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Burn Testing of Polyurethane Foam Shielded with Ceramic Fiber Paper

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Abstract

During the design of a new fresh fuel package, testing was performed to examine and optimize the use of polyurethane foam, in combination with ceramic fiber paper, to protect a nylon neutron moderator from melting in a regulatory fire test. The characteristics tested were the polyurethane foam density and thickness of ceramic fiber paper. Burn test specimens included a typical cross section of the package lid. The test specimens were monitored with several thermocouples during the fire test and cool down period.

The primary objective was to determine the lightest density polyurethane foam and minimum thickness of ceramic fiber paper capable of protecting the nylon moderator from melting. The total stack height of the foam and ceramic fiber paper was constant and a specified design constraint. The results demonstrated that six pound per cubic foot foam and one-half inch of ceramic fiber paper provided sufficient thermal protection for the nylon moderator.

1.0 Introduction

Bucket burn testing is a simple and efficient method for performing burn tests on various materials. The “bucket” is merely a standard five-gallon, thin gauge metal bucket for holding the test specimen(s). Bucket burn tests are typically used to study the thermal performance of polyurethane foam. Polyurethane foam, specifically General Plastics Last-A-Foam FR-3700 will be used as an impact absorber and thermal barrier in the package. The purpose of these tests was to determine, for a representative one-dimensional geometry through the thickness, what density of foam is necessary to prevent the package nylon neutron moderator from melting. The ceramic fiber paper and its thickness were also evaluated for affect on thermal protection performance. The event for which the nylon moderator must be protected is the regulatory fire in accordance with 10CFR71 Section 71.73(c)(4) [1]. The bucket burn tests simulated the regulatory fire test with a 30 minute exposure to an engulfing flame on the lid of the bucket. The buckets are burned horizontally with the flame directed at the lid, see Figure 1. A shield protects the side of the bucket from direct flame exposure, to minimize edge affects caused by elevated temperatures on the sides and back of the bucket. This thermal protection is enhanced by the fact that the tests are conducted under a ventilated hood, which reduces the heating of the air surrounding the test setup.

A total of four bucket burn tests were performed. The geometry and layout of each of the buckets were similar. The test variables were foam density and thickness, and number of ceramic fiber paper layers. The total stack height was kept constant; therefore an additional layer of ceramic fiber paper required a decrease in the foam thickness. The ceramic fiber paper used in these tests was ¼” thick.

The ceramic fiber paper contains no asbestos, is primarily comprised of alumina silica fibers, has a melting temperature of 3200°F, and a maximum use temperature of 2300°F. The nylon moderator tested was 1.25” thick and has a melting temperature between 482°F and 509°F. None of the nylon moderator test specimens exhibited any signs of damage or melting. The bucket burn tests were conservative in terms of both flame temperature and flame time exposure. The actual flame temperatures achieved in the testing were approximately 1800°F to 2000°F, whereas the regulatory flame temperature is specified to be 1475°F. Second, the regulatory exposure to the fire is specified to be 30 minutes from the start of the fire, whereas for the testing the 30 minute timer was not started until the face (lid) of the bucket reached 1475°F. Therefore, each bucket was exposed to the flame for approximately 32 minutes. The flame nozzle was placed approximately 4 inches from the bucket face (lid) and 1 inch below the bucket center. The nozzle placement is typical for General Plastics burn tests.

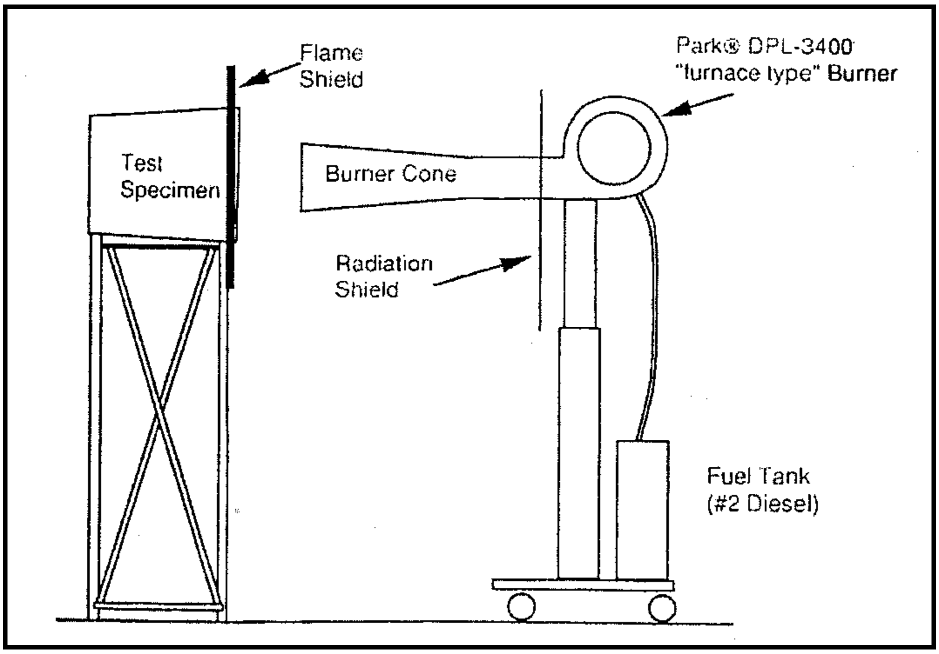


Figure 1 – Bucket Test Arrangement

2.0 Instrumentation

Each bucket was monitored for temperature during the burn test with 18 thermocouples. Small holes were drilled in the shell of the bucket for the thermocouples. The thermocouples were punched into the foam at various elevations and depths, see Figure 2. Additional thermocouples were placed in contact with various components, also noted in the aforementioned figure. Some of the components like the top of the aluminum plate and bottom of the foam block had small grooves machined out for the thermocouple wires. The grooves allowed flush interfaces with the nylon moderator. A data recorder was used to collect the temperature information during the fire tests and during the cool down period, which typically lasted an hour and a half (until the specimen could be handled for the post-inspection). The data was recorded at 15 second intervals.

3.0 Bucket Configurations

The bucket configurations are set up to model a typical section of the package lid. The buckets have an 11 gauge stainless steel (Type 304) lid, followed by one or two layers of ceramic fiber paper. The Last-A-Foam FR-3700 foam is behind the ceramic fiber paper and directly in front of the nylon moderator. Under the nylon moderator is an aluminum plate that models the combined package poison and inner lid sheet. Under the aluminum plate there is an air gap that is approximately the distance between the inner lid surface and the corner of a fuel assembly.

After the air gap is a steel plate that has a mass similar to the package fuel weight per equivalent package surface area. The steel plate was supported by layers of alumina-silica board, which is a heat resistant product. The alumina-silica board was chosen because it off-gasses very little when heated and is effectively benign in the testing process. The steel plate was restrained on the top side with four small screws fastened through the wall of the bucket. The aluminum plate and other materials were propped up by another set of four small screws fastened through the wall of the bucket, also they were blocked up with four pieces of alumina-silica board, see Figure 5 to view the blocking after half the bucket shell is removed. The screws were isolated from contacting the shell of the bucket with ceramic fiber paper. The screws and blocking maintained the desired air gap. Additional care was taken in the assembly of the test buckets to isolate the components from heat input through the side of the buckets. This included wrapping a layer of ¼" ceramic fiber paper around the inside circumference of the buckets.

The bucket test specimens were typically configured as shown in Figure 2. The configuration for the fourth bucket was almost identical to the third bucket. The testing on the fourth bucket was intended to be a confirmation of the test results achieved with the third bucket test. The only difference between the third and fourth buckets was that the third bucket did not have the ceramic fiber paper cut-out around the vent hole in the bucket lid, whereas the other buckets did have the ceramic fiber paper cut-out around the vent hole. Additionally, the vent hole location between the four buckets was slightly different. The first and fourth buckets had the vent hole at the center plane, but offset a couple inches toward the top of the bucket. The second and third buckets had their vent holes at the center plane, but offset a couple inches toward the bottom. The location of the vent hole did not appear to significantly impact the results. The vent hole in each bucket was approximately 1" in diameter, which is standard for General Plastics burn tests. Additional venting in each bucket occurred through the lid-to-bucket seam. The lid was skip welded to the bucket, which left sections around the perimeter open for venting. Although, these sections are separated from the foam by layer(s) of ceramic fiber paper, the foam off-gassing can pass through the paper, but at a potentially reduced rate. An example of the venting or off-gassing can be seen in Figure 5, note the black residue pattern from the vent hole and traces around the lid perimeter. Table 1 summarizes the different parameters tested with each bucket.

Table 1 – Bucket Test Parameters

Parameters	Bucket 1	Bucket 2	Bucket 3	Bucket 4
Ceramic Fiber Paper Layers / Total Thickness (in)	1 / 0.25"	2 / 0.50"	2 / 0.50"	2 / 0.50"
Foam Density (pcf)	8	8	6	6
Foam Thickness (in)	4.00	3.75	3.75	3.75
Vent Hole Location (relative to center)	above	below	below	above
Vent Hole Paper Cut-Out	yes	yes	no	yes

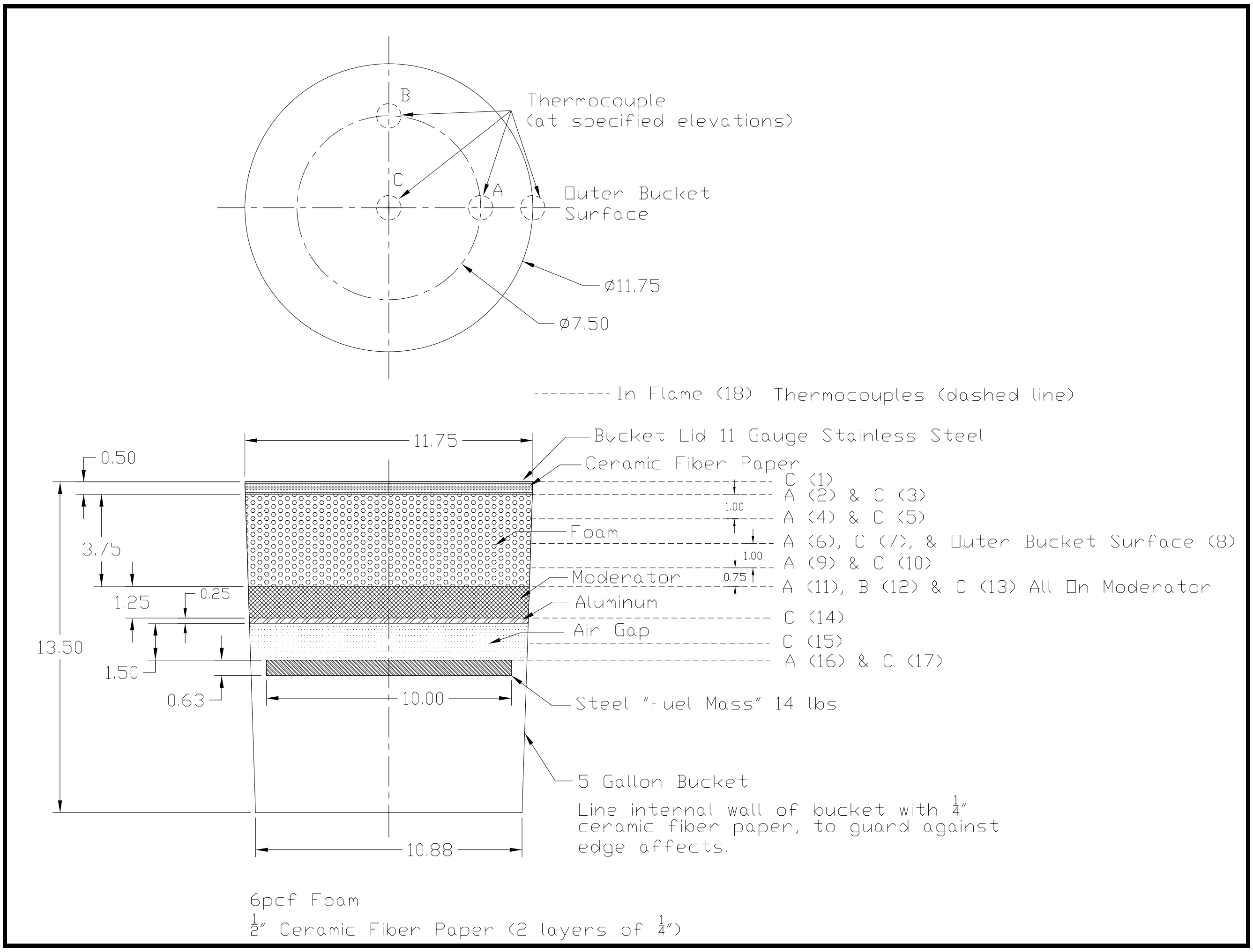


Figure 2 – Typical Bucket Configuration, Cross Section and Plan View

4.0 Temperature Data

The maximum nylon moderator temperature for each of the four buckets in order was: 469°F, 184°F, 297°F, and 260°F. The average temperature of the nylon moderator for each bucket in order was: 234°F, 151°F, 218°F, and 172°F. At no time did the temperature of the nylon moderator reach its melting temperature of 482°F. The nylon moderator maximum average temperatures were approximately 2 to 3 times less than its melting temperature. The trend between results shows that having two layers of ¼" thick ceramic fiber paper provides better thermal protection than one layer. The charts in Figure 3 and 4 show the temperature data recorded for bucket 4 versus time, and the average temperature data compared between bucket 3 and bucket 4.

Table 2 – Moderator Temperature Data

Temperature Data	Units	Bucket 1	Bucket 2	Bucket 3	Bucket 4
Peak Moderator Temperature	°F	469	184	297	260
	°C	243	84	147	127
Average Moderator Temperature	°F	234	151	218	172
	°C	112	66	103	78

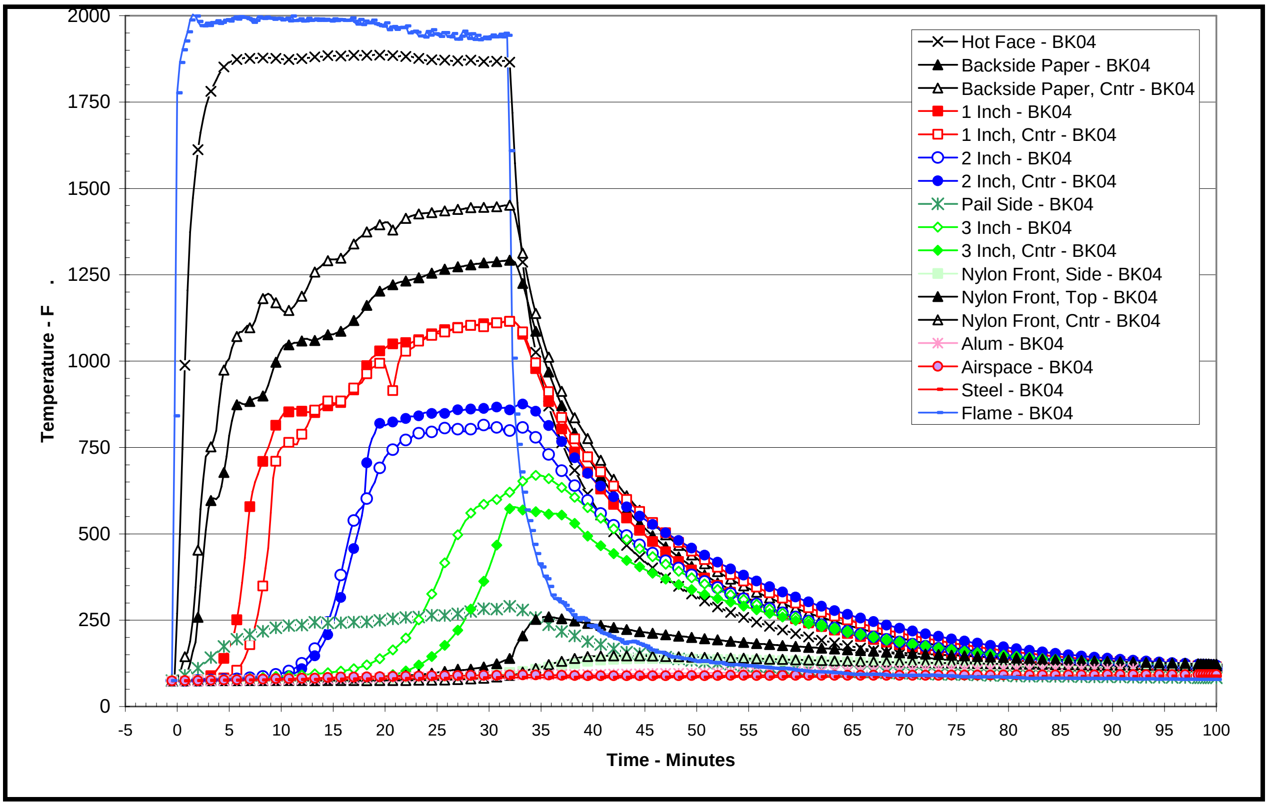


Figure 3 – Typical Temperature Profile (Bucket 4)

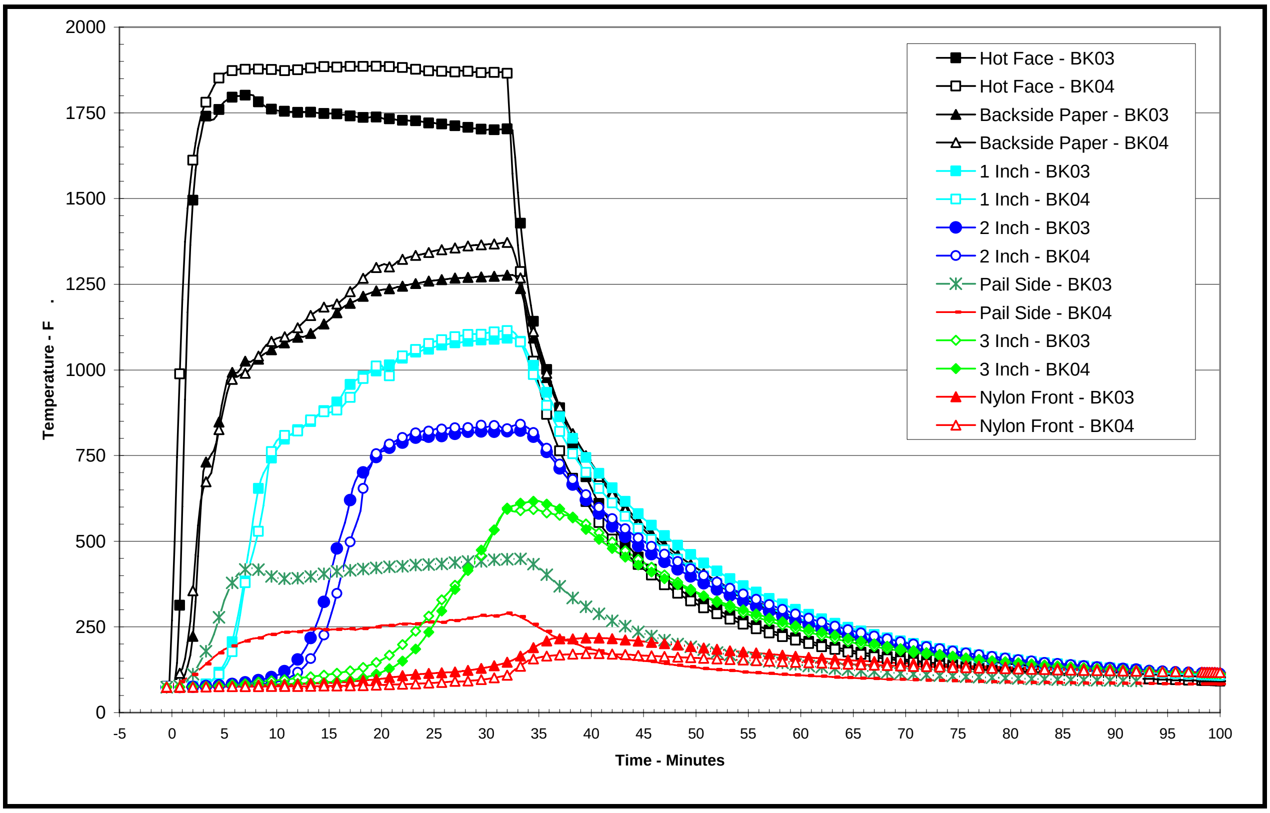


Figure 4 – Typical Temperature Profile Comparison (Bucket 3 vs. Bucket 4)

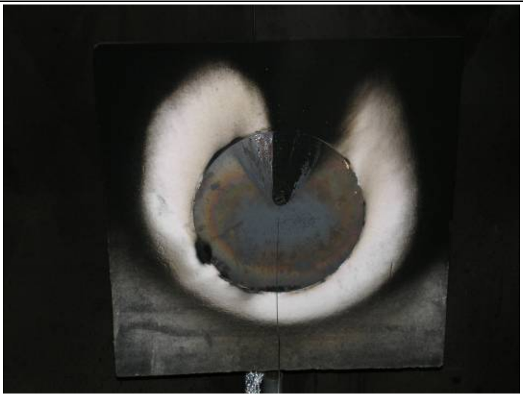
5.0 Post Test Inspection

A post test inspection was conducted on each test bucket after sufficient cooling had occurred to permit handling. The inspection involved first weighing the bucket and then dissecting the bucket. The post test weighing provides a measure of the gross loss due to out-gassing from the foam during the test. Since a portion of the decomposed foam exists as char or was trapped in the ceramic fiber paper, etc., the true measure of the foam decomposition came from weighing the remaining foam by itself, see Table 3.

The physical dissection of the test buckets consisted of using an air powered grinding wheel to remove the lid by cutting the skip welds, and then cutting down the sides of the bucket and around the base to permit the removal of the bucket's side wall. Approximately half (180 degrees) of the bucket's side wall was removed. The ceramic fiber paper was intact, but loaded with char product, see Figure 5 for a typical bucket dissection. The ceramic fiber paper was white prior to testing. No discernable difference was noted in the ceramic fiber paper (other than color) with and without the vent cutout. The foam char was not continuous under the ceramic fiber paper. There were large voids in some places. The large char voids could partially explain why the ceramic fiber paper helps, because it continues to protect foam not hidden from the heat source by the char. No visible signs of damage or melting were detected on any of the nylon moderator specimens. However, some of the nylon moderator surfaces did exhibit discoloration from condensed volatiles. The peak nylon moderator temperature of 469°F in bucket 1 is explained by the shape of the remaining foam. The foam had localized burn through near that thermocouple, leaving it exposed to more heat input. All of the foam specimens exhibited decreased thickness from bottom to top of the horizontal buckets, which is explained by heat rising (vertically) within the bucket. However, bucket 1 had a larger localized burn through than any of the other buckets. The suspected cause of the larger localized burn through is variations in the burn testing like char formation and degradation. The thickness of the remaining foam was more for the 8pcf than 6pcf, which is expected. The 6 pcf buckets had approximately 13% of their unburned foam remaining, indicating overall repeatability between the tests. The 8 pcf buckets differed from each other having 18% and 25%, respectively, of their unburned foam remaining. The difference between the 8 pcf buckets is due to the use of one versus two layers of ceramic fiber paper, respectively, for those tests.

Table 3 – Mass Information

Mass Information	Units	Bucket 1	Bucket 2	Bucket 3	Bucket 4
Ceramic Fiber Paper Layers / Total Thickness	in	1 / 0.25”	2 / 0.50”	2 / 0.50”	2 / 0.50”
Foam Density	pcf	8.00	8.00	5.98	6.08
Initial Foam Mass	grams	768	718	538	538
Remaining Foam Mass	grams	139.5	181	71.5	72
Remaining Foam Mass with Char	grams	263.5	264	180.5	190
Initial Nylon Moderator Mass	grams	2130	2130	2130	2133
Remaining Nylon Moderator Mass	grams	2130	2130	2130	2133
Aluminum Plate Mass	grams	1020	1020	1020	1019
Steel Plate Mass	grams	6263	6263	6263	6268
Percent Foam Remaining from Original	%	18.16	25.21	13.29	13.38
Duration of off-gas vent flame after burner removal.	min:sec	11:32	10:17	7:16	6:30



Lid (showing off-gas pattern)

Ceramic Fiber Paper

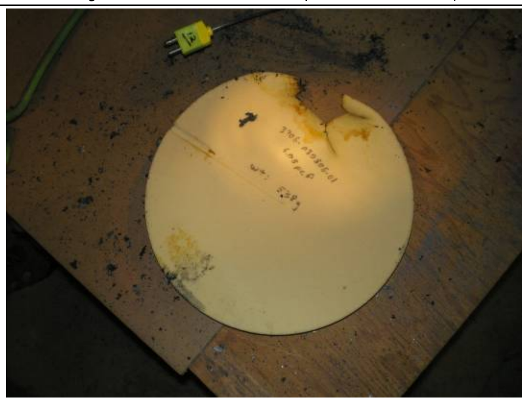
Char

Bucket Dissection

Remaining Foam (showing gap under char)

Nylon Moderator (Flame Side)

Remaining Foam (Flame Side)



Remaining Foam (Back Side)

Figure 5 – Post Test Inspection of Bucket 4

6.0 Conclusions

The objectives of the bucket burn tests were to evaluate the thermal protection performance of different densities of General Plastics Last-A-Foam FR-3700 polyurethane foam and different thicknesses of ceramic fiber paper. The ultimate concern of the testing was the vulnerability of the nylon moderator to melt under conditions similar to the 30 minute regulatory fire case, 10CFR71 Section 71.73(c)(4). The secondary concern was limiting the overall weight of the package, which precluded using an overly conservative foam density. Four bucket tests were performed that simulated a cross-section of the package lid. Table 4 compares the bucket tests against each other with regard for the effects of insulating layers of ceramic fiber paper, the effects of foam density, and test variability. The first two buckets both had 8 pound per cubic foot (pcf) polyurethane foam, the first bucket had a single ¼” layer of ceramic fiber paper in front of the foam while the second bucket had two layers totaling a ½”. The second bucket showed noticeably better thermal protection. The second bucket had 25% of the foam remaining after the burn, while the first bucket had 18%. Additionally, the second bucket had lower average temperature at the flame side nylon moderator surface (151°F versus 234°F).

The third and fourth buckets both used 6 pcf foam and two layers of ceramic fiber paper (totaling a ½”). The only differences between these tests were the presence or absence of the cut-out of the ceramic fiber paper around the vent hole and orientation of the vent hole. The third bucket did not have the ceramic fiber paper cut-out. Both buckets had approximately 13% of the foam remaining after the burn. However, the average flame side nylon moderator surface temperature differed from 218°F in the third bucket to 172°F in the fourth bucket. Given that both buckets had relatively the same amount of unburned foam after the test, it appears that the increased average temperature of the third bucket is from the proximity of the thermocouples relative to local hotspots (thin parts) in the foam. It is suspected that if more than three thermocouples had been used on the front (flame side) face of the nylon moderator, then the average temperatures would have been closer together. Ultimately, the 8 pcf foam used in the first two buckets provides a greater level of protection than the 6 pcf foam. This result was completely expected. However, the 6 pcf foam with the two layers of ¼” thick ceramic fiber paper (½” thick total) did protect the nylon moderator from melting for at least 30 minutes of exposure to an engulfing ~1900°F flame. Therefore, the 6 pcf foam with two layers of ceramic fiber paper appears to offer the lowest weight with an adequate level of protection.

Table 4 – Bucket Comparisons

Bucket Comparisons, a vs b	Remaining Foam Mass, a	Remaining Foam Mass, b	% Diff	Ave Moderator Temp, a	Ave Moderator Temp, b	% Diff
Bk 01 vs Bk 02 [effect of insulation]	139.5	181	+29.7	234	151	-35.5
Bk 02 vs Bk 03 [effect of density]	181	71.5	-60.5	151	218	+44.4
Bk 03 vs Bk 04 [test variability]	71.5	72	+0.7	218	172	-21.1

7.0 References

1. Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Energy — Packaging and Transportation of Radioactive Material*.