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Characterization of Radiation Hardened Polyurethane Foams for DOE Decontamination and Decommissioning (D&D) Operations

Andy Rivas

Savannah River National Laboratory

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1.0 Abstract

The use of polyurethane foams has been under investigation to see if they can be used in DOE decontamination and decommissioning (D&D) operations, specifically to fixate and shield any remaining contamination that is left in any voided structure such as a glovebox. To fix this problem, SRNL attempted to characterize different commercial epoxy foams to evaluate their foam characteristics in different environments, temperature profiles, viscoelastic behavior, shielding capability, and any changes to these characteristics when different weight percent additives were included in the foam matrix. The use of these foams has not been realized yet because of excessive heat generation and flammability concerns during the curing process. For this reason, fire resistant foams had their thermal profiles analyzed using a FLIR camera and it was observed that all foams had their peak temperatures stay below 100°C. These foams were also exposed to a variety of humidity's and temperatures to see if any physical properties would change. It was observed that only the 3M fire barrier foam at a relative humidity's above 80% experienced any change in physical characteristics such as weight. The foams viscoelastic behavior was going to be analyzed to find their glass transition temperature, but it is theorized that it will increase with the addition of additives by the Flory-Fox equation. Finally, with the addition of high density additives, it was observed that Bi provided the best shielding capability with Foam iT 14 because they were the densest foam additive combination out of all samples and the iT 14 could absorb Bi into its matrix the most efficiently.

2.0 Introduction

Since World War 2, the United States has built and used more than 20,000 nuclear facilities for power producing reactors, research reactors, uranium producing facilities, plutonium producing facilities, chemical processing facilities, waste management facilities, and other kinds of buildings [1]. In recent years, a number of these nuclear facilities have been moving towards moving their nuclear waste to long term storage, or final disposition. These facilities face monumental challenges in cleaning up the legacy waste that is left in these facilities in the time frame between the facility being inactive through the time that final disposition operations commence while ensuring that no holdup material is released to the environment. Current disposition workers are trying their best to remove as much radioactive material holdup, which is "nuclear material deposited in the equipment, transfer lines, and ventilation systems of processing facilities" [2], but face the problem of not having the most effective decontamination methods to remove the contaminated material. Over the years of operation, these facilities begin to accumulate significant amounts of uranium and/or plutonium that could even reach the kilogram range if sufficient time passes [2].

Gloveboxes are notorious offenders of containing this type of contamination. Seeing how each nuclear facility have multiple gloveboxes, SRNL has identified a solution that is utilizing a two-part epoxy foam that will fill the interior of the gloveboxes to shield anyone outside of the glovebox from any radioactivity. Effective shielding will be obtained with the addition of highly dense materials into the foam matrix during the mixing process. This has the end goal of being able to shield radiological workers before and during the removal and decommissioning of the gloveboxes. The additives, Bi, Bi_2O_3, Na_2WO_4, and WO_3, were chosen from the previous work done on this project by modeling their effectiveness utilizing Monte Carlo N-Particle X software (MCNP-X) [3]. The new foams being tested in this current round of experimentation are Foam iT 7FR, Foam iT 23FR, 3M Fire Barrier foam, and Hilti CP620 foam. These foams were chosen from an extensive literature search with the criteria of finding foams that would be the most fire resistant. Foam iT 8 and Flex Foam iT 14 were the highest performing foams in the previous experiments and are being further investigated in this current study [3]. The ratios of

concentrations of foam to additives that will be tested are 8:1, 4:1, 2:1. For the 8:1 ratio for example, there will be 8 grams of foam per gram of additive to the mixture.

3.0 Goals and Objectives

3.1 Goal

The purpose of this research project is to test various foams and high-density material additive combinations to find the most efficient composite material that will be able to provide optimal shielding and characterize these material physical properties to better understand how they will react in a wide range of temperatures and humidity's. How these foams expand will also be investigated to see how they do so in a closed system, such as a glove box in a facility.

3.2 Objectives

The objective of this experiment is to make a library of data of physical characteristics of each foam and additive combination that will have data concerning how the material cures and performs in different environments with varying temperatures, humidity's, and how it will act and perform after being irradiated. This compilation of data will be used to give our customers recommendations on which foam combinations would be ideal for their specific needs. Specifically, these four things are being investigated:

- Expansion data from each foam combination
    - Measure the amount of foam needed to fill a given volume of space. Each foam combination expands differently from each other and expand differently given the environmental conditions they are put in. This is important because in a closed system, such as a glove box, one does not want to overestimate or underestimate the appropriate amount of foam to be used.
- Thermal data for each foam combination
    - Measure the peak temperature of the foam as it cures to ensure that it will not become so hot that it'll become a hazard to the radiological workers. Also measure the foams flame retardant capability.
- Radiation shielding data for each foam combination
    - Measure the radiation shielding efficiency of each foam combination to see how effective the shielding was for gamma rays from Co-60, Cs-137, and Am-241.

- Dynamic Mechanical Analyzer (DMA) data for each foam combination
    - Measure the change in viscoelastic behavior of the different foams before and after being exposed to the varying environments, ie temperatures and radiation. Background information on this is found in Appendix F and Appendix G.

4.0 Experimental Procedure

4.1 Preparing the Foam Samples for Curing

Polyurethane is synthesized from the reaction of isocyanate and polyl molecules with the presence of a catalysts, such as a human hand mixing the two molecules together. To have a successful polymerization of the monomers, the amount of isocyanate (NCO) and hydroxyl (OH) groups must be roughly equal so that all the monomers have a chance to react [8]. Flexible foams have their polyl molecules being long and flexible while rigid foams have these polyl molecules with a high degree of cross linking and are tougher then the flex foam polyl molecules. Because of these differences, closed cell foams are denser, and more water resistant [7]. Based on this, one would expect the rigid foam to provide slightly better shielding because it is denser. The polyurethane reaction is shown below in figure 4.1:

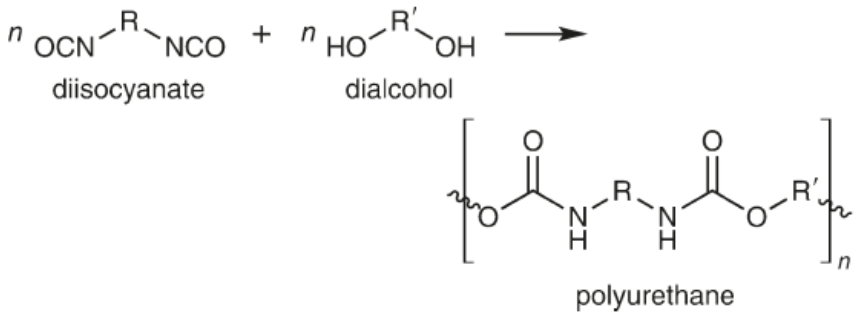

Figure 4.1: Polyurethane Reaction [8]

The two types of foams being used are either flexible or rigid foams. All iT foams that have the word “Flex” in it and the 3M foam are flexible or open cell foams. The iT foams that don’t have the word “Flex” in it and the Hilti foam are rigid or closed cell foams. Table 4.1 below shows all the foams that were used in this study, their qualification of flexible or rigid, and the approximate final expansion volume of each foam from the instructions provided by the manufacturer. Table 4.1 also continues to show the A:B mix ratios of each foam. Assuming that

each constitute has roughly equal density, the ratio by weight was approximated to be a ratio by volume. For example, for Flex Foam iT 23FR, the 85:100 percent by weight would be nearly equivalent to 13.6:16 percent by volume as shown in table 4.1. The calculations performed for the mixing ratios for the DMA foams are provided in Appendix A in section 7. Table 4.2 below shows the calculated average weights of the environmental chamber and DMA foams and the amount of additive that would need to be added to satisfy each weight percent for each type of foam. The calculations for the DMA foam weights are provided in Appendix D in section 7. While curing, all foams had their heat generation observed using a Forward-looking infrared (FLIR) camera to see if at any point in the curing process, the foam becomes too hot, ie greater than 100 °C. Provided in Appendix E, is the procedure to make each foam with and without additive.

Table 4.1: Characteristics of Foams used

Foam Used	Rigid or Flexible	Final Expansion Volume
FlexFoam iT 7FR	Flexible	8X
Foam iT 8	Rigid	8X
FlexFoam iT 14	Flexible	4X
FlexFoam iT 23FR	Flexible	2X
3M Fire Barrier Foam	Flexible	5X
Hilti CP620 Foam	Rigid	6X

Foam Used	A:B Mix Ratio by Volume	A:B Mix Ratio by Weight
FlexFoam iT 7FR	1:1 pbv	100:88 pbw
Foam iT 8	N/A	2:1 pbw
FlexFoam iT 14	1:2 pbv	100:190 pbw
FlexFoam iT 23FR	N/A	85:100 pbw
3M Fire Barrier Foam	N/A	N/A
Hilti CP620 Foam	N/A	N/A

Foam Used	A:B Volumes Poured for a Total Poured Volume of 30 mL for the environmental chamber	A:B Volumes Poured for a Final Expanded Volume of 25 mL for the DMA
FlexFoam iT 7FR	15 mL A 15 mL B	1.5 mL A 1.5 mL B
Foam iT 8	20 mL A 10 mL B	2 mL A 1 mL B
FlexFoam iT 14	10 mL A 20 mL B	2 mL A 4 mL B
FlexFoam iT 23FR	13.6 mL A 16 mL B	4.5 mL A 5.3 mL B
3M Fire Barrier Foam	30 mL	5 mL
Hilti CP620 Foam	30 mL	4 mL

Table 4.2: Weight Percent of Additives to be Used for Foams

	$Weight\ of\ Env\ Chamber\ Foams / Weight\ of\ DMA\ Foams$			
$\boldsymbol{Foam\ Used / WT\%}$	100%	12.5%	25%	50%
FlexFoam iT 7FR	$\mathbf{31.78/3.31}$	$\mathbf{3.972/0.413}$	$\mathbf{7.944/1.655}$	$\mathbf{15.89/1.660}$
Foam iT 8	$\mathbf{31.82/3.31}$	$\mathbf{3.977/0.414}$	$\mathbf{7.954/0.827}$	$\mathbf{15.91/1.654}$
FlexFoam iT 14	$\mathbf{29.40/6.12}$	$\mathbf{3.675/0.765}$	$\mathbf{7.350/1.530}$	$\mathbf{14.70/3.061}$
FlexFoam iT 23FR	$\mathbf{31.10/10.16}$	$\mathbf{3.887/1.269}$	$\mathbf{7.775/2.540}$	$\mathbf{15.55/5.079}$
3M Fire Barrier Foam	$\mathbf{28/}$	$\mathbf{3.5/}$	$\mathbf{7/}$	$\mathbf{14/}$
Hilti CP620 Foam	$\mathbf{28/}$	$\mathbf{3.5/}$	$\mathbf{7/}$	$\mathbf{14/}$

4.2 Foam Properties Under Investigation

For each foam, the properties that were being observed to determine which foam additive combination is the most efficient were mixture density, curing efficiency, thermal generation, expansion rate, and radiation shielding capability. Below is more detail of each:

- Utilizing a MicroClimate 3 Compact Environmental Chamber, a chamber that can be used to change the environment that a sample experiences by changing the humidity or the temperature, the foams will be tested at 25 °C at 20%, 40%, 50%, 60%, 80%, 90% humidity and at 50% humidity at 5 °C, 15 °C, 25 °C, 35 °C, 45 °C, and 55 °C. Figure 4.1 shows the foams inside the environmental chamber after they have been tested at 55 °C and 90% relative humidity. This is important information to know because we do not want the foams to underperform or not be able to cure properly given one of these extreme environments. The procedure followed to use the environmental chamber are below:
    1) Turn on the environmental chamber
    2) On the top panel, next to the display, click the conditioning system and the humidity system to go operational so that they may be changed by the user.
    3) Now on the display, utilize the up and down arrows to go to the desired setting that needs to be changed and use the right and left arrows to change the setting to the desired temperature or humidity. Once all the settings are selected, use the left arrow to back out of the settings menu to the main display.
    4) Wait 5 to 10 minutes to make sure the environmental chamber reaches the desired settings before leaving it overnight to run the experiment.

Figure 4.1: Foams inside Environmental Chamber post 55°C and 90% R.H.

- Utilizing the FLIR camera, temperature profiles were obtained for each foam to observe the heat being generated during the curing process, the time it took to reach peak temperature, and to see how quickly that heat could be dissipated. This is important to know to avoid a thermal runaway situation, where the temperature of the foam would keep increasing to potentially dangerous temperatures for the radiological workers. The FLIR camera was set up so that it would be looking down on the foams while they cure. A picture of the setup is below:

Figure 4.2: Setup of FLIR Camera

- Utilizing the 3 gamma sources at varying energies, Co-60, Cs-137, and Am-241 at the SRNL Building 735-2B, and a FLIR identiFINDER 2, the radiation shielding capability per unit volume and the attenuation coefficients for each foam additive mixture was characterized. These three gamma sources were picked because they provide an appropriate range of gamma energies to test the shielding. Co-60 gives off a high energy gamma ray at 1.1732 MeV, Cs-137 gives off a medium range gamma ray at 0.6617 MeV, and Am-241 gives off a low energy gamma ray at 0.0595 MeV [9]. This was accomplished by the following steps:
    1) The identiFINDER was used to measure the dose rate of the source with no distance between the source. This is the maximum measurement that could be taken.
    2) A reading was taken with the detector 30 cm away from the source, a distance greater than the height of the foam sample. This is the unshielded measurement.

3) With the detector staying 30 cm away from the source a measurement was taken with the blank foam sample in between providing shielding. This is the base measurement that will be used to show how well the additives performed.
4) With the detector staying 30 cm away from the source a measurement was taken with each foam additive mixture sample in between providing shielding. This is the measurement that will be used to show how well the additives performed. The difference in reading between this measurement and the measurement taken with the blank sample is the amount of shielding the additives were successfully able to accomplish. The setup is shown below;

Figure 4.4: Foam Sample Irradiation Experiment Setup with 30 cm Standoff

5) The above procedure was also repeated with the source at the surface of the foam. This was in an effort to normalize the data to account for the height differences between the foams.

5.0 Results

5.1 Properties of Foam Samples Cured Outside the Environmental Chamber with and without Additives

5.1.1 *Blank Foams Cured outside the Environmental Chamber*

5.1.1.1 Expansion profiles

Each foam sample that was cured and allowed to expand outside of the environmental chamber had its height and diameter measured in centimeters before being placed into the environmental chamber. This was done to examine if the foams had a change in volume because of the environmental conditions exposed to them inside the chamber. The results of these observations are summarized in Appendix B in section 7. From the data it is evident that the different environments did not influence the foams that were cured outside the chamber, except the 3M foam that did have a noticeable increase in weight after being exposed to high humidity's.

5.1.1.2 Peak Temperatures of Curing Blank Foams

Each blank foam samples temperature profile and peak temperature were examined utilizing a FLIR camera to observe the maximum amount of heat that was generated during the curing process. The peak temperature in °C and the time it took to reach that peak temperature in minutes, for the blank foams samples are summarized below in table 5.1. Three different thermal profiles were taken from three different foams and the largest temperature with its associated time is recorded below. From Figure 5.1 with the thermal profiles taken of each foam sample at peak temperature, one can see that Foam iT 7, Foam iT 8, and Foam iT 14 tend to have their hottest parts on one side of the foam, Foam iT 23 and Hilti have their temperatures more uniformly distributed, and the 3M foam has spikes more towards the middle of the foam. All foams, but the Hilti, reach their max temperatures in several minutes while curing and all foams cool back down to room temperature within 20 minutes after expansion is completed. The foam that can cause some worry is the Hilti foam. All foams but the Hilti don't come close to the 100°C but the Hilti reaches a max temperature of 90.8°C while curing at room temperature. Given a hotter environment, such as Florida, the foam could have the potential to reach the 100°C danger zone. The Hilti also reaches this peak temperature relatively quickly in just 37 seconds, giving workers very little time to react if a runaway thermal reaction was occurring. Much of the Hilti is between 65°C and 80°C but observing a peak of 90.8°C, even if it is only in

a few locations, shows that the foam has the potential of reaching those temperatures if given the right conditions to do so.

Table 5.1: Peak Temperature and Associated Time to Reach it for Blank Foams

Foams	Peak Temperature (°C)	Time to Reach Peak Temp. (mins)
FlexFoam iT 7FR	53.7	2'57"
Foam iT 8	66.2	4'33"
FlexFoam iT 14	42.2	2'57"
FlexFoam iT 23FR	53.2	4'24"
3M Fire Barrier Foam	65.0	1'43"
Hilti CP620 Foam	90.8	37'

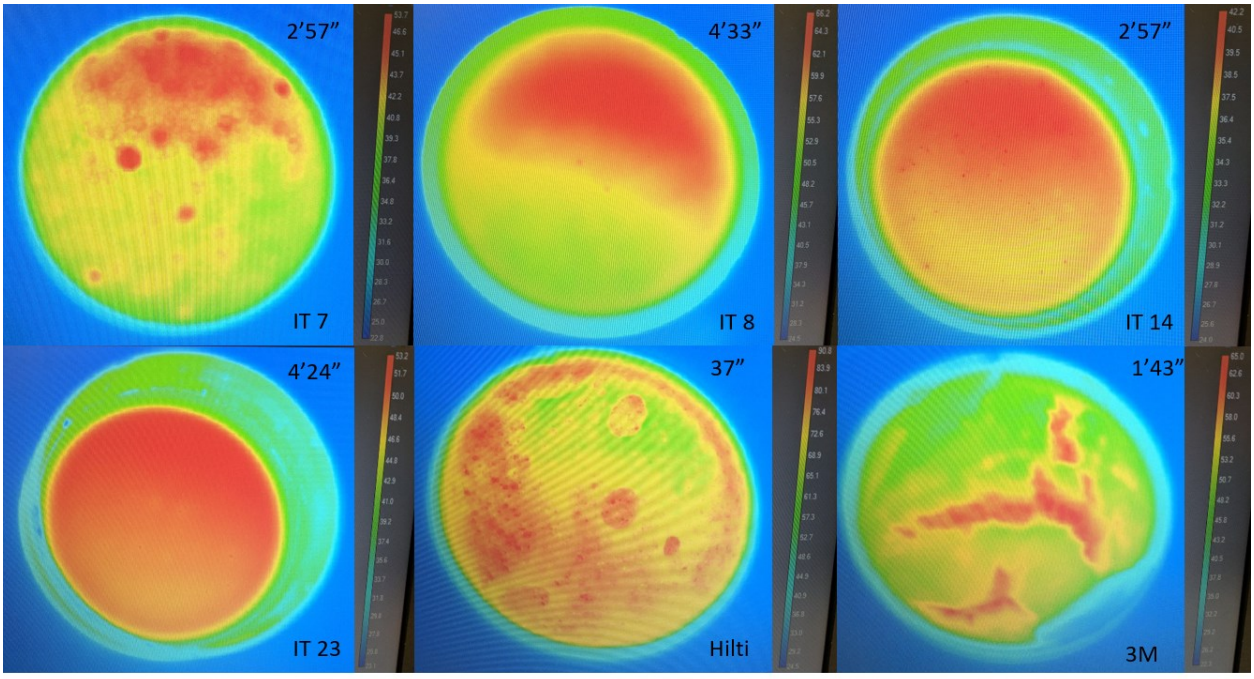

Figure 5.1: Thermal Profiles of Blank Samples

5.1.2 *Foams with Additives Cured outside the Environmental Chamber*

5.1.2.1 Expansion profiles

The same procedure as above was followed for foam additive mixtures to see if the addition of additives affected the foams final volume in any way. The results of these observations are summarized in Appendix B in section 7. From the data, it appears that the additives may have caused a slight bump in the curing heights but this may be due to human error in applying the foam components in the cup. After putting the foam samples into the environmental chamber for 24 hours, it is expected that it will only affect the 3M foam but to a lesser degree since the 3M matrix now has additive filling the voids that the water would have filled in a blank sample.

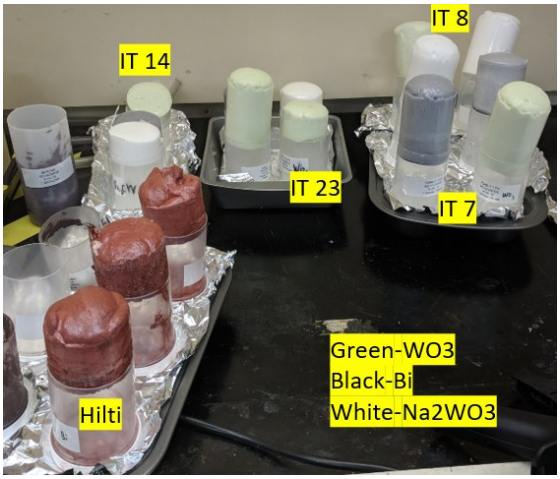

Figure 5.3: Foam with Additives Curing

5.1.2.2 Peak Temperatures of Curing Foams with Additives

The same procedure as above was followed for foam additive mixtures to see if the addition of additives affected the foams curing peak temperature in any way. The results of these observations are summarized below in table 5.2. The peak temperatures of each foam with additive stayed equal to the peak temperature of the blank samples except for the Hilti samples. With Bi and Na_2WO_4 at 25 weight percent as the additive for the Hilti samples, the peak temperatures spiked to 98.1°C and 100.6°C respectively. Again, this was at room temperature that the foam was curing. If the foam would cure at a higher temperature, like that of Florida, then it would have the potential of being even higher.

Table 5.2: Peak Temperature and Associated Time to Reach it for Foams with Additives

		Percent Weight of Additive Added to the Foam Samples
Foams	**Additive**	25% (4:1)
		$\boldsymbol{Peak\ Temp}/_{\boldsymbol{Time}}$
FlexFoam iT 7FR	Bi added	$\mathbf{53.2\ °C}/_{\mathbf{3'28"}}$
	Bi_2O_3 added	$\mathbf{50.0\ °C}/_{\mathbf{3'12"}}$
	Na_2WO_4 added	$\mathbf{49.7\ °C}/_{\mathbf{2'32"}}$
	WO_3 added	$\mathbf{50.7\ °C}/_{\mathbf{4'47"}}$
Foam iT 8	Bi added	$\mathbf{66.8\ °C}/_{\mathbf{4'23"}}$
	Bi_2O_3 added	$\mathbf{63.6\ °C}/_{\mathbf{6'6"}}$
	Na_2WO_4 added	$\mathbf{66.9\ °C}/_{\mathbf{5'47"}}$
	WO_3 added	$\mathbf{66.3\ °C}/_{\mathbf{4'46"}}$
FlexFoam iT 14	Bi added	$\mathbf{42.4\ °C}/_{\mathbf{3'15"}}$
	Bi_2O_3 added	$\mathbf{41.7\ °C}/_{\mathbf{3'39"}}$
	Na_2WO_4 added	$\mathbf{42.3\ °C}/_{\mathbf{4'}}$
	WO_3 added	$\mathbf{41.3\ °C}/_{\mathbf{2'48"}}$

FlexFoam iT 23FR	Bi added	$52.9\ °C/_{3'49"}$
	Bi_2O_3 added	$48\ °C/_{4'42"}$
	Na_2WO_4 added	$51.8\ °C/_{4'53"}$
	WO_3 added	$50.2\ °C/_{4'51"}$
3M Fire Barrier Foam	Bi added	/
	Bi_2O_3 added	/
	Na_2WO_4 added	/
	WO_3 added	/
Hilti CP620 Foam	Bi added	$98.1\ °C/_{35"}$
	Bi_2O_3 added	/
	Na_2WO_4 added	$100.6\ °C/_{1'10"}$
	WO_3 added	/

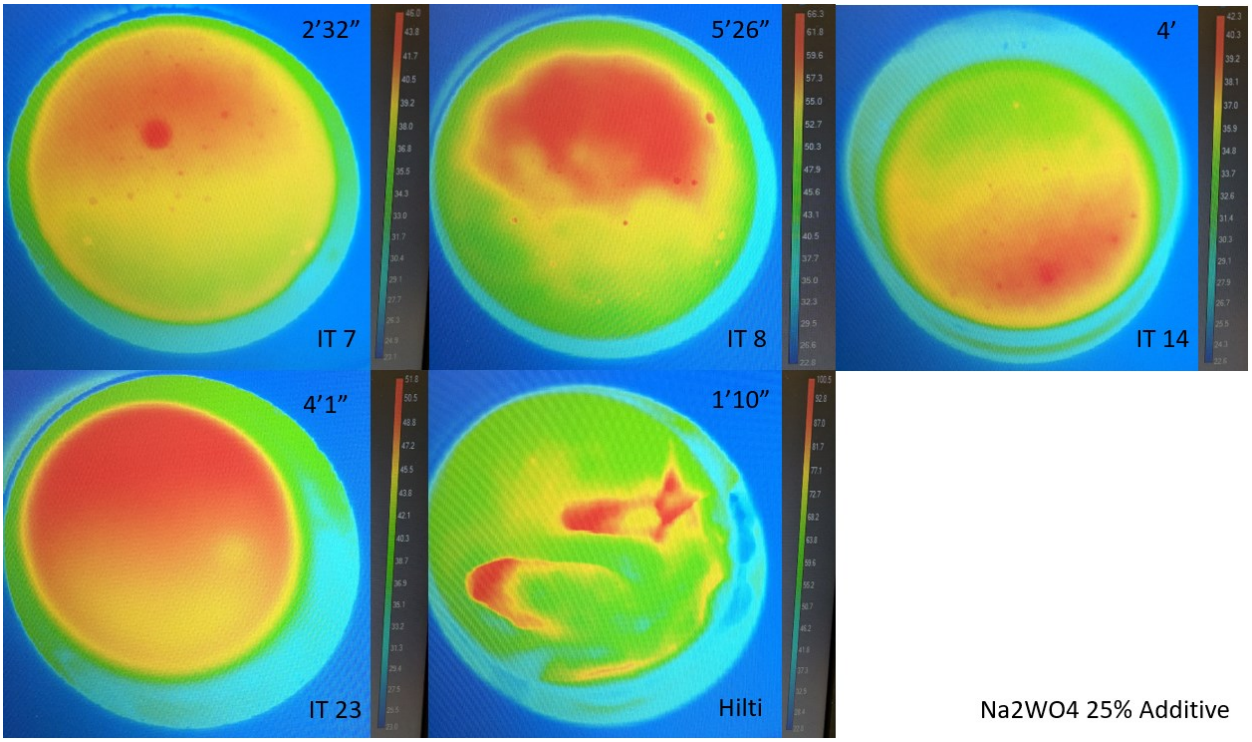

Figure 5.4: Thermal Signatures of Na2WO4 25% Additive Samples

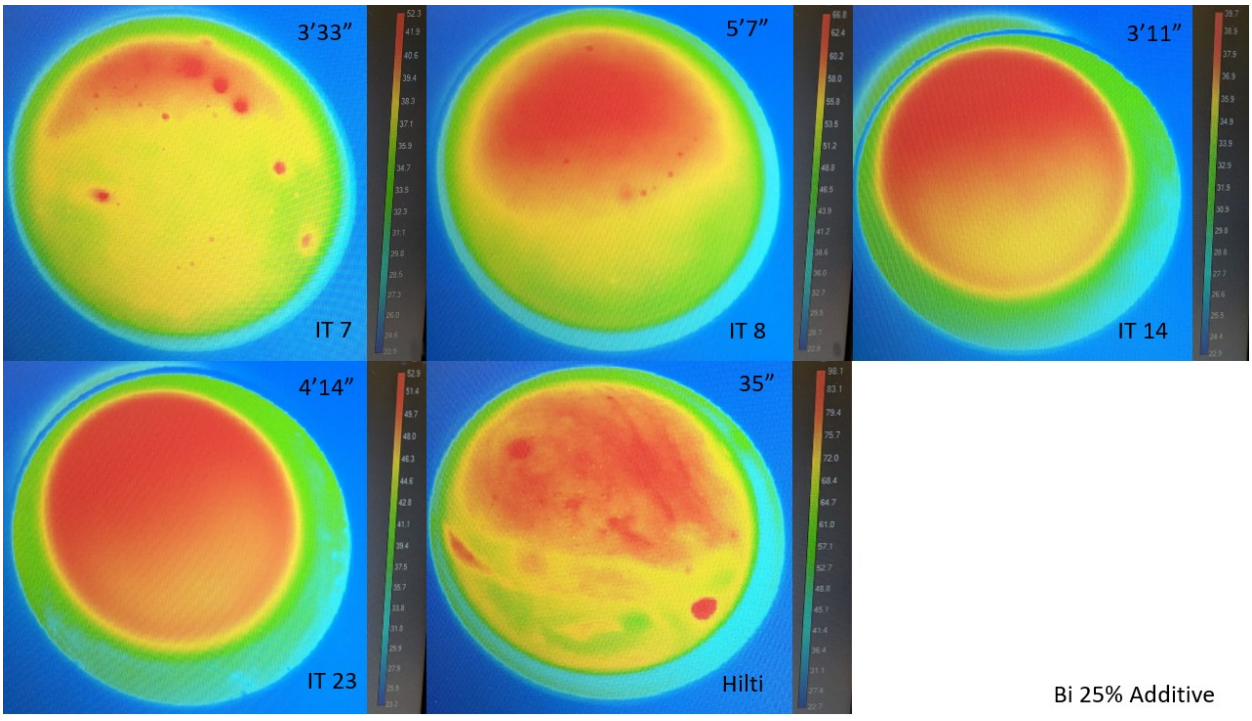

Figure 5.5: Thermal Signatures of Bi 25% Additive Samples

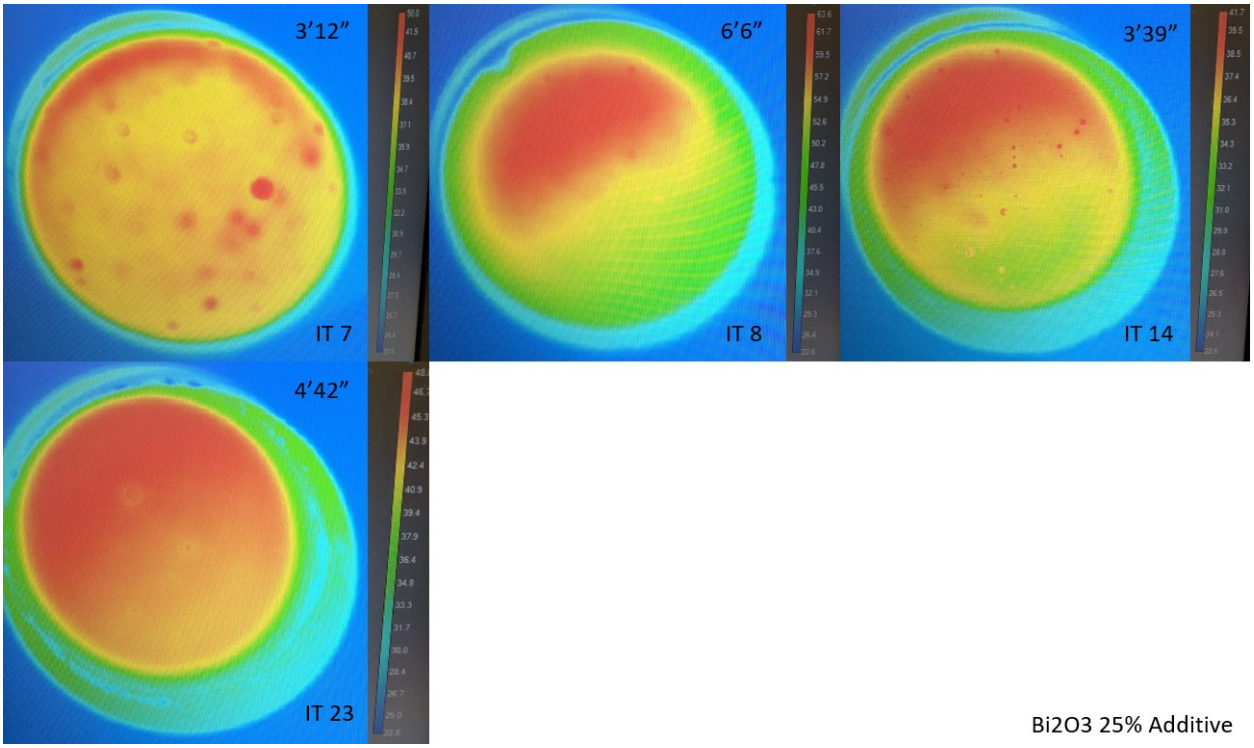

Figure 5.6: Thermal Signatures of Bi2O3 25% Additive Samples

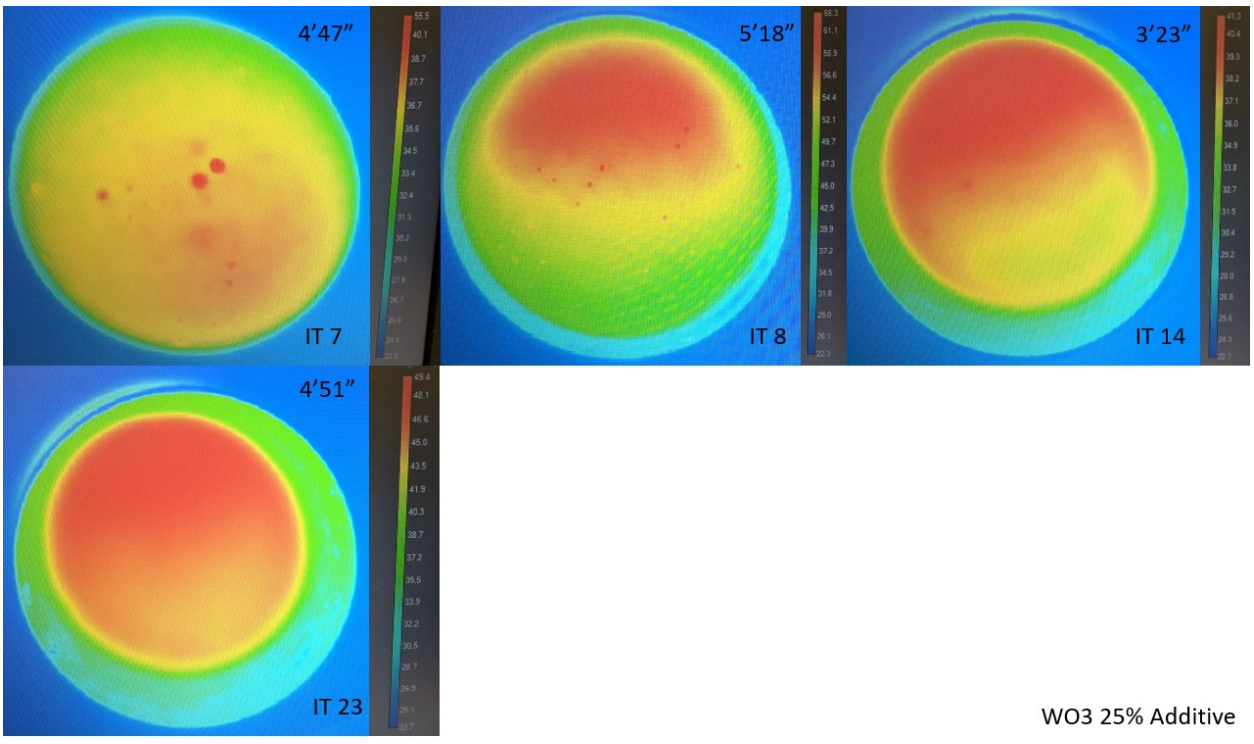

Figure 5.7: Thermal Signatures of WO3 25% Additive Samples

5.2 Shielding Capability of Blank Foam Samples vs. Foams with Additives Samples

Utilizing the 3 gamma sources at varying energies, Co-60, Cs-137, and Am-241 at the SRNL Building 735-2B and a FLIR identiFINDER 2, the radiation shielding capability of Bi, Bi_2O_3, $NaWO_4$, and WO_4 at 12.5 and 25 weight percent in each foam were individually tested by utilizing the procedure outlined in section 4.2. Before utilizing the foams for shielding, a base dose rate was taken with each source at 30 cm standoff. These results are presented in table 5.3:

Table 5.3: Sources used to test shielding capability

Source	Energy (Mev)	Dose at 30 cm (mrem/hr)
Am-241	0.0595	1.325
Cs-137	0.6617	2.997
Co-60	1.1732	0.228

Each foam sample was placed in front of the identiFINDER's 2 sensor to observe the change in dose rate. This was repeated 3 times and an average of the readings was taken to ensure a more accurate result. This data is summarized in Appendix D in section 7.

Measurements were also taken at the surface of the foam. To normalize the data, the shielding percentage was divided by the shielding volume of foam that was in front of the detector. This volume was calculated utilizing the height of the foam sample and the radius of the detector. From these measurements, attenuation factors of each foam were also found to allow for easy comparisons to other materials and to provide a selling point in knowing how thick one needs to make the foam to attain equivalent shielding as an inch of lead for example. These attenuation factors can be found in Appendix D.

The best performers in this experiment are expected to be the material that would be the densest and the material with the highest electron density. Below is a table summarizing these characteristics for each additive used in this experiment in table 5.4:

Table 5.4: Sources used to test shielding capability

Additive	Density (g/cc)	# of Electrons

Bi additive	9.78	83
Bi_2O_3 additive	8.90	190
Na_2WO_4 additive	4.19	128
WO_3 additive	7.16	98

From this table one would expect Bi at a higher weight percent to perform the best with the densest foam.

5.2.1 *Am-241 Shielding Capability per cm^3 at 0 cm Standoff*

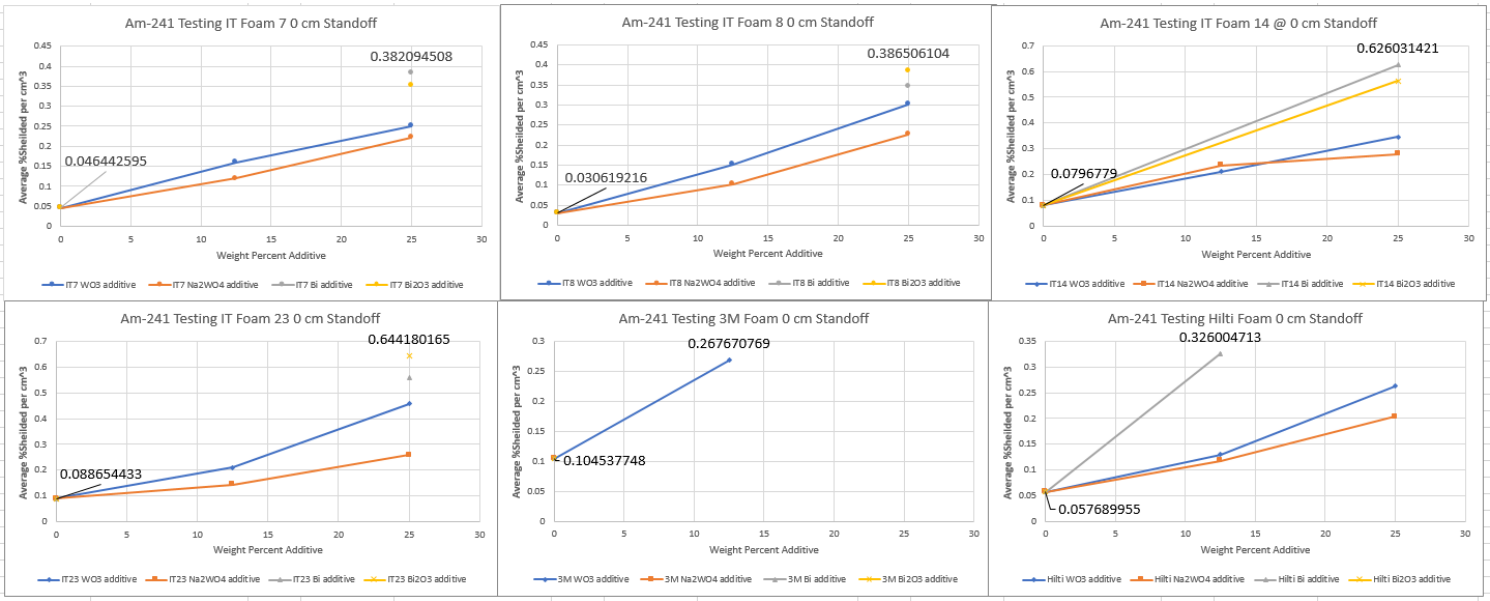

Figure 5.8: All Foam Shielding Capability per cm^3 at 0 cm Standoff for Am-241

From the graphs above, although the IT 23 Bi2O3 additive foam has the highest number for shielding per cm^3, that was the only sample that could be made and it had 31 weight percent of additive added to it. IT 14 on the other hand had all samples around 25 weight percent and thus provides the best comparison of additives. Looking at the top right graph, as expected, Bi did provide the best shielding out of all the additives at 0.626% per cubic centimeter of foam. The data also follows the trend of the denser material provides the best shielding with Na2WO4 providing the least shielding, since it is the least dense, and Bi providing the most shielding, since it is the densest. Electron density also plays a role in shielding, this is why Bi2O3

sometimes is able to provide more shielding then the Bi samples. What determines which one will perform better also depends on how well the additive is able to be incorporated in the foam matrix while it is curing.

Looking at the 0 weight percent additive data point, signifying the blank samples, 3M was able to provide the most shielding with no addition of additives followed by IT 23 and IT14. With the addition of WO3 at 12.5 weight percent, the 3M is still able to outperform all other foams with the same additive at the same weight percent because the 3M foam itself is much denser than any other foam. Further testing with the 3M must be done to see if this trend continues and to see if the addition of additive to the 3M matrix is able to improve any mechanical properties.

Looking at IT 14 and IT 23, without additives IT 23 can shield more than the IT 14 but when additives are added, IT 14 is able to shield more. This shows that although IT 23 is denser then IT 14, IT 14 can absorb additives into its matrix more readily and provide the best shielding out of all the foams once additives are added. 3M still needs to be tested at higher weight percent to see if it can incorporate additives in its matrix as well as the IT 14 and be able to provide the overall best shielding out of all foams.

5.2.2 *Cs-137 Shielding Capability per cm^3 at 0 cm Standoff*

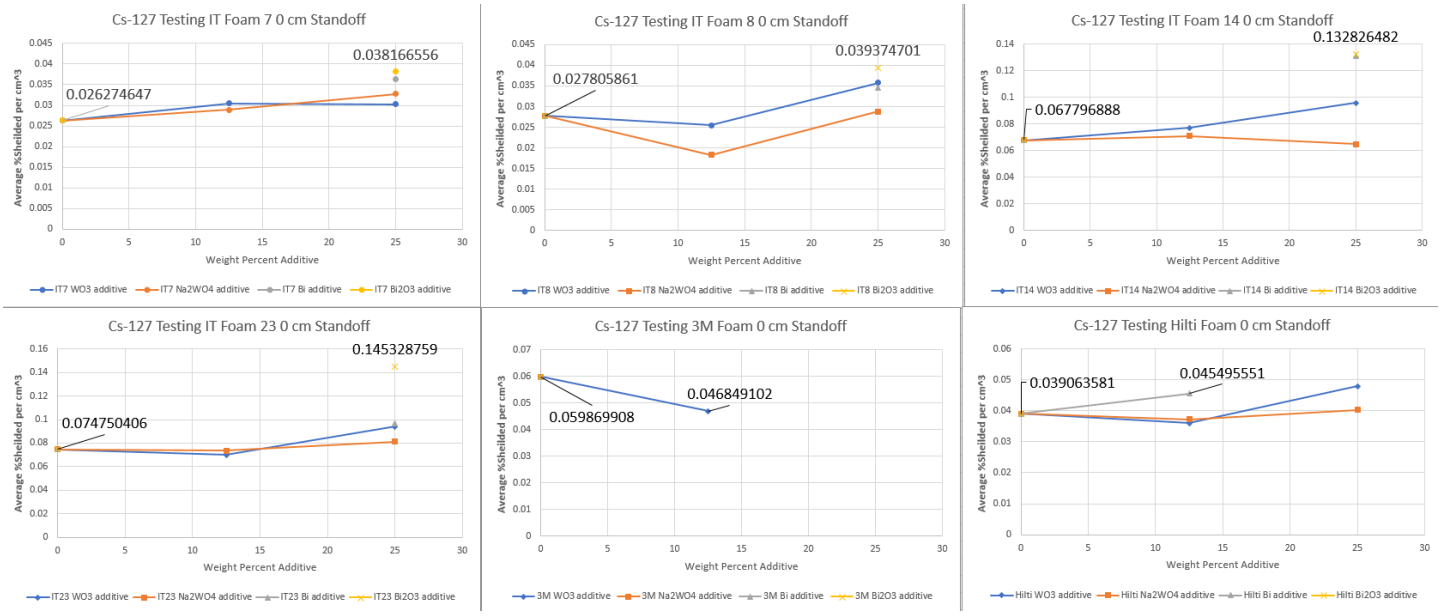

Figure 5.9: All Foam Shielding Capability per cm^3 at 0 cm Standoff for Cs-137

From the graphs above, again although the IT 23 Bi2O3 additive foam has the highest number for shielding per cm^3, that was the only sample that could be made and it had 31 weight percent of additive added to it. IT 14 on the other hand had all samples around 25 weight percent and thus provides the best comparison of additives. Looking at the top right graph, Bi and Bi2O3 are very close to each and it is reasonable that Bi would still be slightly better than Bi2O3 at shielding, just like for Am-241.

What was interesting about this source was that for some of the foam samples when 12.5% additive was added to the foam, they performed noticeably worse than when they were just blanks. It is believed that this is because when the additives are added into the foam, they disrupt the matrix and don't allow the foam to cure properly and set at their normal density. With the additives, they might be causing an interstitial defect to form in the foam, causing the volume to increase with minimal additional mass, resulting in an overall decrease in density. When the foams reach 25% additive added, this disruption is compensated by the additional density of the additive and the foam can rebound back to where they were as blanks. This all goes back to how well the additive can be incorporated into the foam matrix. Na2WO4 having the largest grain size, was expected to disrupt the foam matrix the most and have a larger effect on how well the foam cures versus other additives. As can be seen on the graphs, this is the case. Further testing needs to be done to attain higher weight percent to see if this trend continues and SEM may be necessary to see if the interstitial defect theory is a valid explanation for this phenomenon.

5.2.3 *Co-60 Shielding Capability per cm^3 at 0 cm Standoff*

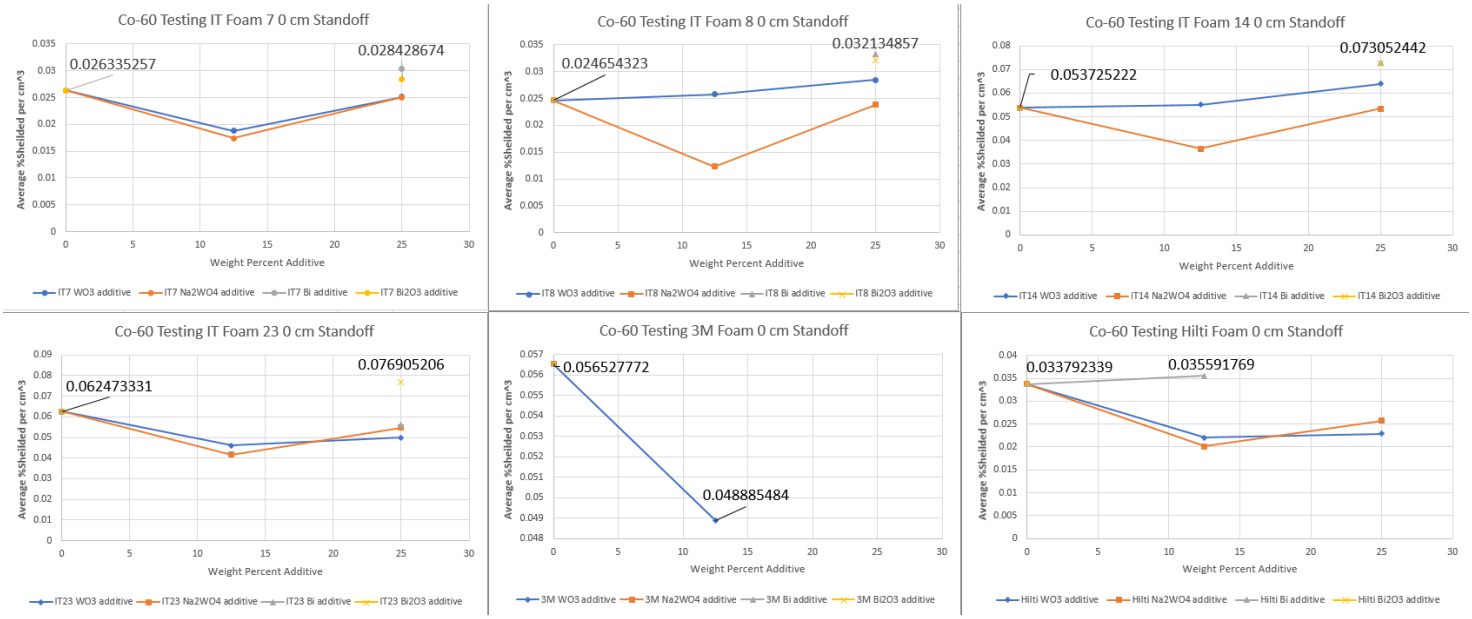

Figure 5.10: All Foam Shielding Capability per cm^3 at 0 cm Standoff for Co-60

From the graphs above, again although the IT 23 Bi2O3 additive foam has the highest number for shielding per cm^3, that was the only sample that could be made and it had 31 weight percent of additive added to it. IT 14 on the other hand had all samples around 25 weight percent and thus provides the best comparison of additives. Looking at the top right graph, Bi has the slight edge over the Bi2O3 for the best foam regarding shielding capability.

As discussed for the Cs-137 source, the Co-60 again has the dip at the 12.5 weight percent mark but it is even more pronounced now. With the higher energy gammas from the Co-60 source, it is expected that the foam would not be able to shield it as well. Potentially with the interstitial defect playing a role in its decrease in shielding capability, it is compounded with the higher energy source making it more evident than with the other two sources. Based on the Cs-137 and the Co-60, it is expected that if the Am-241 was also tested at a lower weight percent, it would also show a dip in the graph.

6.0 Conclusions

The first property under investigation in this study was to find the peak temperatures, how long it takes the foams to reach it, and if the addition of additives caused the peak temperature to rise. It was observed that all foams had their peak temperature occur between 40°C and 70°C, except the Hilti that had its peak temperature being 90.8°C. All foams also reached their max temperature given a few minutes, except the Hilti which accomplished the feat in 37 seconds. After adding additives, all the foams stayed at the same peak temperatures with roughly the same time, except the Hilti that had a slightly elevated temperature approaching 100°C occurring at the same time as the blank.

The next property that was investigated in this study was to see if the foams would have any of their physical characteristics change from being exposed to different environments. After running all the blank foam samples at all the mentioned temperatures and humidity's, it was found that only the 3M foams experienced any kind of significant weight change when exposed to very high humidity's such as 80% relative humidity. This is because the 3M foams would absorb the water vapor that was in the chamber causing the foam to swell and become tackier with the water intake.

The next property that would have been tested was running all the foam samples through a dynamic mechanical analyzer (DMA) to examine their viscoelastic behavior. This would have been done to find the foams glass transition temperature and to see if adding additives would have shifted that temperature at all. Through an extensive literature search, it is hypothesized that the foam samples that would have had additives added would have had their glass transition temperature shifted up by the Flory-Fox equation. This equation states that the higher the

molecular weight of a material, the higher its glass transition temperature will be. With this logic, a higher weight percent sample will have a higher glass transition temperature.

Finally, the last property tested was the foams shielding capability. This data was normalized by dividing the average shielding percent of each foam by the shielding volume of foam used. This allowed for a more accurate comparison between the foams and yielded foam iT 14 with Bi additive at 25 weight percent as the most capable foam at attenuating gamma radiation from the three sources tested. As was seen with the higher energy gammas, a certain amount of additive must be used before the foam is able to benefit from the increased shielding capability.

As a final product, a foam that would be sold to our customers as a spray would be ideal so that radiological workers will be apply the spray quickly and easily in whatever 3D space they must fill. As a general rule of thumb, the easier we can make the application of the foam by requiring less intermediate steps, the better the foam will be able to sell and the more that it can be used in these nuclear facilities.

7.0 Appendixes

Appendix A: Mixing Ratio Calculations for DMA Foam Samples from Table 4.1

-FlexFoam iT 7FR

$$1{:}\,1\ pbv\ mixing\ ratio$$

$$8X\ Expansion$$

$$25\ mL\ final\ expansion$$

$$25 = 8(A + B)$$

$$A = B$$

$$3.125 = 2A$$

$$A = 1.5\ mL$$

$$B = 1.5\ mL$$

- Foam iT 8

$$2{:}\,1\ pbw\ mixing\ ratio$$

$$8X\ Expansion$$

$$25\ mL\ final\ expansion$$

$$25 = 8(A + B)$$

$$A = 2B$$

$$25 = 8(3B)$$

$$25 = 24B$$

$$B = 1.04\ mL$$

$$A = 2B = 2.08\ mL$$

$$A = 2.0\ mL$$

$$B = 1.0\ mL$$

- FlexFoam iT 14

$$1{:}\,2\ pbv\ mixing\ ratio$$

$$4X\ Expansion$$

$$25\ mL\ final\ expansion$$

$$25 = 4(A + B)$$

$$B = 2A$$

$$25 = 4(3A)$$

$$25 = 12A$$

$$A = 2.08\ mL$$

$$B = 2A = 4.16\ mL$$

$$A = 2.0\ mL$$

$$B = 4.0\ mL$$

- FlexFoam iT 23FR

$$85{:}\,100\ pbw\ mixing\ ratio$$

$$2X\ Expansion$$

$$25\ mL\ final\ expansion$$

$$25 = 2(A + B)$$

$$100A = 85B$$

$$A = 0.85B$$

$$25 = 2(1.85B)$$

$$25 = 3.70B$$

$$B = 6.76\,mL$$

$$A = .85B = 5.74\,mL$$

$$A = 5.50\,mL$$

$$B = 6.50\,mL$$

This caused a vast overexpansion. As a result, the calculations were carried out with a final expansion of 20 mL and yielded an appropriate expansion.

$$20\,mL\ final\ expansion$$

$$20 = 2(A + B)$$

$$100A = 85B$$

$$A = 0.85B$$

$$20 = 2(1.85B)$$

$$20 = 3.70B$$

$$B = 5.40\,mL$$

$$A = .85B = 4.6\,mL$$

$$A = 4.60\,mL$$

$$B = 5.40\,mL$$

-3M

$$5X\ Expansion$$

$$25 = 5A$$

$$A = 5\,mL$$

- Hilti

$$6X\ Expansion$$

$$25 = 6A$$

$$A = 4\,mL$$

Appendix B: Foam Sample Dimensions discussed in sections 5.1.1 and 5.1.2 of Foam Samples that Cured Outside the Environmental Chamber with and without Additives Respectively

All heights and diameters are in centimeters and all volumes are cm^3. The weight of each sample is measured in grams.

5.1.1 *Blank Foams Cured outside the Environmental Chamber*

Table 1B: Pre-environmental Chamber Blank Foam Sample Dimensions

	$Weight/Height/Diameter$					
$Foams/Temperatures$	**55 °C 15%**	**55 °C 25%**	**25 °C 50%**	**55 °C 50%**	**26 °C 90%**	**55 °C 90%**
FlexFoam iT 7FR	31.2835 / 10.140 / 6.007	31.5385 / 10.046 / 6.123	31.474 / 9.365 / 6.224	32.6249 / 10.117 / 6.094	31.4529 / 9.849 / 6.086	31.3618 / 9.267 / 6.184
Foam iT 8	31.1377 / 7.155 / 6.234	31.3372 / 7.455 / 6.215	31.4378 / 6.857 / 6.202	31.8768 / 6.699 / 6.225	32.4424 / 7.344 / 6.202	32.1688 / 7.283 / 6.208
FlexFoam iT 14	29.4432 / 3.292 / 6.140	28.3516 / 2.542 / 6.199	30.2123 / 3.002 / 6.193	29.7872 / 3.037 / 6.212	28.7950 / 2.618 / 6.186	29.2786 / 2.636 / 6.186
FlexFoam iT 23FR	31.5385 / 3.285 / 6.185	31.1917 / 3.139 / 6.265	32.0902 / 3.754 / 6.184	31.0578 / 3.215 / 6.193	30.4028 / 3.150 / 6.244	30.0863 / 3.123 / 6.127
3M	64.2374 / 7.159 / 6.205	52.7693 / 6.935 / 5.907	50.8965 / 6.747 / 6.105	59.6116 / 8.39 / 6.12	63.5284 / 7.937 / 6.115	35.2213 / 4.213 / 6.124
Hilti	39.9785 / 7.888 / 6.233	48.7063 / 9.694 / 6.260	37.4755 / 7.835 / 6.241	41.7614 / 7.787 / 6.246	55.0030 / 8.55 / 6.239	30.9350 / 6.539 / 6.248

Table 2B: Pre-environmental Chamber Blank Foam Sample Dimensions

	Final Volume

$Foams/Temperatures$	55 °C 15%	55 °C 25%	25 °C 50%	55 °C 50%	26 °C 90%	55 °C 90%
FlexFoam iT 7FR	287.37	295.81	284.93	295.08	286.51	278.34
Foam iT 8	218.39	226.16	207.15	203.88	221.86	220.45
FlexFoam iT 14	97.47	76.72	90.43	92.04	78.68	79.22
FlexFoam iT 23FR	98.70	96.77	112.75	96.84	96.46	94.80
3M	216.48	190.05	197.50	246.81	233.10	124.09
Hilti	240.69	298.36	239.68	238.60	261.39	200.49

Table 3B: Post-environmental Chamber Blank Foam Sample Dimensions

	$Weight/Height/Diameter$					
$Foams/Temperatures$	55 °C 15%	55 °C 25%	25 °C 50%	55 °C 50%	26 °C 90%	55 °C 90%
FlexFoam iT 7FR	$\frac{31.0293}{\frac{10.021}{6.073}}$	$\frac{31.3166}{\frac{10.1}{6.11}}$	$\frac{31.2459}{\frac{9.544}{6.196}}$	$\frac{32.4844}{\frac{10.058}{6.176}}$	$\frac{32.2507}{\frac{9.778}{6.208}}$	$\frac{31.7113}{\frac{9.322}{6.155}}$
Foam iT 8	$\frac{30.8448}{\frac{7.186}{6.218}}$	$\frac{31.1157}{\frac{7.111}{6.257}}$	$\frac{31.2908}{\frac{7.01}{6.25}}$	$\frac{31.8456}{\frac{6.839}{6.222}}$	$\frac{32.3891}{\frac{7.487}{6.255}}$	$\frac{32.3057}{\frac{7.122}{6.219}}$
FlexFoam iT 14	$\frac{29.2575}{\frac{3.292}{6.246}}$	$\frac{28.1935}{\frac{2.532}{6.248}}$	$\frac{30.1546}{\frac{3.224}{6.168}}$	$\frac{29.7541}{\frac{2.934}{6.208}}$	$\frac{29.416}{\frac{2.700}{6.294}}$	$\frac{29.7553}{\frac{2.602}{6.226}}$
FlexFoam iT 23FR	$\frac{31.3976}{\frac{3.255}{6.184}}$	$\frac{31.0786}{\frac{3.094}{6.226}}$	$\frac{32.0573}{\frac{3.847}{6.238}}$	$\frac{31.0527}{\frac{3.225}{6.231}}$	$\frac{31.3147}{\frac{3.138}{6.311}}$	$\frac{30.7879}{\frac{3.233}{6.3}}$

3M	61.4183 6.895 6.159	51.556 6.977 6.152	50.9817 6.598 6.189	58.8349 8.198 6.223	71.007 8.202 6.19	42.2629 4.262 6.352
Hilti	39.6698 7.867 6.2	48.4923 9.702 6.14	37.4567 8.117 6.256	41.568 7.857 6.191	56.3753 9.018 6.218	31.5219 6.358 6.291

Table 4B: Post-environmental Chamber Blank Foam Sample Dimensions

	Volume / ***Change in Volume*** / ***Change in Weight***					
Foams / ***Temperatures***	**55 °C** **15%**	**55 °C** **25%**	**25 °C** **50%**	**55 °C** **50%**	**26 °C** **90%**	**55 °C** **90%**
FlexFoam iT 7FR	290.27 1.01% 0.813%	296.14 0.11% 0.70%	287.77 0.99% 0.72%	301.31 2.11% 0.43%	295.97 3.30% 2.53%	277.37 0.34% 1.11%
Foam iT 8	218.21 0.08% 0.94%	218.65 3.32% 0.71%	215.06 3.82% 0.47%	207.94 1.99% 0.097%	230.07 3.70% 0.16%	213.34 1.86% 0.43%
FlexFoam iT 14	100.86 3.48% 0.63%	77.63 1.19% 0.56%	96.33 6.53% 0.19%	88.81 3.52% 0.11%	84.01 6.76% 2.16%	79.22 0.01% 1.63%
FlexFoam iT 23FR	97.76 0.95% 0.45%	94.20 2.66% 0.36%	117.57 4.27% 0.10%	98.34 1.55% 0.02%	98.16 1.77% 3.00%	100.78 6.30% 2.33%
3M	205.42 5.11% 4.34%	207.39 9.12% 2.30%	198.22 0.36% 0.17%	249.34 1.03% 1.30%	246.83 5.90% 11.77%	135.06 8.84% 20.0%
Hilti	237.51 1.32% 0.77%	287.27 3.72% 0.44%	249.5 4.09% 0.05%	236.52 0.87% 0.46%	273.84 4.76% 2.50%	197.63 1.43% 1.90%

5.1.2 *Foams with Additives Cured outside the Environmental Chamber*

Table 5B: Pre-environmental Chamber Foam Additive Sample Dimensions

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)

		$Weight/_{Height}/_{Diameter}$	$Weight/_{Height}/_{Diameter}$	$Weight/_{Height}/_{Diameter}$
FlexFoam iT 7FR	Bi added	— / —	32.0812 / 7.145 / 6.24	— / —
	Bi_2O_3 added	— / —	38.6164 / 9.184 / 6.075	— / —
	Na_2WO_4 added	30.9437 / 9.376 / 6.097	39.0821 / 9.453 / 6.012	— / —
	WO_3 added	35.3259 / 8.153 / 6.236	38.3023 / 9.102 / 6.096	— / —
Foam iT 8	Bi added	— / —	40.0085 / 7.55 / 6.216	— / —
	Bi_2O_3 added	— / —	39.5573 / 7.178 / 6.234	— / —
	Na_2WO_3 added	35.7088 / 8.974 / 6.209	40.1653 / 9.282 / 6.318	— / —
	WO_3 added	36.1711 / 8.122 / 6.243	39.6363 / 7.298 / 6.27	— / —
FlexFoam iT 14	Bi added	— / —	36.5272 / 3.004 / 6.236	— / —
	Bi_2O_3 added	— / —	36.64885 / 2.814 / 6.186	— / —
	Na_2WO_4 added	32.8101 / 2.867 / 6.114	37.3741 / 3.513 / 6.107	— / —
	WO_3 added	32.8386 / 3.016 / 6.26	37.1393 / 3.444 / 6.191	— / —

FlexFoam iT 23FR	Bi added	— —	$\frac{36.9146}{\frac{3.86}{6.214}}$	— —
	Bi_2O_3 added	— —	$\frac{32.5574}{\frac{3.036}{6.212}}$	— —
	Na_2WO_4 added	$\frac{33.8004}{\frac{2.438}{6.251}}$	$\frac{37.5467}{\frac{3.262}{6.217}}$	— —
	WO_3 added	$\frac{33.9877}{\frac{2.822}{6.241}}$	$\frac{37.269}{\frac{2.553}{6.17}}$	— —
3M	Bi added	— —	— —	— —
	Bi_2O_3 added	— —	— —	— —
	Na_2WO_4 added	— —	— —	— —
	WO_3 added	— —	— —	— —
Hilti	Bi added	$\frac{26.2639}{\frac{5.521}{6.242}}$	$\frac{35.9663}{\frac{6.653}{6.215}}$	— —
	Bi_2O_3 added	— —	— —	— —
	Na_2WO_4 added	$\frac{29.7441}{\frac{6.453}{6.231}}$	$\frac{27.8372}{\frac{5.49}{6.251}}$	— —
	WO_3 added	$\frac{25.0493}{\frac{5.164}{6.217}}$	— —	— —

Table 6B: Pre-environmental Chamber Foam Additive Sample Dimensions

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)
		Volume	Volume	Volume
FlexFoam iT 7FR	Bi added		218.50	
	Bi_2O_3 added		266.20	
	Na_2WO_4 added	232.22	268.35	
	WO_3 added	249.01	265.65	
Foam iT 8	Bi added		229.12	
	Bi_2O_3 added		219.09	
	Na_2WO_4 added	271.71	291.00	
	WO_3 added	248.62	225.34	
FlexFoam iT 14	Bi added		91.75	
	Bi_2O_3 added		84.57	
	Na_2WO_4 added	84.17	102.90	
	WO_3 added	93.07	103.68	

FlexFoam iT 23FR	Bi added		117.06	
	Bi_2O_3 added		92.01	
	Na_2WO_4 added	105.67	99.02	
	WO_3 added	118.29	76.33	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added			
Hilti	Bi added	168.95	201.83	
	Bi_2O_3 added			
	Na_2WO_4 added	196.77	168.48	
	WO_3 added	156.76		

Appendix D: Shielding Capability of Blank Foam Samples vs. Foams with Additives Samples

5.3.1 *Irradiated Blank Foam Samples*

Table 1D: Blank Foam Samples Shielding percentages

	Shielding Percentage per cm^3		
$\boldsymbol{Foams/_{Source}}$	Am-241	Cs-137	Co-60
FlexFoam iT 7FR	0.0464		
Foam iT 8	0.0306		
FlexFoam iT 14	0.0797		
FlexFoam iT 23FR	0.0887		
3M	0.1045		
Hilti	0.0577		

Table 2D: Attenuation Factors of Blank Foam Samples

	Attenuation Factors (cm^-1)		
$\boldsymbol{Foams/_{Source}}$	Am-241	Cs-137	Co-60
FlexFoam iT 7FR	0.0098		
Foam iT 8	0.0063		
FlexFoam iT 14	0.0166		
FlexFoam iT 23FR	0.0185		
3M	0.0229		
Hilti	0.0124		

5.3.2 *Irradiated Foams with Additives Samples*

Table 3D: Foam Additive Samples Shielding percentage per cm^3 from Am-241

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)

		Shielding Percentage per cm^3	Shielding Percentage per cm^3	Shielding Percentage per cm^3
FlexFoam iT 7FR	Bi added		0.3821	
	Bi_2O_3 added		0.3520	
	Na_2WO_4 added	0.1196	0.2224	
	WO_3 added	0.1599	0.2502	
Foam iT 8	Bi added		0.3464	
	Bi_2O_3 added		0.3865	
	Na_2WO_4 added	0.1025	0.2269	
	WO_3 added	0.1519	0.3023	
FlexFoam iT 14	Bi added		0.6260	
	Bi_2O_3 added		0.5639	
	Na_2WO_4 added	0.2352	0.2794	
	WO_3 added	0.2102	0.3465	
	Bi added		0.5593	

FlexFoam iT 23FR				
	Bi_2O_3 added		0.6442	
	Na_2WO_4 added	0.1446	0.2582	
	WO_3 added	0.2109	0.4573	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.2677		
Hilti	Bi added	0.3260		
	Bi_2O_3 added			
	Na_2WO_4 added	0.1180	0.2029	
	WO_3 added	0.1303	0.2624	

Table 4D: Attenuation Factors of Foam Additive Samples from Am-241

		Percent Weight of Additive Added to the Foam Samples

Foams	Additive	12.5% (8:1)	25% (4:1)	50% (2:1)
		Attenuation Factors (cm^-1)	**Attenuation Factors (cm^-1)**	**Attenuation Factors (cm^-1)**
FlexFoam iT 7FR	Bi added		0.1197	
	Bi_2O_3 added		0.1159	
	Na_2WO_4 added	0.0273	0.0273	
	WO_3 added	0.0677	0.0676	
Foam iT 8	Bi added		0.1015	
	Bi_2O_3 added		0.1151	
	Na_2WO_4 added	0.0231	0.0593	
	WO_3 added	0.0353	0.0806	
FlexFoam iT 14	Bi added		0.1567	
	Bi_2O_3 added		0.1379	
	Na_2WO_4 added	0.0515	0.0629	
	WO_3 added	0.0457	0.0800	

FlexFoam iT 23FR	Bi added		0.1434	
	Bi_2O_3 added		0.1663	
	Na_2WO_4 added	0.0308	0.0577	
	WO_3 added	0.0463	0.1089	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.0680		
Hilti	Bi added	0.0870		
	Bi_2O_3 added			
	Na_2WO_4 added	0.0260	0.0466	
	WO_3 added	0.0284	0.0624	

Table 5D: Foam Additive Samples Shielding percentage per cm^3 from Cs-137

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)
		Shielding Percentage per cm^3	**Shielding Percentage per cm^3**	**Shielding Percentage per cm^3**
FlexFoam iT 7FR	Bi added		0.0363	
	Bi_2O_3 added		0.0382	
	Na_2WO_4 added	0.0289	0.0328	
	WO_3 added	0.0304	0.0303	
Foam iT 8	Bi added		0.0344	
	Bi_2O_3 added		0.0394	
	Na_2WO_4 added	0.0183	0.0289	
	WO_3 added	0.0255	0.0358	
FlexFoam iT 14	Bi added		0.1315	
	Bi_2O_3 added		0.1328	
	Na_2WO_4 added	0.0711	0.0650	

	WO_3 added	0.07719	0.0960	
FlexFoam iT 23FR	Bi added		0.0966	
	Bi_2O_3 added		0.1453	
	Na_2WO_4 added	0.0737	0.0813	
	WO_3 added	0.0698	0.0939	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.0468		
Hilti	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added	0.0373	0.0403	
	WO_3 added	0.0360	0.0479	

Table 6D: Attenuation Factors of Foam Additive Samples from Cs-137

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)
		Attenuation Factors (cm^-1)	**Attenuation Factors (cm^-1)**	**Attenuation Factors (cm^-1)**
FlexFoam iT 7FR	Bi added		0.0063	
	Bi_2O_3 added		0.0080	
	Na_2WO_4 added	0.0060	0.0069	
	WO_3 added	0.0063	0.0063	
Foam iT 8	Bi added		0.0072	
	Bi_2O_3 added		0.0082	
	Na_2WO_4 added	0.0038	0.0060	
	WO_3 added	0.0053	0.0075	
	Bi added		0.0277	
	Bi_2O_3 added		0.0280	

FlexFoam iT 14	Na_2WO_4 added	0.0148	0.0135	
	WO_3 added	0.0161	0.0202	
FlexFoam iT 23FR	Bi added		0.0203	
	Bi_2O_3 added		0.0309	
	Na_2WO_4 added	0.0154	0.0170	
	WO_3 added	0.0146	0.0199	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.0098		
Hilti	Bi added	0.0095		
	Bi_2O_3 added			
	Na_2WO_4 added	0.0077	0.0115	

	WO_3 added	0.0074	0.0132	

Table 7D: Foam Additive Samples Shielding percentage per cm^3 from Co-60

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)
		Shielding Percentage per cm^3	**Shielding Percentage per cm^3**	**Shielding Percentage per cm^3**
FlexFoam iT 7FR	Bi added		0.0303	
	Bi_2O_3 added		0.0284	
	Na_2WO_4 added	0.0174	0.0250	
	WO_3 added	0.0188	0.0251	
Foam iT 8	Bi added		0.0333	
	Bi_2O_3 added		0.0321	
	Na_2WO_4 added	0.0123	0.0239	
	WO_3 added	0.0258	0.0285	
	Bi added		0.0730	

FlexFoam iT 14	Bi_2O_3 added		0.0727	
	Na_2WO_4 added	0.0365	0.0534	
	WO_3 added	0.0551	0.0639	
FlexFoam iT 23FR	Bi added		0.0562	
	Bi_2O_3 added		0.0769	
	Na_2WO_4 added	0.0416	0.0547	
	WO_3 added	0.0461	0.0498	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.0489		
Hilti	Bi added	0.0356		
	Bi_2O_3 added			

	Na_2WO_4 added	0.0202	0.0258	
	WO_3 added	0.0221	0.0229	

Table 8D: Attenuation Factors of Foam Additive Samples from Co-60

		Percent Weight of Additive Added to the Foam Samples		
Foams	**Additive**	12.5% (8:1)	25% (4:1)	50% (2:1)
		Attenuation Factors (cm^-1)	**Attenuation Factors (cm^-1)**	**Attenuation Factors (cm^-1)**
FlexFoam iT 7FR	Bi added		0.0063	
	Bi_2O_3 added		0.0059	
	Na_2WO_4 added	0.0036	0.0052	
	WO_3 added	0.0039	0.0052	
Foam iT 8	Bi added		0.0069	
	Bi_2O_3 added		0.0067	
	Na_2WO_4 added	0.0025	0.0049	
	WO_3 added	0.0053	0.0059	

FlexFoam iT 14	Bi added		0.0151	
	Bi_2O_3 added		0.0150	
	Na_2WO_4 added	0.0075	0.0110	
	WO_3 added	0.0114	0.0132	
FlexFoam iT 23FR	Bi added		0.0116	
	Bi_2O_3 added		0.0159	
	Na_2WO_4 added	0.0113	0.0113	
	WO_3 added	0.0103	0.0103	
3M	Bi added			
	Bi_2O_3 added			
	Na_2WO_4 added			
	WO_3 added	0.0103		
	Bi added	0.0074		

Hilti	Bi_2O_3 added			
	Na_2WO_4 added	0.0041	0.0053	
	WO_3 added	0.0045	0.0047	

Appendix D: Mixing Ratio Calculations for amount of additive needed for DMA Foam Samples from Table 4.2

For the DMA additive samples, the weight of each foam was needed to calculate the appropriate amount of additive to use to ensure a 12.5, 25, and a 50 additive weight percent for each DMA sample. This was accomplished with the ratio below. The average weight of an environmental chamber foam was found by averaging the weights of all the blank samples from table 1B.

$$\frac{Average\ Weight\ of\ Environmental\ Chamber\ Foam}{Volume\ of\ Environmenal\ Chamber\ Foam\ Samples} = \frac{Weight\ of\ Foam\ in\ DMA\ samples}{Volume\ of\ DMA\ samples}$$

-FlexFoam iT 7FR

$$\frac{31.77727143\ g}{30\ mL} = \frac{W_{IT7\ DMA}}{3.125\ mL}$$

$$W_{IT7\ DMA} = 3.310\ g$$

- Foam iT 8

$$\frac{31.8182857\ g}{30\ mL} = \frac{W_{IT8\ DMA}}{3.12\ mL}$$

$$W_{IT8\ DMA} = 3.310\ g$$

- FlexFoam iT 14

$$\frac{29.39985714\ g}{30\ mL} = \frac{W_{IT14\ DMA}}{6.247\ mL}$$

$$W_{IT14\ DMA} = 6.122\ g$$

- FlexFoam iT 23FR

$$\frac{31.09871429\ g}{30\ mL} = \frac{W_{IT23\ DMA}}{9.8\ mL}$$

$$W_{IT23\ DMA} = 10.159\ g$$

Appendix E: Instructions in how to prepare each foam sample

E.1 *Foam iT Samples*

FlexFoam iT 7FR, Foam iT 8, FlexFoam iT 14, and FlexFoam iT 23FR were prepared by following the directions provided by the manufacturer. These instructions are provided below [4]:

1) Pre-mix the 2 part epoxy A and B of the foam by stirring or shaking them thoroughly before dispensing for 5 minutes.
2) In the fume hood and following Table 4.1, use 20 mL syringes to take out the appropriate amount of solution A and solution B to then put in the mixing cup so that the total volume added is 30 mL. This can be done by either referencing the volume ratio column or the weight ratio column of the provided instructions. When able, the volume ratio column was used for all measurements.
3) Mix the two mixtures in the appropriate ratio into the 253 mL plastic container for roughly 50 seconds to begin the curing process.
4) The mixed sample was then placed in a secondary baking dish container to sit while curing for extra safety.
5) The samples would then be placed inside the environmental chamber so that we can observe how they cure at different temperatures.
6) The samples are then checked if curing was successful by using a Q tip to see if the top has solidified at 30 minutes, 2 hours, and then 24 hours after the curing process began.
1) If preparing with additives, measure out the amount of additive to be used with a scale and put the appropriate amount of additive at the bottom of the cup before adding any foam components.

7) If preparing the sample for DMA testing, constitute A and B are added to plastic scintillation vials in amounts so that the final foam expanded volume was about 25 mL. These exact numbers are provided in Table 4.1.

E.2 *3M Samples*

3M Foams were prepared by following the directions provided by the manufacturer. These instructions are provided below [5]:

1) Holding the cartridge upright, the cap was unscrewed
2) The rear knob on the epoxy gun was then pulled to extend the rack to put the cartridge in
3) Approximately 28 mL was then poured into the small plastic scintillation vial and the foam was thoroughly mixed for approximately 15 seconds.
4) The samples are then checked if curing was successful by using a Q tip to see if the top has solidified at 30 minutes, 2 hours, and then 24 hours after the curing process began.
5) To add additives to the foam, a pre-determined amount was placed at the bottom of the cup and then approximately 3 sets of pulling the trigger all the way of 3M foam was applied and mixed thoroughly with the appropriate weight percent added for each trial. This would allow approximately 57 grams of 3M to be dispensed into the cup.

E.3 *Hilti Samples*

Hilti Foams were prepared by following the directions provided by the manufacturer. These instructions are provided below [6]:

1) Holding the cartridge upright, the cap was unscrewed
2) On the foam gun, the dispenser was released and the piston rod was pulled back.
3) The cartridge was then inserted into the dispenser.
4) Approximately 28 mL was then poured into the small plastic scintillation vial and the foam was thoroughly mixed for approximately 15 seconds.

5) The samples are then checked if curing was successful by using a Q tip to see if the top has solidified at 30 minutes, 2 hours, and then 24 hours after the curing process began.
6) To add additives to the foam, a pre-determined amount was placed at the bottom of the cup and then approximately 4.5 sets of pulling the trigger all the way of the Hilti foam was applied and mixed thoroughly with the appropriate weight percent added for each trial. This would allow approximately 30 grams of Hilti to be dispensed.

Appendix F: Future Direction of DMA Studies Background Information on Foam Samples Cured Outside the Environmental chamber

For each foam, the viscoelastic behavior of each will be investigated by conducting a dynamic mechanical analysis. A RSA-G2 Solids Analyzer will be used in this study for a DMA of all the foam types, cured outside the environmental chamber with and without additives, cured inside the environmental chamber with and without additives, and irradiated foam samples with and without additives, to see how different curing environments and being irradiated affects the material when put under tension or compression and find the glass transition temperature. Glass transition temperature is the temperature that the foams will transition from a rigid state to a flex state. This is important because the foam must still be able to perform as expected when used in non-ideal environments and while being irradiated. How to read a DMA graph and what each section means is provided below in figure 4.3.

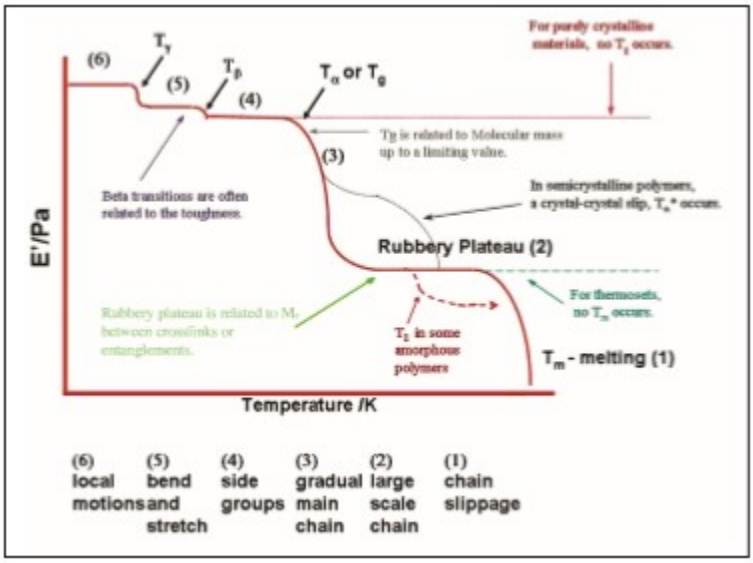

Figure F.1: Sections of a DMA Graph [11]

F.1 DMA of Blank Foam Samples

After testing is completed with the DMA on the blank foams, a graph similar to the one in figure 5.2 below is expected. Looking at the blue graph, this is the DMA graph for a Flex foam that has its glass transition temperature to be about -50°C. While the orange line, which represent a Rigid foam, has its glass transition temperature much higher at around 130°C. It is expected that rigid foams would have much higher glass transition temperatures then the flex foams since we can feel if it is rigid or not by the way it feels at room temperature. The rigid foam is also expected to perform better in tension and in compression testing since their molecular chains are shorter than the flex foams.

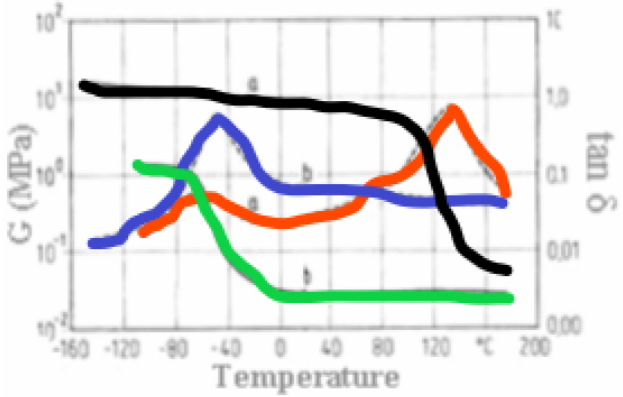

Figure F.2: DMA Graph of Both Flex and Rigid Polyurethane Foams [10]

F.2 DMA of Foams with Additives

Assuming a successful cure and an even dispersion of the additive throughout the foam, the glass transition temperature, tension strength, and compressive strength are expected to increase with increased additive added to the foam samples due to the Flory-Fox equation below.

$$\frac{1}{T_g} = \frac{x1}{T_{g,1}} + \frac{1 - x1}{T_{g,2}}$$

This equation illustrates that the higher the samples molecular weight holding all else equal, the higher the glass transition temperature will be. [13] This is illustrated with the graph below where material 2 is the material with a higher molecular weight then material 1:

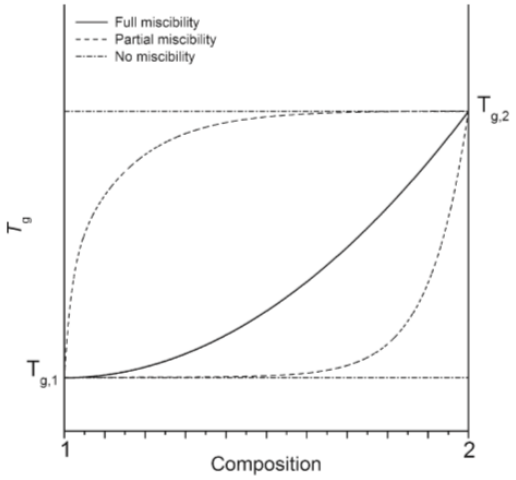

Figure F.3: Graph Representing a Composites Dependence on Molecular Weight [13]

The table below has the molecular weights of the additives. From this and following the relation that the Flory-Fox equation gives, one would expect that Bi_2O_3 would high the highest glass transition temperature and Bi would have the lowest.

Table 5.3: Molecular Weights of Foam Additives

Additive	Molecular Weight (g/mol)
Bi additive	209

Bi_2O_3 additive	466
Na_2WO_4 additive	278
WO_3 additive	232

Appendix G: Future Studies of Foam Samples Cured Inside the Environmental Chamber

G.1 Expansion Profiles of Blank Foam Samples

The height and diameter of the foam samples cured inside the environmental chamber were measured in centimeters. This was done to examine if there was any significant volume change if the foams were cured in an optimal environment versus if cured in an environment that has non-ideal temperature or humidity. It is expected that the foams will cure in less time at higher temperatures, since this should speed up the reaction rates between components, and the foams will have a larger volume after curing at higher humidity's, since more water will be able to enter the foam matrix while curing.

G.2 DMA of Blank Foam Samples

With the foams curing inside the environmental chamber at a high humidity, one would expect the Flory-Fox equation to yield a lower glass transition temperature. This is what would be expected because water entering the foam while it is curing only has a molecular weight of 18 g/mol while the foam and the additive would have a molecular weight above 100 g/mol. Because the glass transition temperature would be lower, one would expect its tensile and compressive strength to also be lower.

G.3 Expansion profiles of Foams with Additives

The same procedure as above was followed for foam additive mixtures to see if the addition of additives affected the foams final volume in any way. The results of these observations will be summarized in Appendix B in section 7. As previously discussed, the only changes that would be expected would occur at high humidity's.

G.4 DMA of Foams with Additives

As discussed in F.2, by the Flory-Fox equation, one would expect the glass transition temperature to increase. But if the foam is curing in a high humidity environment where water can be introduced into the matrix, then the glass transition temperature of the foam will decrease because of this.

8.0 References

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