while thermal transfer resistance decreases with increased foam density.

Thermal degradation (weight loss and burn depth) is presented in Figure 9. The weight loss and burn depth for foam densities from low to high density are quite linear.

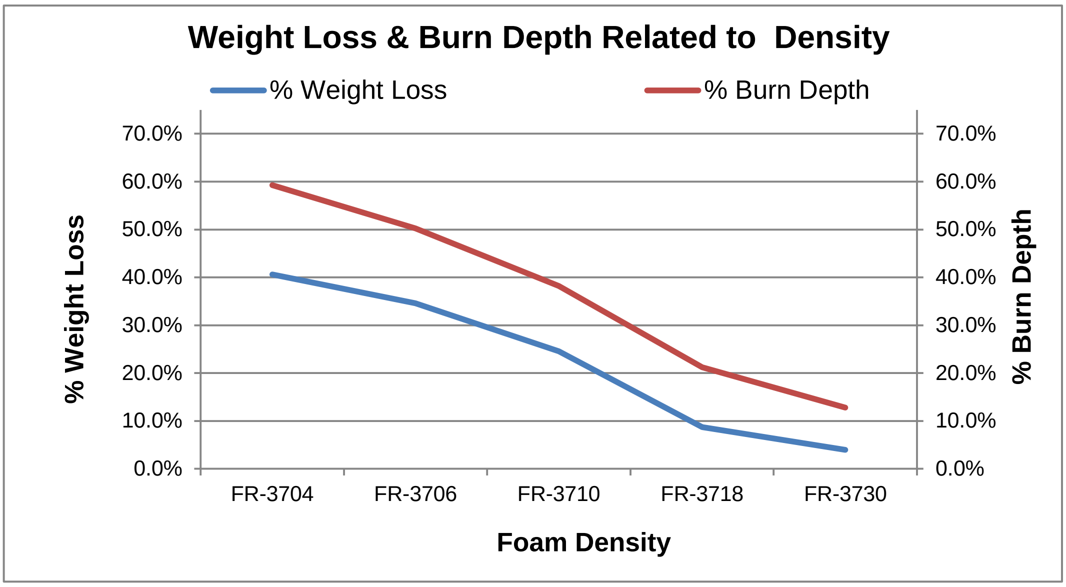

Figure 9 Weight Loss & Burn Depth Related to Density

The 18 pcf density foam (see Figure 10) displayed the lowest maximum temperature at the foam back surface, as well as taking the longest time to reach the maximum temperature at the foam back surface. The 30 pcf density foam had a slightly higher maximum temperature as compared to the 18 pcf density foam, and also reached the maximum temperature in less time. None of the foam densities experienced a foam temperature greater than 45 ºC at the foam back surface. Furthermore, all the foam densities showed a **rate of rise (ºC per minute) at the foam back surface of less than 0.2 ºC per minute over the entire duration** taken to reach the maximum temperature at the foam back surface, demonstrating outstanding thermal transfer resistance.

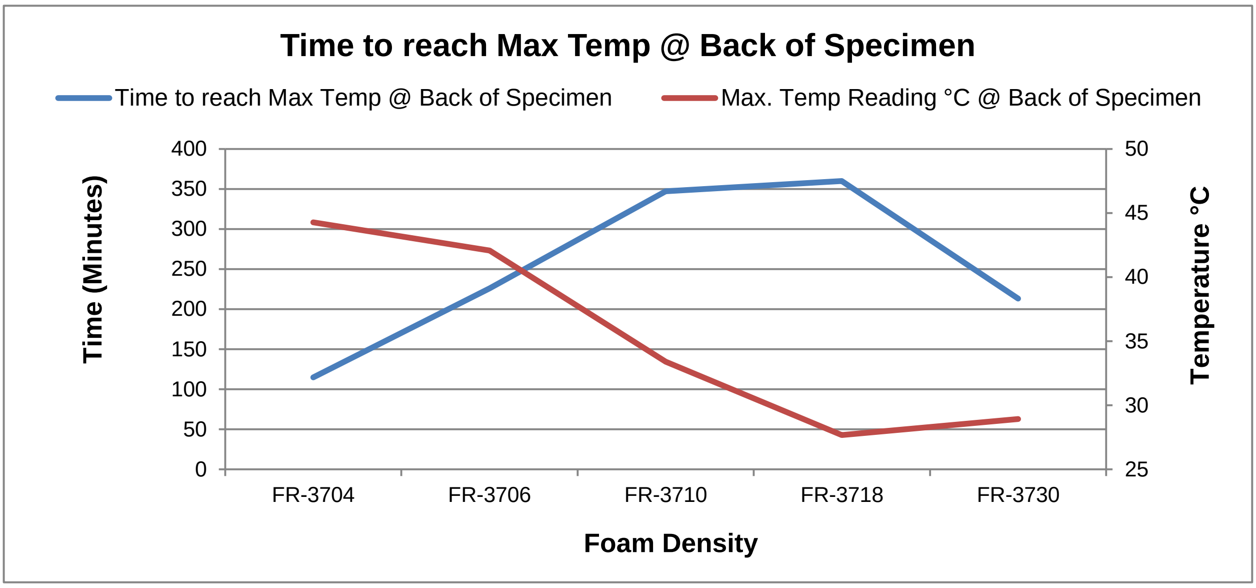

Figure 10 Time to Reach Max Temp

Regarding foam intumescence, the 10 pcf density foam experienced the highest amount of intumescent char while demonstrating similar thermal performance (maximum temperature and rate) to the 18 pcf density foam. Furthermore, video recordings confirm the 10 pcf density foam demonstrated the greatest ability to continuously produce an intumescent char layer during the test.

Intumescence Test Results

Figure 11 presents a picture of FR-3710 foam specimens immediately after removal from the muffle furnace and the intumescent char layer removed. The uncompressed foam specimens displayed an average intumescent growth of 177%, based on the foam dimensions immediately measured prior to thermal exposure within the muffle furnace. The compressed foam specimens displayed an average intumescent growth of 238%, based on the foam dimensions immediately measured prior to thermal exposure within the muffle furnace. The post-test solid foam height for the uncompressed foam specimens was reduced by an average of 19% due to material loss (intumescence) of the foam specimen during thermal exposure. The post-test solid foam height for the compressed foam specimens was increased by an average of 7% due to plastic memory of the foam specimen during thermal exposure. The final specimen weight loss due to thermal assault was, on average, approximately 8% greater for the compressed foam specimens as compared to the uncompressed foam specimens.

Figure 11 Small Scale Intumescence

Should a post-crash fire take place, the ability of the FR-3700 series foam to intumesce and continue protecting the nuclear payload does not appear to be lessened due to extreme thermal conditions. It appears plastic memory and the resultant growth of the foam, combined with intumescence may have additional advantages. Considering the 5 chosen densities of foam (4, 6, 10, 18, and 30 pcf densities), the 18 pcf density foam appears to be the best balance of insulating properties and conductive heat transfer, while the 10 pcf density foam provided the best intumescent properties and overall, performed thermally close to the 18 pcf density foam.

Conclusions

General Plastics Manufacturing Company's LAST-A-FOAM® FR-3700 series foam has a history of successful use for radioactive material shipping containers. Whether the compression of the FR-3700 series foam specimens is dynamic or static, the passive protection of LAST-A-FOAM® FR-3700 series foam, when used as an impact liner in transport containers, is specially designed to allow predictable impact-absorption performance under dynamic loading.

Under thermal assault, LAST-A-FOAM® FR-3700 series foam demonstrates outstanding thermal transfer resistance. The resultant growth of the foam due to plastic memory, combined with an intumescent, insulating char in fire situations, keeps excessive heat from dangerous nuclear payloads.

The information presented in this paper will help designers of radioactive material shipping containers understand the value of time in an accidental fire that LAST-A-FOAM® FR-3700 series foam offers. The slow rate of heat transfer through the LAST-A-FOAM® FR-3700 formulation provides first responders sufficient time to respond to a radioactive material shipping container accident that includes an accidental fire.

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