Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Disclaimer:

We put science to work.™

Savannah River National Laboratory™

OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

A U.S. DEPARTMENT OF ENERGY NATIONAL LABORATORY • SAVANNAH RIVER SITE • AIKEN, SC

Dynamic Impact Testing of Rigid Polyurethane Foams

M.D. Kranjc

March 2017

SRNL-STI-2017-00326, Revision 0

SRNL.DOE.GOV

DISCLAIMER

Printed in the United States of America

Prepared for
U.S. Department of Energy

SRNL-STI-2017-00326
Revision 0

Keywords: *Example keywords*

Retention: *Permanent*

Dynamic Impact Testing of Rigid Polyurethane Foam

M.D. Kranjc

March 2017

Prepared for the U.S. Department of Energy under contract number DE-AC09-08SR22470.

Savannah River National Laboratory™

OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

EXECUTIVE SUMMARY

At the request of SRNL/Packaging Technology and Pressurized Systems, a Dynamic Impact Tester was developed by SRNL/Materials Evaluation that provides ease of use and the ability to test rigid polyurethane foam of various densities and sizes. In this initial testing comparisons were made between the properties of a currently approved foam product (General Plastics LAST-A-FOAM® FR3724) to those of an alternative supplier's product (Paragon Dow Beta Foam). The basis for how the equipment and test methodology were developed is discussed. Overall, the testing showed very good correlation of energy absorption (ft-lb/in^3) versus %Crush data between General Plastics LAST-A-FOAM® FR3724 literature data and Paragon Dow Beta Foam on the Dynamic Impact Tester developed.

A significant amount of elastic rebound occurred in the Paragon Dow Beta Foam sample during impact. This was captured and measured using high speed video. The energy absorption graph between the FR-3700 Series foam and Dow Beta foam was offset without accounting for the elastic impact and only measuring %deformation (crush) with calipers before and after impact. When full elastic impact via high speed video was measured the data matched up very well.

The SRNL/Material Evaluation Group recommends confirming these data by performing similar dynamic crush tests on GP FR-3724 samples. Additional recommendations for future work in this area are also discussed in this report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials (now ASTM International)
FPS	Frames per Second
GP	General Plastics
PCF	Pound per Cubic Foot (lb/ft3)
PSI	Pounds per Square Inch
PU	Polyurethane
RAM	Radioactive Material
SRNL	Savannah River National Laboratory
TTS	Time Temperature Superposition

1.0 Introduction

At the request of SRNL/Packaging Technology and Pressurized Systems, an in house Dynamic Impact Tester was developed. The primary goal was to compare dynamic impact data for rigid polyurethane (PU) foam from different vendors. The initial phase of this project focused on rigid PU foam samples with a density of 24 +/- 2 lb/ft3 from General Plastics (GP) and from Paragon Inc.

General Plastics is currently one of the primary producers of the rigid PU foam that is approved/used in current licensed Type B radioactive material (RAM) packaging. GP pumps their proprietary multi-component PU precursor into a nozzle that mixes these components and injects it into the RAM packaging annular space. Here, the two parts react to form a rigid polyurethane foam within the packaging vessel. The PU foam is used primarily for thermal insulation and energy absorption, and replaces older materials such as Celotex® fiberboard. General Plastics reports impact data as Dynamic Crush Strength (PSI) and Energy Absorption (ft-lb/in^3) in a Design Guide [6].

A number of test methods were considered for this testing [1-4]. The Design Guide [6] references ASTM D1596 [5] and MIL-P-26514 as the test methods for their data. ASTM D1596-14 [5] was chosen as a guide.

Packaging Technology ordered rigid PU foam samples with a density of 24 +/- 2 lb/ft^3 from GP as well as a second vendor, Paragon Inc. The GP product is called LAST-A-FOAM® FR-3724, with the last two digits indicating foam density in lb/ft^3. Recent technical literature (obtained off the website February 2017) from GP [7] does not report impact data but recommends that Dynamic Crush Strength be calculated from Static Crush Strength obtained from a standard Stress/Strain Test performed on a Tensile/Compression Tester (ex. Instron) at typically much slower strain rates than a dynamic impact test.

Instron does make impact testers that can test (crush) samples at high velocity. These are specific test machines that measure impact strength at high velocity and are different than the standard tensile/compression testers readily available in SRNL. Sales personnel at Instron indicated the estimated cost of a dynamic/high-velocity impact test system was $100 to $200K, depending on what options were required. The velocity of the impactor in such devices is likely controlled on a frictionless track so that the impactor is accurately guided towards and onto the sample at variable speeds. As an alternative, SRNL/Materials Evaluation developed a dynamic impact tester using relatively inexpensive materials for proof of concept.

2.0 Experimental Methods

2.1 TESTING APPARATUS AND PROCEDURE

ASTM D1596-14 describes "an apparatus having a guided dropping load platen … (and)…inputs a dynamic force into a test specimen". The standard is somewhat vague in exactly how to perform the test but provides good insight. The general principles of ASTM D1596-14 were adopted in the development of the alternative apparatus.

The apparatus used in this report consists of a solid metal cylinder that is 43.8 lbs, 5" in diameter, 8" in height, and has flat surfaces at each end. The cylinder is dropped through a clear acrylic plastic pipe (5.25 in. ID, 5 feet long) so as to direct the load onto a sample of rigid foam. A clear plastic pipe was desirable to see if there was any loss in energy during the drop due to friction, to confirm if the impactor came down on the sample evenly, and to observe if there was significant bouncing or rebound of the metal impactor resulting in any additional significant crushing after the initial impact.

R&D Directions were written for the test method and to ensure the safety of personnel involved. The R&D Directions are shown in Appendix B. It is acceptable to use R&D Directions per SRNL procedure PL-AP 4006, Attachment 8.1 (The Work Control Document Need Decision Tree). A Rigging Trained technician used an electric hoist to safely lift the metal cylinder into the top of the acrylic tube. The acrylic tube was securely mounted and strapped onto an aluminum A-frame located in building 723-15A. These securing mounts as well as a securing base were manufactured using the 3D printers in SRNL/Mechanical Systems and Custom Equipment Development. The securing base was especially useful in that it both secured the base of the tube and had legs so that no air cushion developed during the dropping of the 43 pound impactor. (Thanks to Kip Neikirk for suggesting test location (723-15A), designing and having the 3D printed parts made, securing an electric quick release hook for the metal impactor, and guiding me through the Safety protocol).

2.2 HIGH SPEED VIDEO

FastCam MC2 High Performance High Speed Video System from Photron Inc. was used to record the full crush event from initial point of contact of impactor and sample to release of impactor from sample during rebound. Photron FASTCAM Viewer Version 3641 software was used to save and analyze the data.

The following setup conditions were used:

EQUIPMENT
Lens: Telephoto Wideangle 1:1.3
Signal Convertor Equipment and Box: MC2 S/N and FastCam MC2.1 Convertor Box
LapTop: Dell Precision (circa 1999)

VIDEO SETTINGS
Speed: 1,000 frames/sec (fps)
Resolution: 512 x 512

The maximum video speed with this setup is 2,000 fps but 1,000 fps was chosen to help reduce file size. In addition, 1,000 fps seemed to adequately freeze and capture minimum sample thickness during the dynamic crush. Editing of test video (cropping out unnecessary portions of the video) also had a huge effect on file size reduction. Using the telephoto/wideangle lens, the full height of the test sample was captured in the picture frame. Using the Cross Cursor Mode, comparison could be made between caliper thickness and the number of pixels (or some arbitrary unit of distance) between top and bottom of the sample prior to crush to determine a conversion factor.

3.0 Results and Discussion

3.1 INITIAL DETERMINATION OF HOW TO CONFIGURE PROJECT TESTING

A partial list of GP literature data is shown in Table 1 [6, 7]. Dynamic Impact Energy (ft-lb/in^3) vs % Crush is plotted in Figure 1 and %Crush vs Strength (psi) is plotted in Figure 2. Both figures use data from Table 1. In reference [6] GP goes into a fair amount of detail about the methods used to generate the data in Table 1, but the exact methods and calculations are not clearly defined. In reference [7] GP states that "While impact data may be helpful in the selection of a foam density for a particular application, it is often more practicable to use the static crush strength values in Quality Assurance Testing". Conversion equations are provided in reference [7] to convert Static Crush Strength to Dynamic Crush Strength. Static and Dynamic Crush strength curves are compared in Figure 3.

Figure 3 shows the Crush Strength curves are similar in shape for Static and Dynamic Crush, however, strength is shifted up for Dynamic conditions, which use higher velocities during crush than the Static Test (2 in/min). It was not exactly clear how the Dynamic Crush Strength (PSI) is generated in Figure 2 and Table 1. Note that the volume fraction of air in the 25 lb/ft^3 (pcf) foam is about 60% (40% PU) and the volume fraction of air in the 10 pcf foam is about 84% (16% PU).

Looking at Energy Absorption (ft-lb/in3) vs %Crush in Figure 1, one can determine what sort of experiments could be carried out to make Dynamic Crush comparisons between samples from different vendors. The samples that SRNL/Packaging Technology initially requested to be tested had a density of 24 +/- 2 lb./ft^3. The Energy Absorption vs %Crush curve in Figure 4 is generated from GP data in Table 2 and shows excellent linearity ($R^2 = 0.999$). Sample sizes were determined based on this data and 24 lb/ft^3 samples were ordered from Paragon and GP. Once testing began it was determined that not all samples were needed so several are available for additional testing if desired.

3.2 DYNAMIC CRUSH STRENGTH IMPACT TESTING OF PARAGON FOAM (DOW BETA FOAM)

The first samples to arrive were from Paragon. Paragon uses multi-part polyurethane foam purchased from Dow Chemical called Beta Foam. The liquid components are pumped to and mixed in an injection nozzle during package preparation. PU foam is generated during the exothermic reaction between the liquid components after extrusion into the package vessel. Two sets of Dow Beta foam were requested and tested from Paragon; samples where thickness is parallel to foam rise during production and samples that are perpendicular to foam rise.

Test data for Paragon's Dow Beta foam is given in Table 3 and graphed on Figure 5. Table 3 reports both a %Crush and a %Strain value. %Crush in Table 3 is calculated by measuring volumetric changes in the sample before and after crush {(initial volume-final volume)/initial volume)}. % Strain, however, reflects only the linear deformation in the direction of impact {(initial height – final height)/initial height)}. The crush surfaces were flat, however, dimensions perpendicular to the direction of crush (ex. diameters for cylinder samples) were convex in shape. For block samples the two lateral lengths were measured at the top, middle, and bottom of the block and the average of these three values were averaged for the lengths of the two sides. For cylinders, diameters were measured at the following locations: 0^o & 180^o, 60^o & 240^o, and 120^o & 300^o. Top, middle, and bottom locations were measured, therefore, diameter was the average of nine measurements for each sample. Appendix A indicates the degree to which the sample sides bulge out convex after crush.

Note in Table 3 that %Strain is always larger than %Crush. This is mentioned because initial preliminary data was always reported as %Crush, as described above. It wasn't until later (after testing the GP FR-3700 foam samples) that we began to take a critical look at how to calculate what GP was referring to as %Crush. GP does not mention how the reported %Crush data [6] is generated, leading to some confusion over the data gathered. The concern at this point was that %Crush was not much over 10% and significantly higher values were expected. . This is evident in Figure 5.

Once this initial Dow Beta Foam data was generated, some of the uncrushed samples were machined down in thickness or the sample height in the crushing direction was decreased. These were samples I1, I2, J1, J2, K1, K2, L1, and L2. Dimensions, Energy Absorption, and %Crush for these samples are given in Table 3 and plotted in Figure 6. Figure 6 is included because it suggests a sample thickness (height) effect. This is indicated in the 3.0" and 1.5" diameter samples that have a height of less than 1" (all are samples that were cut down from original height). Relating this effect to foam performance in the specific packaging application is unknown. Additional investigations would be needed to better determine these effects and optimize testing conditions.

3.3 DYNAMIC CRUSH STRENGTH IMPACT TESTING OF GENERAL PLASTICS FOAM (FR-3700)

General Plastics samples arrived about 6 months after the Paragon samples. Test data for the GP LAST-A-FOAM ® FR-3700 samples are given in Table 5 and graphed on Figure 7, similar to how the Paragon Dow Beta Foam was analyzed. The literature data for the GP FR-3724 and test data for Paragon Dow Beta Foam are also shown in the graph for comparison.

Expectation was that testing of the GP FR-3724 samples would tell us if the test was valid or not, if we were not doing the calculations similar to how GP generated the Impact data, or if experimental set-up had to be significantly tweaked. From Figure 7 we knew that either the calculations were not similar to GP's or something else was needed. At this point it was decided to do some Static Crush testing.

3.4 STATIC CRUSH STRENGTH TESTING OF FR-3700 AND DOW BETA FOAM

Standard Compressive Stress/Strain curves were generated for the GP and Paragon samples on an Instron Tensile/Compression Tester located in building 773-A room B016. The following are relevant test conditions:

Test Speed: 1.90 in./min.
Load Cell Capacity: 44,000 lbs
Peak Force: 30,665 lbs
% Strain at Peak: 83%

Results are shown in Figure 8. There appears to be very good correlation between the tested values and General Plastics literature values. After discussion with SRNL/Packaging Technology personnel it was determined that during the dynamic crush tests, a relatively significant elastic deformation regime was occurring, but not being represented in the final measured deformation data. This was confirmed with a review of the high speed video collected during the Paragon foam crush testing.

3.5 HIGH SPEED VIDEO OF DOW BETA FOAM IMPACT TESTING

Prior to the initial Dynamic Crush Strength Impact testing of the Dow Beta foam, SRNL/Packaging Technology personnel (Kurt Eberl) suggested that it would be interesting to do high speed video recording at the point of impact, which we did. It was unfortunate that the laptop that recorded this data crashed and was unusable just prior to testing of the GP FR-3700 samples. Fortunately, the video for the Dow Beta foam was analyzed at the time of testing and video as well as recorded dimensions saved separately from the laptop.

After looking at the Static Crush Strength data and the samples crushed on the Instron, closer inspection was needed on how the %Crush values were calculated. At this point %Strain values were calculated as shown in Tables 3 and 4. Again this was calculated by dividing the change in sample thickness after crush by the initial thickness. All dimensions were taken using calipers. This is how %Strain was calculated in Figures 5 and 7 and the data clearly show that the tested Energy Absorption values were still too low.

Once Figures 5 and 7 were generated, the earlier high speed video and Excel data from 6 months prior was examined. As mentioned, high-speed video was only used for the Beta Foam because just prior to testing, the laptop became inoperable. Data from Table 3 are reproduced in Table 5 as well as additional % Strain generated using high speed video. The calculation is shown in Table 5 with L_o being initial sample height and L, the crushed height, is the height captured on video. The video shows that there is significant elastic rebound of the sample after the lowest point of crush of the sample. The previous Tested %Strain did not capture this because it was measured using calipers after crush testing. The impactor compresses the sample more than that measured by the calipers after test. This led to the early confusion prior to calculating %Strain using the high speed camera data. GP did not clearly indicate how the literature data was calculated.

Figure 5 was replotted using the %Strain calculated from video (Table 5) in Figure 9. Figure 9 shows that Paragon's Dow Beta Foam performs similarly to how the GP FR-3724 LAST-A-FOAM is reported to perform from GP Design Guides. This is because the amount of deflection (L_o-L) was actually larger than what the calipers measured. The high speed video was able to capture the additional elastic phase deflection of the sample during the impact. The similarity of material between GP FR-3725 and Dow Beta Foam (23 lb/ft3) is also indicated by the Static Stress/Strain curve in Figure 8.

Table 6 shows raw data from measuring the full crush height on video. The values y_{top} and y_{bottom} are pixelated numbers generated by placing the video screen in Cross Cursor Mode and reading the number when the cross hairs are placed at the top and bottom of the sample. Initially these are determined with the sample in place in the Dynamic Impact Apparatus. Using the measured sample height from calipers a conversion factor can be determined. It is noted that the conversion factors are different for the different samples because of the different sample sizes and distance the sample is from the wideangle telephoto lens. The last four columns in Table 6 show a comparison of final sample crushed height between using the video and using the calipers. In general, the %Difference between the two measurement techniques is quite small, below 3% for most cases. The average difference is 2.18% and the largest difference is 5.67%.

4.0 Conclusions

1) The Dow Beta Foam processed by Paragon appears to perform very similar to General Plastics LAST-A-FOAM® FR-3725 in both Static and Dynamic Crush Tests (see Figures 8 and 9). Several samples of the Dow Beta Foam were tested on the Dynamic Impact Tester described in this report. The results are shown in Table 5 and graphically in Figure 9.
2) It appears that the Dynamic Impact Tester developed by SRNL/Material Evaluation will be useful for determining Dynamic Impact Strength of a variety of rigid polyurethane foams used in RAM packaging designs and other relevant applications. To date, only the Dow Beta foam product has been compared to vendor data in GP Technical Literature[5,6] via this method. A final evaluation of the test method is recommended on GP LAST-A-FOAM® FR-3700 foam samples to verify the validity of the test method. Tested values from the SRNL Dynamic Impact Test can be compared to numbers from the GP Design Guide Literature. A new laptop computer will need to be procured.
3) Using the experimental apparatus described in Section 2.1 and high speed video measurement of crush described in Section 2.2 and Section 3.5 is a good way of capturing the total crush of rigid foam samples at maximum crush. The amount of elastic phase deflection of the sample can also be determined from the video.

5.0 Recommendations and Future Work

1) Perform Dynamic Impact Testing on General Plastics LAST-A-FOAM® FR-3725. This will provide further validation of the Dynamic Impact Test method.
2) Perform impact/crush tests on a variety of LAST-A-FOAM® FR-3700 Series foams of different densities, particularly if different density products are needed in RAM packaging designs or other critical applications.
3) Take a closer look at the level of elastic and inelastic (or permanent) crush of the various samples. The relevancy of such data to the foam application in the RAM packaging designs would need to be carefully evaluated. The primary purpose of this testing was to compare the behavior of two rigid foams of similar density.
4) Perform a study on the effect of sample thickness on Dynamic Testing as mentioned in Section 3.2 and indicated in Figure 6.
5) Dynamic Crush Testing on foam or packaging materials using some type of impactor geometry other than a flat crush surface may be of interest to better simulate actual package transport conditions.
6) It may be worthwhile to run tests in the %Crush range above and below the plateau regions shown on the Dynamic Crush Strength curve in Figure 3. The following are the Crush Strength Plateaus for FR-3700 foam of various densities:

Density (lb/ft3)	% Crush Range of Plateau	Plateau Crush (psi)
10	10 – 40	500
20	10 – 30	1900
25	10 – 20	2700
30	10 - 20	3100

7) If significantly more testing of this nature is anticipated and/or if higher velocities and energies at impact are required, procurement of an Instron Dynamic Impact Tester or similar may be considered.
8) Perform initial Dynamic Mechanical Analysis (DMA) testing on foam samples and determine the feasibility of using accelerated-aging and Time Temperature Superposition (TTS) to evaluate the long term aging behavior of the foam. SRNL has DMA equipment available for such testing. The parameters to be measured and the relevancy of such parameters to foam performance would need to be evaluated. However, DMA is commonly used to evaluate the dynamic mechanical behavior of polymeric materials.
9) Do long term aging studies on foam similar to ASTM D6147 where compression stress relaxation is tested using accelerated high temperature testing. This was used to determine use life of rubber O-rings in Packaging Containers. This could then be used to compare to the method using the DMA
10) Consider potential future applications for which such testing may be relevant for RAM packaging needs.

6.0 References

[1] ASTM D1621-10, "Standard Test Method for Compressive Properties of Rigid Cellular Plastics".
[2] ASTM D256-10, "Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics".
[3] ASTM D6110-10, "Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimen of Plastics".
[4] ASTM E1730-09, "Standard Specification for Rigid Foam for Use in Structural Sandwich Panel Cores".
[5] ASTM D1596-14, "Standard Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material".
[6] "General Plastics LAST-A-FOAM® FR-3700 for Crash and Fire Protection of Nuclear Material Shipping Containers", General Plastics Manufacturing Co., Technical Literature, initial issue April 1991, (reprinted 2003).
[7] "Design Guide LAST-A-FOAM® FR-3700 Crash and Fire Protection of Radioactive Material Shipping Containers", General Plastics Manufacturing Co., Technical Literature, www.generalplastics.com, (2017).

Table 1. LAST-A-FOAM FR-3700 Dynamic Crush Strength (PSI) and Energy Absorption (ft-lb/in^3) at 75 °F, Parallel to Rise (note perpendicular to rise is similar but slightly higher)

% Crush	10 lb/ft3 Density		15 lb/ft3 Density		20 lb/ft3 Density		25 lb/ft3 Density	
	Crush Strength (PSI)	Energy Absorption (ft-lb/in3)	Crush Strength (PSI)	Energy Absorption (ft-lb/in3)	Crush Strength (PSI)	Energy Absorption (ft-lb/in3)	Crush Strength (PSI)	Energy Absorption (ft-lb/in3)
10	471	2	1112	5	1893	8	2861	12
20	453	6	1070	14	1849	23	2828	36
30	477	10	1118	23	1938	39	2968	60
40	512	14	1223	33	2168	56	3380	86
50	595	18	1442	44	2604	76		
60	761	24	1918	58				
65	977	28						

Figure 1. Dynamic Impact Energy (ft-lb/in3) vs % Crush

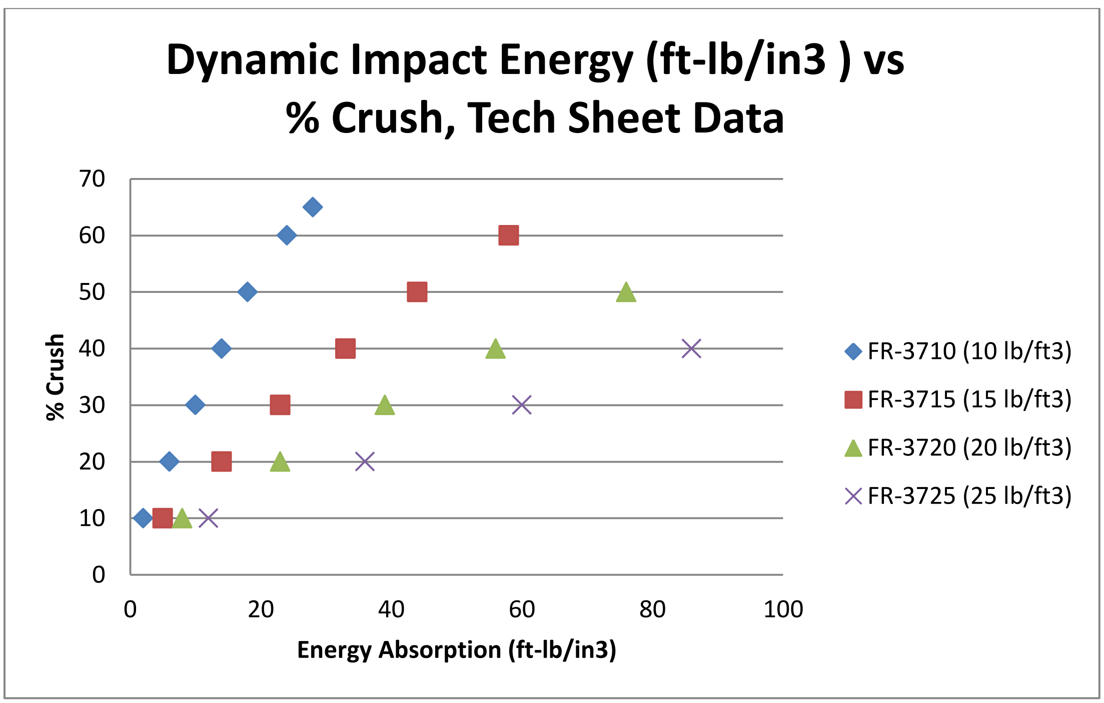

Figure 2. Dynamic Crush Strength

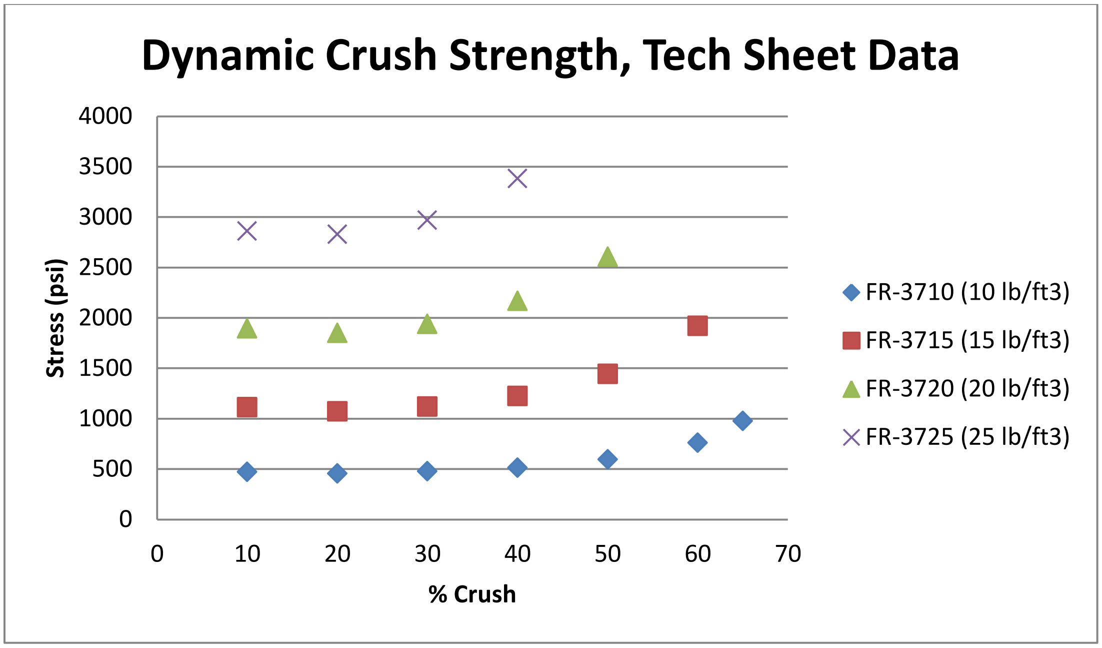

Figure 3. Comparison of Static and Dynamic Crush Strength

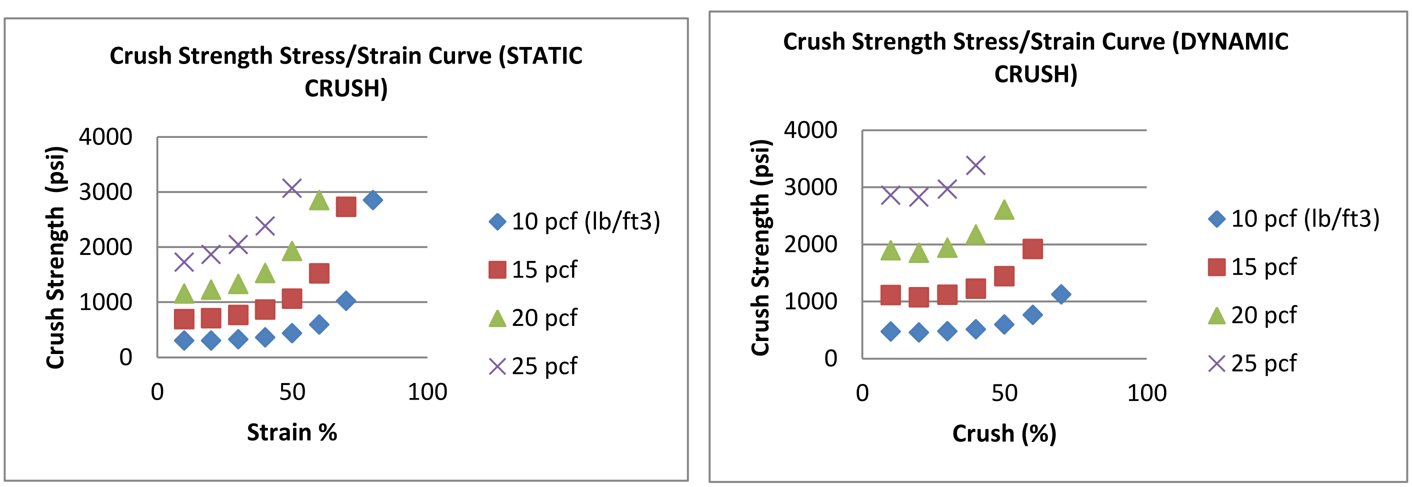

Table 2. Energy Absorption and Crush Strength for GP FR-3724 from [5]

% Crush	24 lb/ft3 Density	
	Crush Strength (PSI)	Energy Absorption (ft-lb/in3)
10	2653	11
20	2616	33
30	2745	55
40	3116	80

Figure 4. Energy Absorption vs %Crush.

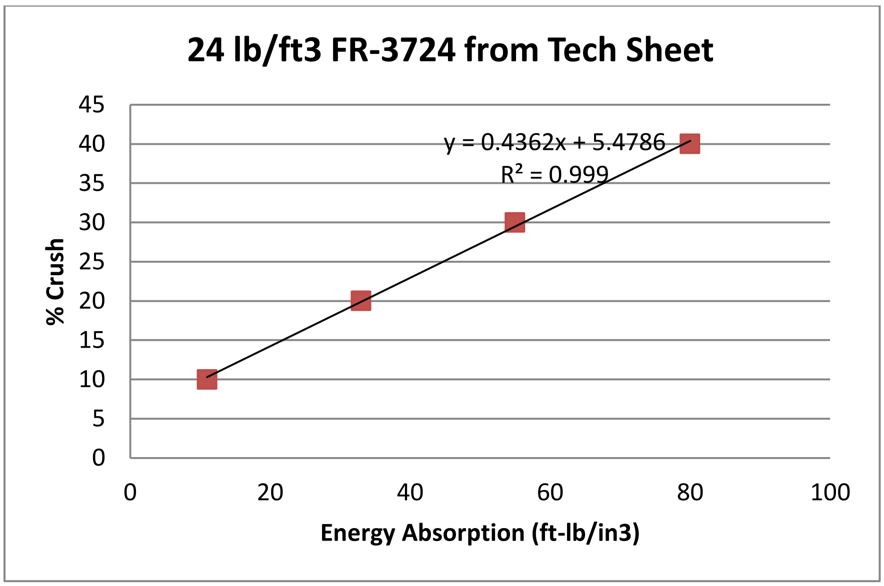

Table 3. Test Data of Dow Beta Foam from Paragon Inc. Parallel and Perpendicular to Rise.

Supplier	Direction of Rise	Sample	Density (lb/ft3)	Sample size	Energy Absorption (ft-lb)/in3	Tested % Strain	Tested % Crush
DOW	Parallel	1A	22.9	1.5"dia x 1.5"	69.91	20.19	11.70
DOW	Parallel	1B	23.3	1.5"dia x 1.5"	69.85	18.59	11.00
DOW	Parallel	2A	23.3	2"dia x 2"	29.35	5.15	2.95
DOW	Parallel	2B	22.7	2"dia x 2"	29.92	5.59	3.53
DOW	Parallel	3C	22.3	3"dia X 2"	13.17	0.74	0.27
DOW	Parallel	3D	22.3	3"dia X 2"	13.24	0.72	0.30
DOW	Parallel	4C	22.4	3"dia X 3"	8.65	0.34	0.38
DOW	Parallel	4D	22.2	3"dia X 3"	8.63	0.32	0.26
DOW	Parallel	5		3.5"x3.5"x1.5"	11.29	0.67	0.67
DOW	Parallel	6		2.0"x2.0"x1.5"	32.1	7.15	4.52
DOW	Parallel	6A	22.3	2.0"x2.0"x1.5"	30.85	5.97	3.54
DOW	Parallel	6B	22.0	2.0"x2.0"x1.5"	30.95	5.95	3.15
DOW	Parallel	6C	22.0	2.0"x2.0"x1.5"	31.13	5.60	3.25
DOW	Parallel	7		1.75"x1.75"x1"	63.56	14.10	9.07
DOW	Parallel	7A	22.9	1.75"x1.75"x1"	62.5	14.81	8.80
DOW	Parallel	7B	22.9	1.75"x1.75"x1"	61.95	14.09	8.63
DOW	Parallel	8		1.75"x1.75"x1.75"	36.56	8.34	4.68
DOW	Parallel	8A	22.4	1.75"x1.75"x1.75"	34.94	8.24	5.32
DOW	Parallel	8B	22.6	1.75"x1.75"x1.75"	34.77	7.70	4.73
DOW	Perpend	A1	22.6	1.5"dia x 1.5"	69.37	18.74	12.76
DOW	Perpend	A2	23.1	1.5"dia x 1.5"	69.53	19.45	12.84
DOW	Perpend	B1	23.1	2"dia x 2"	29.26	5.24	4.27
DOW	Perpend	B2	22.7	2"dia x 2"	29.23	5.82	4.45
DOW	Perpend	B3	23.2	2"dia x 2"	29.02	5.65	4.52
DOW	Perpend	G1	22.5	1.75"x1.75"x1"	60.77	13.9	9.28
DOW	Perpend	G2	22.6	1.75"x1.75"x1"	61.02	14.56	9.77
DOW	Perpend	H1	22.8	1.75"x1.75"x1.75"	34.61	7.72	5.78
DOW	Perpend	H2	23.2	1.75"x1.75"x1.75"	34.48	6.93	5.15
DOW	Perpend	I1	22.7	3"dia x 0.5"	53.71	6.18	4.89
DOW	Perpend	I2	22.6	3"dia x 0.5"	55.20	6.89	5.40
DOW	Perpend	J1	22.8	3"dia x 0.625"	43.28	4.58	3.40
DOW	Perpend	J2	22.7	3"dia x 0.625"	43.27	4.47	3.28
DOW	Perpend	K1	22.6	1.5"dia x 0.5"	230.97	39.07	26.06
DOW	Perpend	K2	22.8	1.5"dia x 0.5"	212.88	38.19	24.71
DOW	Perpend	L1	23.3	1.5"dia x 1"	112.26	27.53	16.83
DOW	Perpend	L2	23.4	1.5"dia x 1"	117.92	28.63	17.78
		avg	22.7				
		st dev	0.4				

Figure 5. Energy vs %Strain. Comparison of FR-3724 data from tech data sheets, and Dow Beta Foam tested.

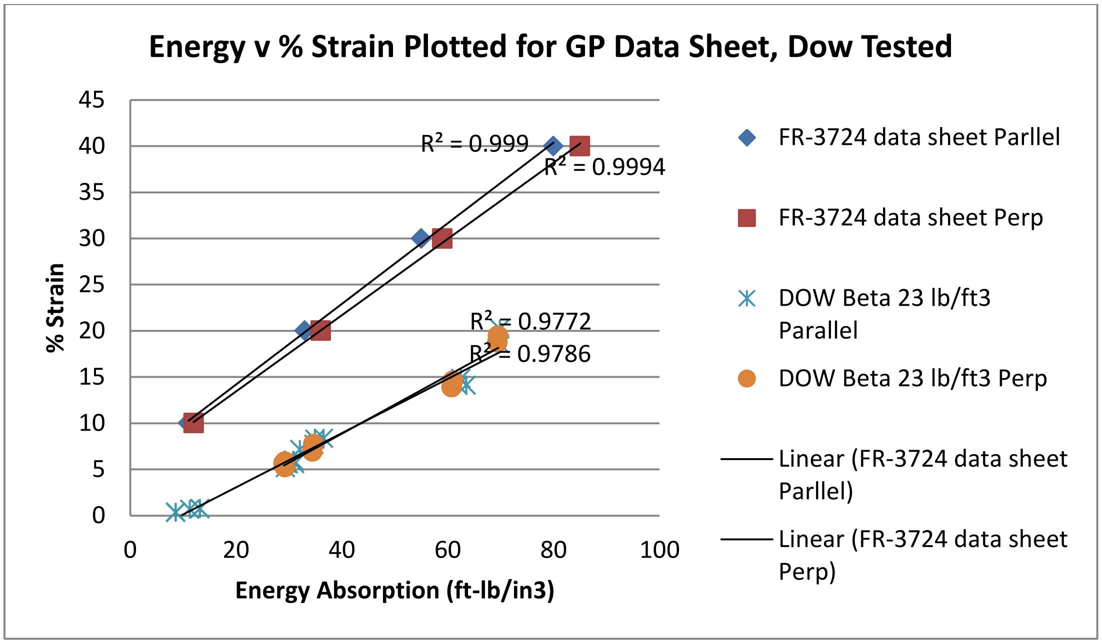

Figure 6. Effect of Sample Thickness and Volume on % Crush

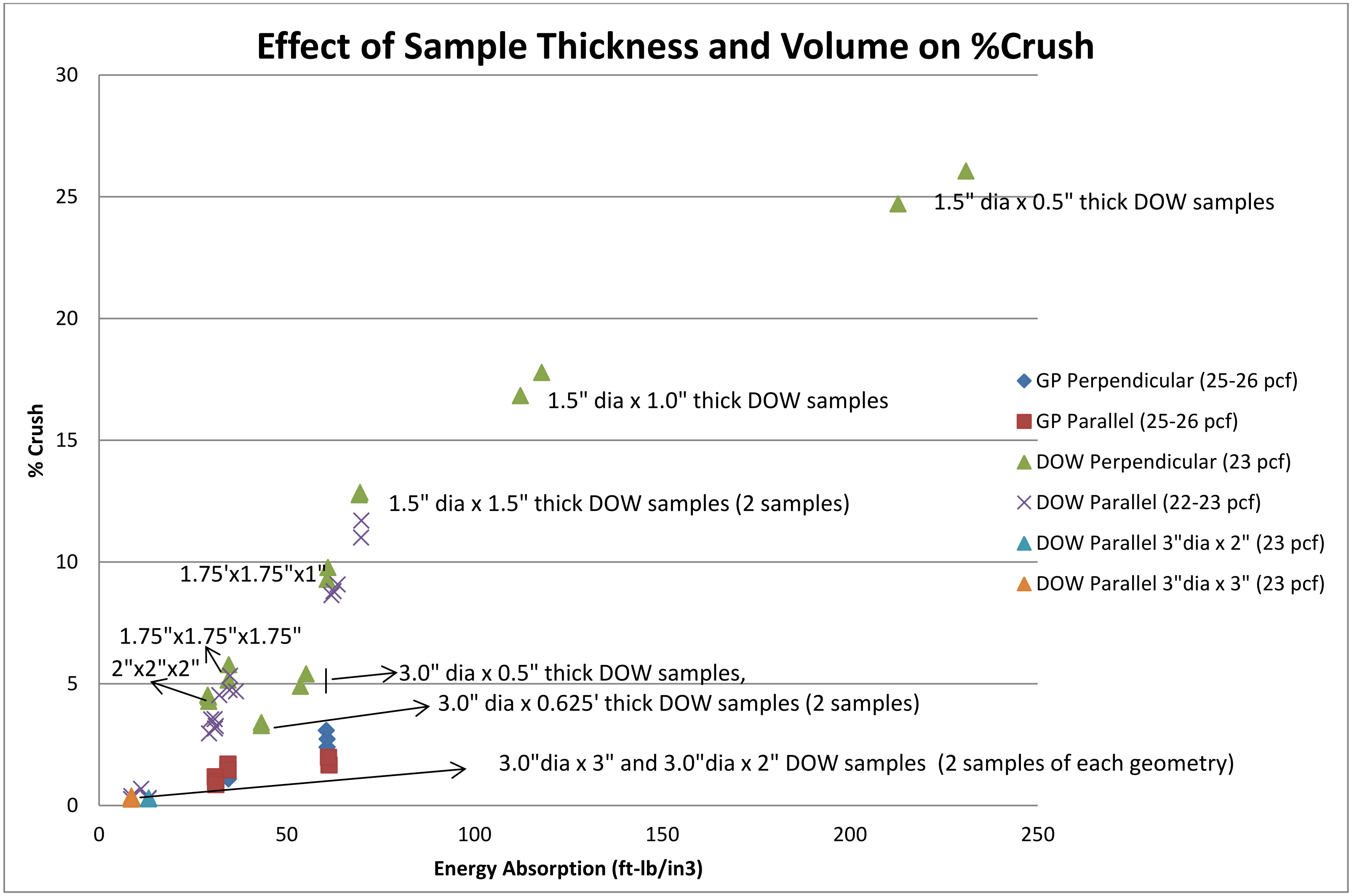

Table 4. Test Data of LAST-A-FOAM FR-3725 from General Plastics Perpendicular and Parallel to Rise.

Supplier	Direction of Rise	Sample	Density	dimensions	Energy Absorption (ft-lb)/in3	Tested % Strain	Tested % Crush
GP	Perp	1A	25.5	1.75"x1.75"x1"	60.79	5.51	2.39
GP	Perp	1B	25.5	1.75"x1.75"x1"	60.79	5.51	2.72
GP	Perp	1C	25.4	1.75"x1.75"x1"	60.61	6.04	3.08
GP	Perp	2A	24.9	1.75"x1.75"x1.75"	34.44	2.22	1.48
GP	Perp	2B	24.8	1.75"x1.75"x1.75"	34.35	2.43	1.59
GP	Perp	2c	25.0	1.75"x1.75"x1.75"	34.55	1.98	1.08
GP	Perp	3A	25.2	2"x2"x1.5"	31.12	1.58	1.03
GP	Perp	3B	25.2	2"x2"x1.5"	31.03	1.55	1.04
GP	Perp	3C	25.2	2"x2"x1.5"	31.06	1.58	1.03
GP	Parallel	1A II	24.7	1.75"x1.75"x1"	61.33	6.19	1.66
GP	Parallel	1B II	24.7	1.75"x1.75"x1"	61.17	6.15	1.97
GP	Parallel	1C II	24.8	1.75"x1.75"x1"			
GP	Parallel	2A II	25.1	1.75"x1.75"x1.75"	34.37	2.23	1.48
GP	Parallel	2B II	25.0	1.75"x1.75"x1.75"	34.35	2.4	1.69
GP	Parallel	2C II	25.1	1.75"x1.75"x1.75"	34.38	2.22	1.46
GP	Parallel	3A II	25.6	2"x2"x1.5"	31.01	1.66	1.17
GP	Parallel	3B II	25.6	2"x2"x1.5"	31.07	1.52	0.97
GP	Parallel	3C II	25.6	2"x2"x1.5"	31.12	1.55	0.85
		avg	25.2				
		st dev	0.3				

Figure 7. Energy vs %Strain. Comparison of FR-3724 data from tech data sheets, FR-3725 samples tested, and Dow Beta Foam tested

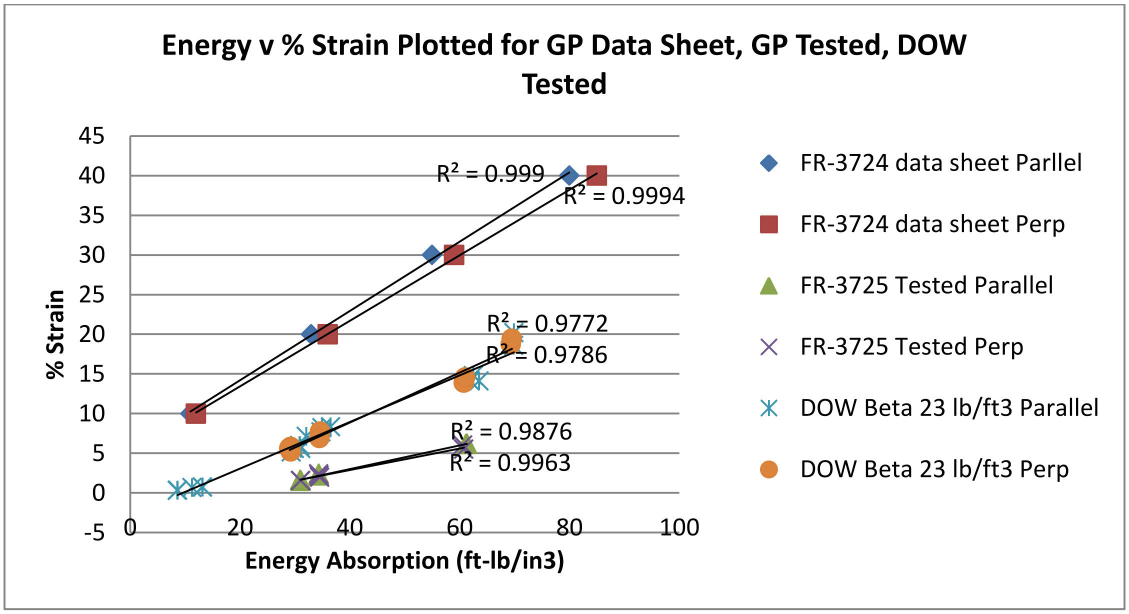

Figure 8. Stress/Strain curves of FR-3724 from General Plastics and Dow Beta Foam from Paragon

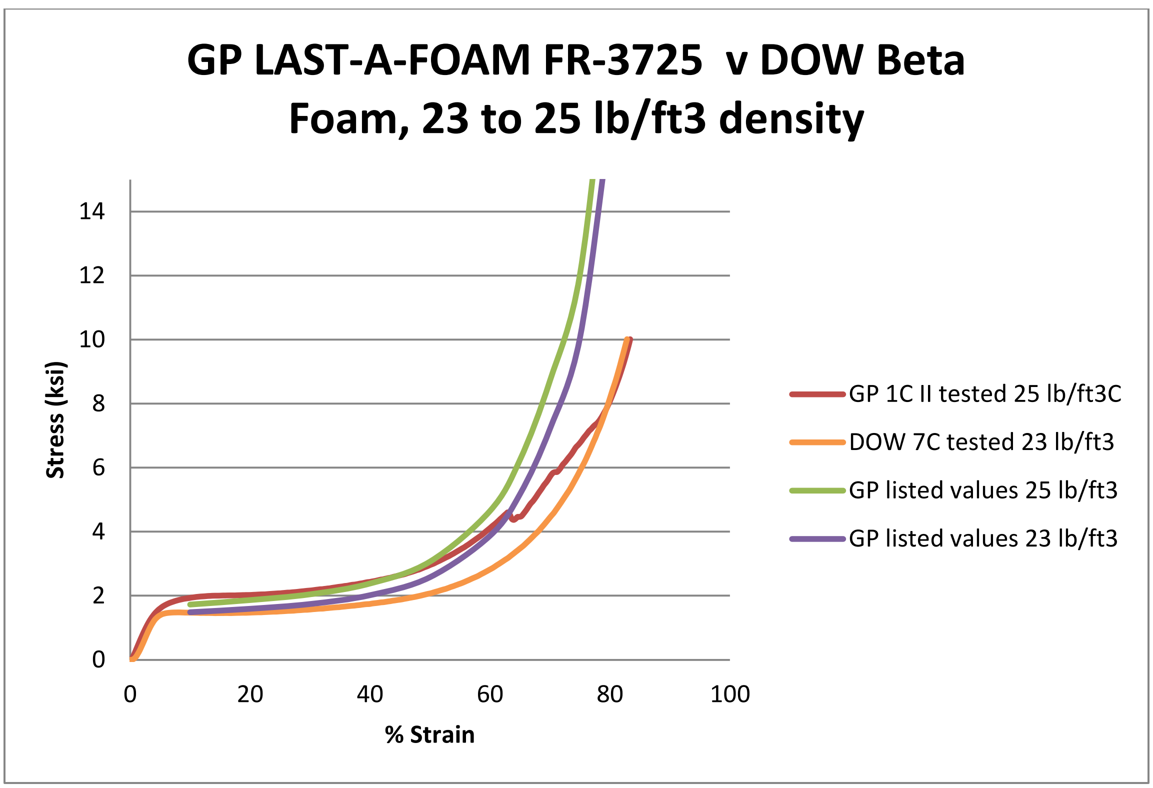

Table 5. Results for Dow Beta Foam from Paragon showing three different ways to calculate %Crush.

Supplier	Direction of Rise	Sample	Density	Sample size	Energy Absorption (ft-lb)/in3	Tested % Strain	Tested % Crush	High Speed Video % Strain		
								Lo (in)	L (in)	% Strain [(Lo-L)/Lo]
DOW	Parallel	1A	22.9	1.5"dia x 1.5"	69.91	20.19	11.70	1.517	0.868	42.8
DOW	Parallel	1B	23.3	1.5"dia x 1.5"	69.85	18.59	11.00	1.517	0.886	41.6
DOW	Parallel	2A	23.3	2"dia x 2"	29.35	5.15	2.95	2.012	1.709	15.1
DOW	Parallel	2B	22.7	2"dia x 2"	29.92	5.59	3.53	1.973	1.647	16.5
DOW	Parallel	3C	22.3	3"dia X 2"	13.17	0.74	0.27	1.998	1.881	5.9
DOW	Parallel	3D	22.3	3"dia X 2"	13.24	0.72	0.30	1.980	1.869	5.6
DOW	Parallel	4C	22.4	3"dia X 3"	8.65	0.34	0.38			
DOW	Parallel	4D	22.2	3"dia X 3"	8.63	0.32	0.26			
DOW	Parallel	5		3.5"x3.5"x1.5"	11.29	0.67	0.67			
DOW	Parallel	6		2.0"x2.0"x1.5"	32.1	7.15	4.52			
DOW	Parallel	6A	22.3	2.0"x2.0"x1.5"	30.85	5.97	3.54			
DOW	Parallel	6B	22.0	2.0"x2.0"x1.5"	30.95	5.95	3.15			
DOW	Parallel	6C	22.0	2.0"x2.0"x1.5"	31.13	5.60	3.25	1.524	1.250	18.0
DOW	Parallel	7		1.75"x1.75"x1"	63.56	14.10	9.07			
DOW	Parallel	7A	22.9	1.75"x1.75"x1"	62.5	14.81	8.80	0.981	0.658	32.9
DOW	Parallel	7B	22.9	1.75"x1.75"x1"	61.95	14.09	8.63	0.991	0.685	30.9
DOW	Parallel	8		1.75"x1.75"x1.75"	36.56	8.34	4.68			
DOW	Parallel	8A	22.4	1.75"x1.75"x1.75"	34.94	8.24	5.32	1.755	1.462	16.7
DOW	Parallel	8B	22.6	1.75"x1.75"x1.75"	34.77	7.70	4.73			
DOW	Perpend	A1	22.6	1.5"dia x 1.5"	69.37	18.74	12.76	1.524	0.966	36.6
DOW	Perpend	A2	23.1	1.5"dia x 1.5"	69.53	19.45	12.84	1.525	0.978	35.9
DOW	Perpend	B1	23.1	2"dia x 2"	29.26	5.24	4.27	2.015	1.735	13.9
DOW	Perpend	B2	22.7	2"dia x 2"	29.23	5.82	4.45	2.020	1.736	14.1
DOW	Perpend	B3	23.2	2"dia x 2"	29.02	5.65	4.52			
DOW	Perpend	G1	22.5	1.75"x1.75"x1"	60.77	13.9	9.28	1.007	0.683	32.2
DOW	Perpend	G2	22.6	1.75"x1.75"x1"	61.02	14.56	9.77	1.003	0.682	32.0
DOW	Perpend	H1	22.8	1.75"x1.75"x1.75"	34.61	7.72	5.78	1.744	1.432	17.9
DOW	Perpend	H2	23.2	1.75"x1.75"x1.75"	34.48	6.93	5.15	1.750	1.451	17.1
DOW	Perpend	I1	22.7	3"dia x 0.5"	53.71	6.18	4.89	0.511		
DOW	Perpend	I2	22.6	3"dia x 0.5"	55.20	6.89	5.40	0.489	0.400	18.2
DOW	Perpend	J1	22.8	3"dia x 0.625"	43.28	4.58	3.40	0.622	0.547	12.1
DOW	Perpend	J2	22.7	3"dia x 0.625"	43.27	4.47	3.28	0.622	0.532	14.5
DOW	Perpend	K1	22.6	1.5"dia x 0.5"	230.97	39.07	26.06			
DOW	Perpend	K2	22.8	1.5"dia x 0.5"	212.88	38.19	24.71			
DOW	Perpend	L1	23.3	1.5"dia x 1"	112.26	27.53	16.83	0.961	0.456	52.5
DOW	Perpend	L2	23.4	1.5"dia x 1"	117.92	28.63	17.78	0.915	0.412	55.0
GP Guide	Parallel		24		11					10
GP Guide	Parallel		24		33					20
GP Guide	Parallel		24		55					30
GP Guide	Parallel		24		80					40
GP Guide	Perpend		24		12					10
GP Guide	Perpend		24		36					20
GP Guide	Perpend		24		59					30
GP Guide	Perpend		24		85					40

Figure 9. Energy vs %Strain. Comparison of FR-3724 data from tech data sheets, and Dow Beta Foam tested. % Strain calculated from High Speed Video

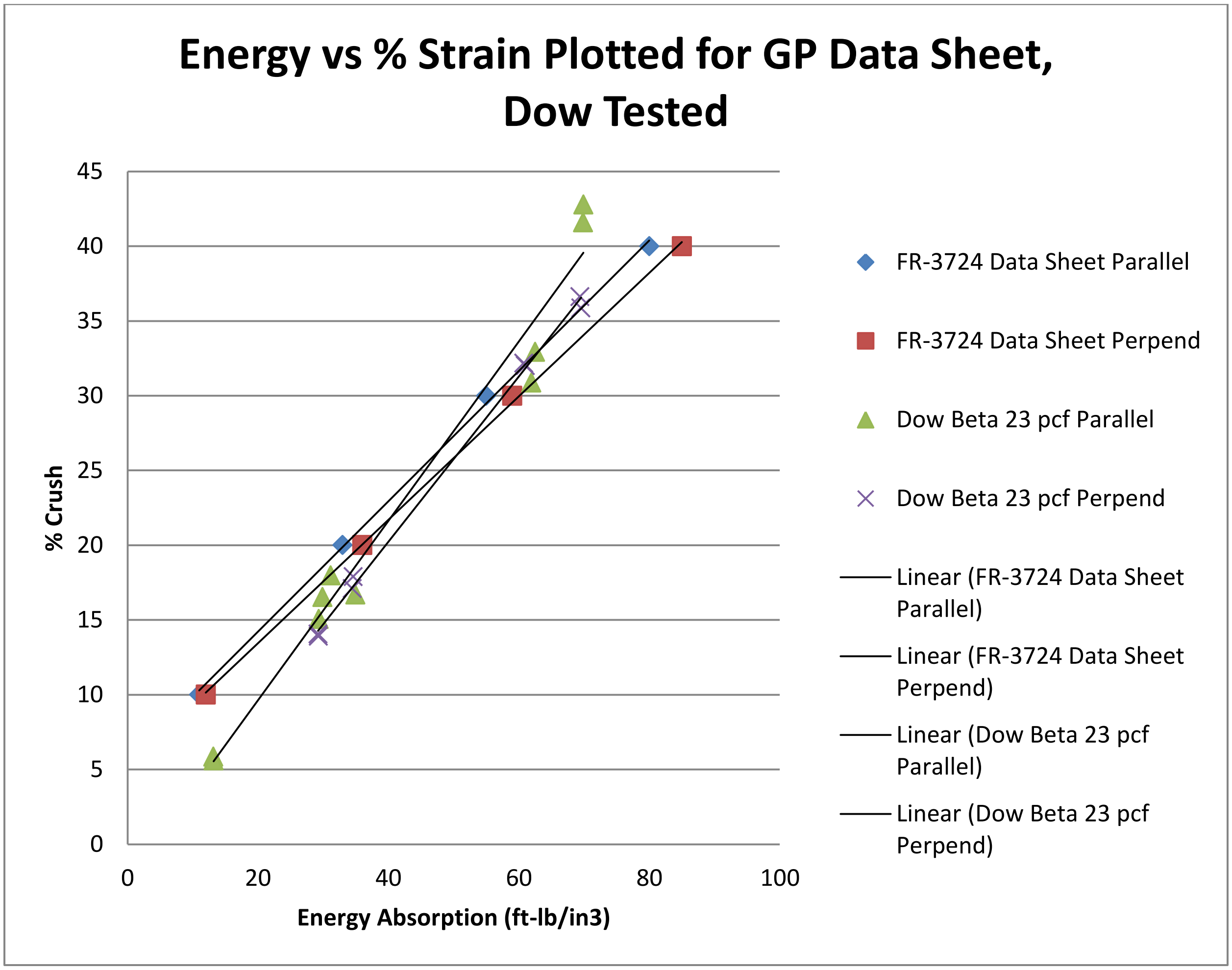

Table 6. Height dimension measurements using the High Speed Video Camera

	Initial condition before crushing						Final video ht				Caliper ht			
Sample	Sample dimensions	y_{top}	y_{bottom}	Δy	measured height (in.)	conversion (y units/in.)	y_{top}	y_{bottom}	Δy	calculated ht (in.)	measured height (in.)	Caliper - video (in)	% Difference	
1A	1.5"dia x 1.5"	59	428	369	1.517	243	136	415	279	1.15	1.2110	0.06	5.27	
1B	1.5"dia x 1.5"	34	402	368	1.517	243	96	377	281	1.16	1.2347	0.07	5.67	
2A	2"dia x 2"	15	474	459	2.012	228					1.9082			
2B	2"dia x 2"	35	477	442	1.973	224	0	410	410	1.83	1.8625	0.03	1.75	
3C	3"dia x 2"	13	495	482	1.998	241	-2	475	477	1.98	1.9827	0.00	0.00	
3D	3"dia x 2"	19	501	482	1.980	243	0	487	487	2.00	1.9655	-0.03	1.77	
5A	3.5" x 3.5" x 1.5"	8	505	497	1.501	331				0.00	1.4953			
5B	3.5" x 3.5" x 1.5"	14	495	481	1.503	320					1.4303			
6C	2" x 2" x 1.5"	36	364	328	1.524	215	71	384	313	1.45	1.4333	-0.02	1.45	
7A	1.75"x1.75"1"	157	428	271	0.981	276	216	445	229	0.83	0.8353	0.01	0.81	
7B	1.75"x1.75"1"	165	443	278	0.991	280	214	451	237	0.85	0.8515	0.00	0.00	
8A	1.75"x1.75"1.75"	38	463	425	1.755	242	73	470	397	1.64	1.6100	-0.03	1.81	
8B	1.75"x1.75"1.75"										1.6030			
A1	1.5"dia x 1.5"	91	435	344	1.5237	226	160	438	278	1.23	1.2832	0.05	4.04	
A2	1.5"dia x 1.5"	83	437	354	1.5255	232	158	443	285	1.23	1.2288	0.00	0.05	
B1	2"dia x 2"	14	496	482	2.0155	239	24	482	458	1.92	1.9098	-0.01	0.28	
B2	2"dia x 2"	17	492	475	2.0205	235	38	491	453	1.93	1.9030	-0.02	1.26	
B3	2"dia x 2"	8	502	494	2.0250	244	26	495	469	1.92	1.9107	-0.01	0.62	
G1	1.75"x1.75"1"	175	427	252	1.0068	250	216	424	208	0.83	0.8668	0.04	4.13	
G2	1.75"x1.75"1"	172	428	256	1.0028	255	205	418	213	0.83	0.8568	0.02	2.62	
H1	1.75"x1.75"1.75"	55	468	413	1.7443	237	62	443	381	1.61	1.6097	0.00	0.03	
H2	1.75"x1.75"1.75"	57	478	421	1.7503	241	92	481	389	1.62	1.6290	0.01	0.72	
I1	3"dia x 0.5"	233	373	140	0.5107	274	261	393	132	0.48	0.4707	-0.01	2.30	
I2	3"dia x 0.5"	178	293	115	0.4888	235	174	281	107	0.45	0.4552	0.00	0.09	
J1	3"dia x 5/8"	133	281	148	0.6223	238	137	276	139	0.58	0.5938	0.01	1.57	
J2	3"dia x 5/8"	125	276	151	0.6223	243	136	279	143	0.59	0.5945	0.01	0.87	
K1	1.5"dia x 0.5"	165	254	89	0.4710	189	193	246	53	0.28	0.2870	0.01	2.27	
K2	1.5"dia x 0.5"	145	246	101	0.5088	199	184	241	57	0.29	0.3145	0.03	8.70	
L1	1.5"dia x 1"	104	296	192	0.9615	200	159	292	133	0.67	0.6968	0.03	4.41	
L2	1.5"dia x 1"	111	291	180	0.9147	197	164	287	123	0.63	0.6528	0.03	4.25	
												0.01	2.18	avg
												0.03	2.17	st dev

Appendix A. Examples of convex bulge of samples after crush

Sample	position	before Impact			after Impact			Amount of convex out (after-b4)(in)			
		side a (in)	side b (in)	ht (in)	side a (in)	side b (in)	ht (in)	side a (in)	side b (in)	ht (in)	Sample Dimensions
6A	top (a side)	1.9845	2.0015	1.5210	2.0010	2.0170	1.4355	0.017	0.015	-0.085	2" x 2" x 1.5"
6A	middle	1.9890	2.0020	1.5195	2.0335	2.0440	1.4285	0.045	0.042	-0.091	
6A	bottom (b side)	1.9890	2.0030	1.5305	2.0085	2.0185	1.4340	0.020	0.015	-0.097	
	avg	**1.9875**	**2.0022**	**1.5237**	**2.0143**	**2.0265**	**1.4327**	**0.0268**	**0.0243**	**-0.0910**	
	st dev	**0.0026**	**0.0008**	**0.0060**	**0.0170**	**0.0152**	**0.0037**	**0.0154**	**0.0153**	**0.0055**	
6B	top (a side)	1.9945	1.9885	1.5205	2.011	2.0065	1.4305	0.017	0.018	-0.090	2" x 2" x 1.5"
6B	middle	1.994	1.987	1.5245	2.0345	2.048	1.4285	0.041	0.061	-0.096	
6B	bottom (b side)	1.9975	2.0005	1.5175	2.014	2.0245	1.432	0.016	0.024	-0.086	
	avg	**1.9953**	**1.9920**	**1.5208**	**2.0198**	**2.0263**	**1.4303**	**0.0245**	**0.0343**	**-0.0905**	
	st dev	**0.0019**	**0.0074**	**0.0035**	**0.0128**	**0.0208**	**0.0018**	**0.0139**	**0.0233**	**0.0053**	
7	1	1.755	1.754	0.999	1.782	1.794	0.865	0.027	0.040	-0.134	1.75" x 1.75" x 1"
7	2	1.756	1.753	1.003	1.807	1.808	0.858	0.051	0.055	-0.145	
7	3	1.754	1.753	1.002	1.811	1.805	0.857	0.057	0.052	-0.145	
7	4	1.755	1.752	1.002	1.808	1.802	0.858	0.053	0.050	-0.144	
7	5	1.755	1.754	1.002	1.788	1.789	0.864	0.033	0.035	-0.138	
	avg	**1.755**	**1.753**	**1.002**	**1.799**	**1.800**	**0.860**	**0.044**	**0.046**	**-0.141**	
	st dev	**0.001**	**0.001**	**0.002**	**0.013**	**0.008**	**0.004**	**0.013**	**0.009**	**0.005**	
8	1	1.754	1.752	1.737	1.798	1.78	1.598	0.044	0.028	-0.139	1.75" x 1.75" x 1.75"
8	2	1.754	1.755	1.741	1.803	1.805	1.599	0.049	0.050	-0.142	
8	3	1.754	1.753	1.742	1.792	1.812	1.599	0.038	0.059	-0.143	
8	4	1.755	1.753	1.742	1.776	1.787	1.597	0.021	0.034	-0.145	
8	5	1.759	1.750	1.735	1.755	1.769	1.594	-0.004	0.019	-0.141	
	avg	**1.755**	**1.753**	**1.739**	**1.785**	**1.791**	**1.597**	**0.030**	**0.038**	**-0.142**	
	st dev	**0.002**	**0.002**	**0.003**	**0.020**	**0.018**	**0.002**	**0.022**	**0.016**	**0.002**	

Appendix B: R&D Direction for Vertical Drop Foam Impact Testing at 723-15A, Rev. 0

R&D Directions	Vertical Drop Foam Impact Testing at 723-15A, Rev. 0

Note: It is acceptable to use R&D Directions per SRNL procedure PL-AP-4006, Attachment 8.1, the Work Control Document Need Decision Tree.

1. **PI:** M. D. Kranjc, 5-7521 Reviewed By [redacted]
2. **Date:** 04/12/2016
3. **Task Title:** Directions for Development of a Vertical Drop Impact Test
4. **Work Group and Location:** MS&T Materials Evaluation, Testing to occur in 723-15A
5. **Applicable Reference Documents (if any):**
   - Procedures (e.g., site, L1 or section specific): WSRC 8Q, Employee Safety Manual 12, General Site Safety Requirements
   - eHAP SRNL-L4430-2015-00006, Dynamic Impact Testing of Packaging Materials
   - SRNL-JHA-2015-00174, Dynamic Impact Testing of Packaging Materials
6. **Hazards (List unique activity-specific hazards):**
   - Dropping approximately a 50 pound cylindrical steel weight within a clear acrylic tube from a height of approximately 60 inches onto a rigid foam (or other) sample located at the bottom of the tube.
   - A hoist will be used to lift the steel weight so it can be dropped through the 60 inch high, 5.25"ID clear acrylic tube. A quick disconnect release hook will be used to release the weight once positioned inside the tube.
7. **Hazard Controls (List unique activity-specific hazard controls for above hazards):**
   - Safety Glasses
   - Steel toed work shoes
   - Hard Hat, especially for personnel operating the hoist and release hook
   - Gloves as required for handling weight and operating racket straps
   - Ear protection in cases where the noise at impact is loud
   - Review Hazards and Controls Provided in the JHA
8. **M&TE**
   - Record M&TE used in the testing and the expiration date(s) of the calibration.

____

____

____

____

Page 1 of 3

9. Directions:

9.1 Test Sample Preparation

9.1.1 Samples to be crushed should be cut into a geometry that can be fitted in the bottom of the acrylic tube. This would include cubes such that the horizontal face to impact has lengths less than approximately 3.5 inches and cylinders such that the horizontal face to impact has a diameter less than or equal to 4 7/8 inches. The heights of the samples (cube or cylinder) can be of varying length. Record these dimensions in a separate log book or data sheet.

9.1.2 The % Crush should stay within specified limits determined by the manufacturer of the samples to be tested. Initial testing will use the linear relationship between % Crush and Energy Absorption (ft-lbs/cu in) of FR-3700 Rigid Polyurethane Foam published by General Manufacturing Co. to determine what sample size to test.

9.2 Equipment Used for Testing

9.2.1 Clear Acrylic Pipe, 5 feet long 5.25 inch ID, 3/8 inch wall thickness.

9.2.2 Electric Hoist on supported rails/A-frame in 723-15A. Must operate hoist, hoist cable, and acrylic tube arrangement is such that there is minimal loss of energy due to friction between the cylinder and walls of the tube.

9.2.3 Frame supporting the hoist and a frame to which the Acrylic Pipe can be attached.

9.2.4 Cylindrical metal impactor. Currently impactor is a cylinder of stainless steel 4 15/16 inches in diameter and 8 inches in height weighing 43.3 lbs. Larger or smaller impactors could be used to vary the Impact Energy.

9.2.5 An electric hoist is to be used. A hook is screwed onto the top face of the impactor to attach to a quick release hook attached to the steel cable on the hoist when using the hoist. For initial testing and proof of concept, if the use of a hoist is difficult and the 43 pound impactor just cannot be positioned and released without problems to the accuracy of the test then the 43 pound impactor can be lifted, positioned, and released by hand. This method is to be used only as a last resort for proof of concept.

9.2.5 Quick Release Hook (Peck and Hale or some similar manufacturer) rated for 1,000 lbs of safe work load.

9.2.6 Strapping to secure the Acrylic Pipe to a frame that will support the acrylic pipe once the 43 lb Impact Cylinder is released at the top of the pipe, travels down the pipe with the force of gravity, and then impacts the sample. Strapping could be bungee type cords, ratchet down straps, etc. The strapping must secure the pipe so there is no movement during the test that results in a loss of energy when the impactor crushes the sample and to ensure no unsafe conditions occur during the impact test.

9.2.7 Tape to ensure that the sample does not move significantly during impact such that the transfer of energy from the drop cylinder to the sample is affected. Tape will attach the sample to the floor within the acrylic pipe.

9.3 Procedure

9.3.1 Tape sample at a location at the bottom of the acrylic pipe that will be during testing to ensure that the sample does not move significantly during impact.

9.3.2 Place pipe over the sample, in a vertical position. Ensure that the acrylic pipe is properly secured using the strapping described in 9.2.6 so that there is no movement of the acrylic pipe that would cause a safety issue and would cause a loss of transfer of energy from the impact cylinder to the sample during testing.

9.3.3 An electric hoist will be used to lift the 43 pound cylindrical metal impactor into position at the top of the acrylic pipe (approximately 5 feet). An eye hook can be screwed into the top of the impact cylinder which can be attached to a quick release hook (see 9.2.5) that is also attached to the hoist cable. The cylinder will be dropped using the quick release mechanism. For initial testing and proof of concept, if the use of a hoist is difficult and the 43 pound impactor just cannot be positioned and released without problems to the accuracy of the test then the 43 pound impactor can be lifted, positioned, and released by hand. This method is to be used only as a last resort for proof of concept. This has been agreed upon by Ray Battles SRNL Safety Engineer.

9.3.4 The impact cylinder should fall down the pipe under gravitational pull and with little loss of energy due to friction on the sides of the acrylic pipe as well as little loss of energy due to the creation of an air cushion in the pipe.

9.3.5 The bottom surface of the impact cylinder should hit the sample to be crushed such that the impact surfaces are parallel and flush. If need be a metal plate can be used on top of the sample to transfer load of the impactor more evenly over the surface of the sample to be crushed. Attachment of the metal plate and crush sample may be required.

9.3.6 Safely retrieve the sample after impact and accurately measure the sample dimensions so that % Crush can be determined. % Crush is determined by the following:

$$\%\,Crush = \frac{Initial\ Volume - Final\ Volume}{Initial\ Volume}$$

9.3.7 Energy generated by the free fall of the metal cylindrical impactor will be transferred to the sample and result in %Crush of sample defined above. Energy Absorption is determined by the following:

$$Energy\ Absorption\ (ft - lb)/(in^3) = \frac{(Impactor\ weight\ (lb.))\ x\ (Height\ of\ drop\ (ft))}{Initial\ volume\ of\ sample\ (in^3)}$$