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RIGID POLYURETHANE FOAM FOR IMPACT AND THERMAL PROTECTION

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INTRODUCTION

Polyurethane foam has been used as a protective medium in nuclear material transportation containers for over 30 years. Other materials used in containers are woods, cork, cellulose fiber, honeycomb, metal fabrications, and other foam types. These other materials have one or more inherent drawbacks including: cost, availability, difficulty of fabrication, uniaxial protection, and poor thermal resistance. The use of polyurethane foams can free the container designer from many of these constraints since the polyurethane foam can be engineered to meet a wide range of impact situations and to provide significant thermal protection. System costs of polyurethane foam are very competitive, especially with in situ (pour-in-place) foam application. The particular foam we will refer to is LAST-A-FOAM FR-3700/FR-6700 rigid polyurethane foam.

IMPACT PROTECTION

To accommodate the wide variety of impact energies to be absorbed the designer must first define the requirements. Of primary importance is the determination of the maximum allowable stress the payload can withstand. Other factors which must be considered are ambient temperatures, radiation exposure, thermal load, handling, moisture exposure, weight constraints, package size, cost, and safety factor.

Protection is achieved by dissipating the kinetic energy available just prior to impact in a way that minimizes the forces which could destroy the package and release the payload to the environment. Since the mass of the payload is often fairly constant we can simplify the analysis by focusing on deceleration.

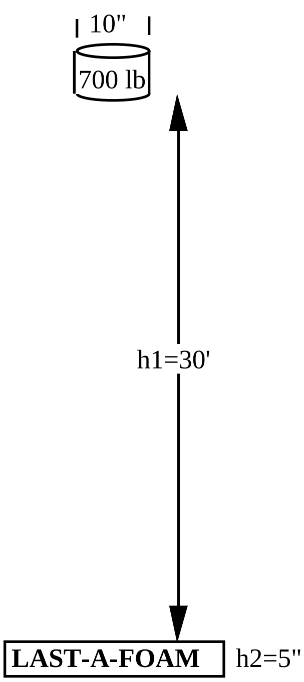
Most people think of soft, squishy, flexible things when they think of foam. When dealing with low energy levels that is exactly what is required, a nice soft cushion to keep things from breaking. However, for high energies the soft cushions are useless or worse. They can bottom out and rebound.

It is important to keep in mind that ONLY DISTANCE CAN MITIGATE IMPACT. The first determination must be how much deceleration distance is necessary to reduce forces to safe levels. A theoretically perfect cushion material would decelerate a payload uniformly through 100% of its thickness. Typical cushion materials have efficiencies of one quarter to one half of the perfect cushion. This means that actual deceleration will be two to four times theoretical.

If the deceleration distance is adequate, the next step is to determine if the energy levels are within the absorbing range of the foam. If the foam is too weak, little or no deceleration will occur upon deflection (but a great deal will occur upon bottoming with resulting high stress). If the foam is too strong little deflection and high deceleration will occur again with resulting high stress. This is where the versatility of polyurethane foam becomes apparent. The designer has a wide range of energy absorbing densities from which to choose.

The following example was developed from an actual application:

A 10-in diameter, 700-lb object falls 30 ft onto a 5-in foam pad.
What foam density would be recommended?
What is the maximum predicted decceleration (g)?



From conservation of energy:

$\cancel{m} \cdot g \cdot h1 = \cancel{m} \cdot A \cdot h2$

$A = h1/h2 \cdot g$ (theoretical) $= \frac{30\,(12)}{5} = 72g$

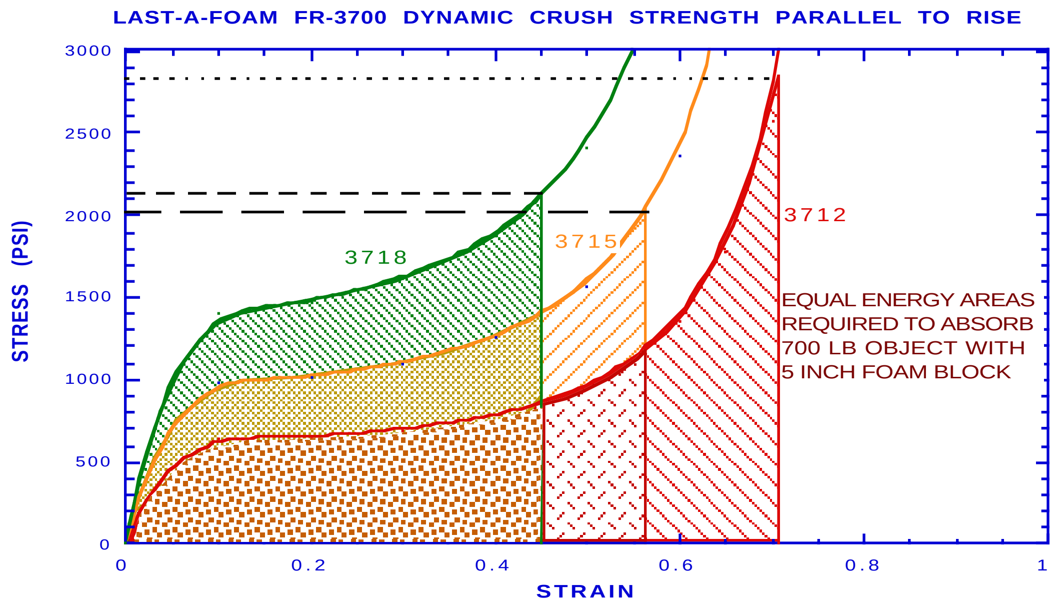
The theoretical value is not possible since the cushion material prevents the object undergoing deceleration from using all of the available distance. Realistic decelerations are about 3 times theoritical. $A \approx 216g$ in this example.

Next determine volume of foam absorbing the impact. In this illustration simply assume that the area of the falling mass will be stopped by a like area of foam times thickness. The kenetic energy at point of impact is:

700 lb x 30 ft = 21,000 ft-lb which will be absorbed by

π (5")(5")(5") = 392.7 cu in of foam.

Assuming that the anticipated deceleration of 216g is acceptable we can now choose the foam density. If we assume a constant impact footprint then the stress/strain curve is directly proportional to the force acting on the package as the foam crushes. By integrating the stress/strain curve for various foam densities and multiplying the result by the impact area we can determine the amount of energy a given volume of foam will absorb when crushed to a specified deflection. In the following chart the shaded area under each curve represents an equal amount of energy absorbed by crushing an equal volume of each of the three foam densities to the deflection shown.



If we had a perfect cushion we could stop the 700-lb cylinder in 5 inches with a constant stress of 642 psi.

Given:

KE = 700 lb x 30 ft, Impact area = π x 5 x 5 = 78.5 sq in

Then:

$$\text{Average stress to absorb energy} = \frac{\text{Weight x h1 x 12}}{\text{Area x h2}}$$

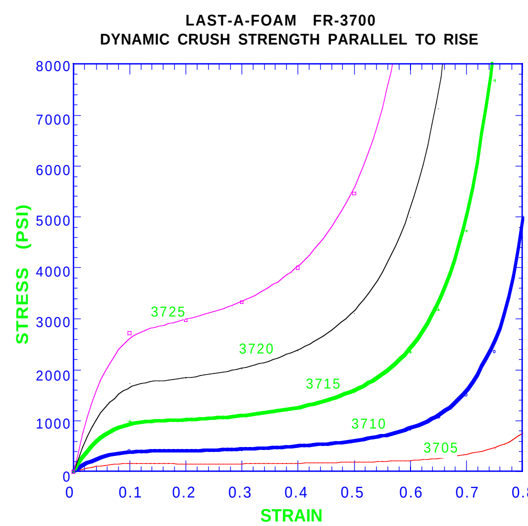
Substituting: $$\text{Average stress} = \frac{\text{700 lb. x 30 ft. x 12 in/ft}}{\text{78.5 sq.in. x 5 in.}} = \text{642 psi}$$

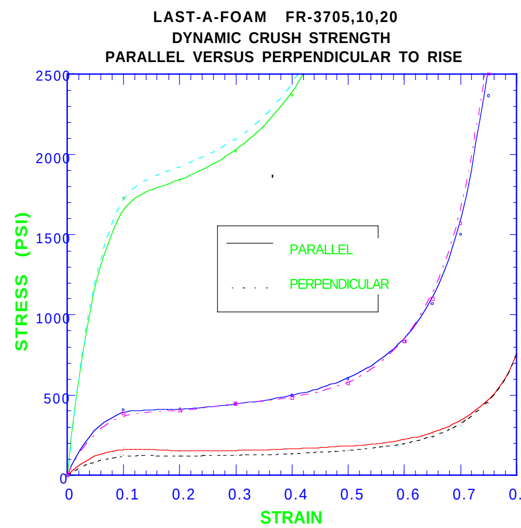
Unfortunately we do not have access to a perfect cushion. That being the case, we have to figure how to achieve the required average stress. In the above chart the shaded areas under each curve are equal to 642 psi-strain. This value is proportional to the energy which can be absorbed by crushing a given volume of foam to the strain levels shown. From the chart we can see that there is little difference in the maximum stress, about 2,000 psi, between the 15 and 18 lb/cu ft density foam, whereas the 12 lb/cu ft density foam requires a stress of 2850 psi to consume 21,000 ft-lb of kinetic energy. The next step is to calculate maximum g. Simply divide the weight into the peak force generated by the impact.

$$\text{Deceleration} = \frac{\text{2000 psi X 78.5 sq in}}{\text{700 lb X g}} = \text{224g}$$

We find that the rule of thumb of actual g being about three times theoretical is reasonably close in this instance. If this deceleration is too severe and space permits, the cushion thickness can be increased with a consequent reduction of g.

If the designer is faced with the need of reducing impact forces while maintaining a minimum cushion thickness, it is possible to use lower density foams in conjunction with a load spreader. The chart on the left below depicts the effect of density on dynamic compressive strength over the typical range of polyurethane foams used for impact absorption.





In the chart at right above the difference between compressive strength in the parallel versus perpendicular to rise directions is shown. It can be seen that there is very little difference in strength from foam orientation. The important factor from a design standpoint is that properly formulated and processed polyurethane foams can be counted on to provide uniform protection regardless of the direction of impact. Also, that the risk of "bottoming out" is minimal since the crushed foam continues to function at increasing levels of strain. The upper limit, when the foam is compressed to a solid polymer, does not occur until the effective density is about 75 lb/fcu ft.

With polyurethane foams the package designer is free to fine tune a design simply by varying density to achieve the desired package performance. Furthermore, much of this design work can be accomplished on paper at a considerable saving of time and money. The foam strength values presented herein are based on empirical testing of small (typically 10 to 64 cu in) specimens uniaxially and unrestrained. Actual applications may include a number of factors which the designer must take into account. These factors may include metal deformation, shape effects, combined shear and compression, confined foam compression, and others. Notwithstanding the foregoing, it has been found that compressive (crush) test data developed for LAST-A-FOAM FR-3700 and presented here (in part) has effectively predicted the impact-absorbing ability of numerous LAST-A-FOAM filled containers.

FIRE PROTECTION

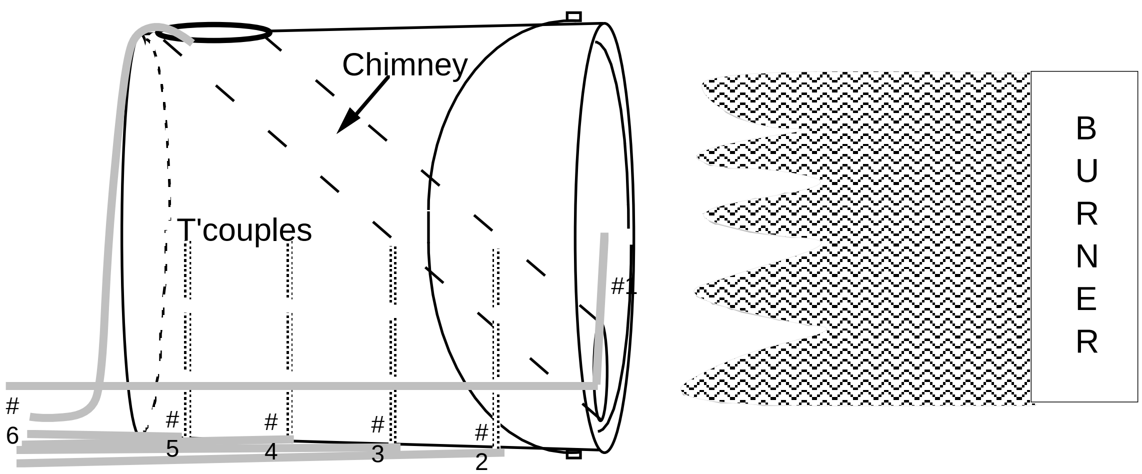
Organic materials withstand fires primarily as an ablative medium. Consequently, the first design consideration is to ensure enough mass to survive the fire. Proper vessel venting is important not only to prevent the possibility of explosive rupture but also to direct the flow of hot gasses to minimize convective heat transfer to the payload. One problem encountered by most organic materials is the possibility of a smoldering fire. When this happens the thermal load on the payload can be very high and of long duration.

As with designing for impact protection, the first step is to define the requirements of the package. To begin with, the maximum allowable payload temperature must be established. Is there a difference between acceptable short- and long-term temperatures? What is the effect of the thermal mass of the payload? Is there radioactive decay heat to dispose of? Once these (and other) questions are answered the designer can address the external thermal threat. Interestingly, the requirements of 10CFR71 (30 minutes at 1,475°F) have often been found to be milder than actual test conditions. Temperatures recorded in pool fire tests typically range from 2,000 to 2,200°F. Furnaces set at 1,475°F prior to the start of testing quickly rise to 2,000+°F if any flammable gasses are generated by the thermal decomposition of the protective medium.

The concept of using a hydrocarbon material as a thermal protective medium may seem counterintuitive. However, test experience has found that some hydrocarbons provide superior performance when compared to materials which do not thermally degrade. In the absence of oxygen, hydrocarbons consume energy as they are being thermally degraded (endothermically). During the thermal exposure the materials ablate, i.e. they are dissipated from the surface by the heat. Away from the heat source the materials can remain quite cool, this is especially true with closed cell polyurethane foams since they are excellent insulators. While the ablation process takes place it is important to vent the breakdown products out of the container. This can cause considerable excitement among observers of qualification tests when they witness flames jetting from the test vessel. At this point the vessel designer can calmly assure the observers that the package is performing as designed. Furthermore, that the venting is good since it shows that heat is being removed from the vessel. The jetting flames are of no consequence since they are no hotter than the surrounding fire. The key to ablative thermal protection is to have a sufficient amount of material so that original material remains after the thermal threat passes. It is also important to prevent thermal paths to the payload, and to prevent smoldering fires inside the container.

The mechanism for smoldering combustion comes from the way in which some organic materials pyrolize. Most materials shrink as they thermally degrade and char. The resultant cracks in the protective material allow the burning surfaces to radiate heat between the opposing faces. If oxygen is drawn into the container and through the crack network, fire can be sustained. These smoldering fires are serious because of their proximity to the payload and because of their long duration. A good working solution is to employ a material which continuously generates an expanding (intumescent), highly fire resistant char during pyrolysis. An expanding char can fill cracks caused by impact damage and extrude through punctures and vent openings in the outer container wall.

In the author's experience, caution would dictate designs with significant safety margins with respect to thermal resistance. When designing thermal safety margins it is risky to simply focus of the test conditions required under 10CFR71. While it is not possible to test for all contingencies which could occur, the designer can achieve a very high level of confidence by testing packages or components under a variety of failure modes. Tests have been performed on LAST-A-FOAM FR-3700 series rigid polyurethane foams in which hypothetical accident conditions have been simulated in the extreme. These tests show the protection afforded by foams of various densities under a combination of conditions. A diagram of the test configuration is depicted below along with photographs of the results of the 15 minute burn test of FR-3708 (note 6-in rule).



It has been found that the manner in which LAST-A- FOAM FR-3700 chars provides outstanding protection. By building an intumescent char the foam seals cracks and punctures that could occur in an accident and develops a protective cocoon around the payload and virgin foam. A common example of an intumescent char can be found in the "snake" which is generated from the little pellets lighted for children on Independence Day. The table below shows the degree of protection afforded by the intumescent char of LAST-A-FOAM FR-3700 polyurethane foams. Three versions of the test specimen were subjected to 2,000+°F flame temperatures directly impinging on the face of the can (or exposed foam surface) for periods of 15 to 45 minutes. The most severe test incorporated a chimney running from the lower front face to the upper rear of the can. Other test versions had the foam covered with a steel lid or completely exposed to the impinging flame. In all cases the foam developed a char that prevented internal smoldering fires from consuming the foam after the external fire threat passed. Substantial amounts of undegraded foam remained in the test specimen at the end of the test period even in those tests lasting 45 minutes.

Intumescent Char Development Tests: 15-minute burns of 5 gallon pails filled with LAST-A-FOAM FR-3704 and FR-3708 with hot face temperature 1,800°F or greater.

TREATMENT--»	**OPEN FACE**		**LID & CHIMNEY**		**LID ONLY**	
SPECIMEN	% FOAM REMAINING	°F @ 9"	% FOAM REMAINING	°F @ 9"	% FOAM REMAINING	°F @ 9"
FR-3704	**53%**	**79°**	**55%**	**256°**	**72%**	**73°**
FR-3708	**72%**	**72°**	**75%**	**169°**	**83%**	**72°**

<u>Intumescent Char Tests:</u> 45-minute burns of 5 gallon metal cans filled with LAST-A-FOAM FR-3700 with densities of 8, 16, and 24 PCF.

		TEMPERATURE °F AFTER 45 MINUTES				
SPECIMEN	% FOAM REMAINING	TCPL--» H.F.	3"	6"	9"	12
FR-3708	**66%**	**2,340**	**799**	**218**	**78**	**93**
FR-3716	**76%**	**2,248**	**640**	**126**	**76**	**86**
FR-3724	**82%**	**2,049**	**274**	**103**	**94**	**102**

QUALITY ASSURANCE

This paper is not a do-it-yourself guide to foaming. Not all polyurethane foams are the same. In addition to the obvious difference between the flexible and rigid versions, there are many variations. Some variations are obvious to the casual observer, while other differences cannot be detected short of specific physical properties testing. The critical mission of nuclear shipping containers demands that the foaming work be left to those most knowledgeable of the processing and formulation of polyurethane foams. This position may not always fall on receptive ears since there are many foam systems on the market where the manufacturer will be happy to sell the foam to anyone for any purpose. However we believe the designer/user will find that care in the selection of their foam provider will pay large dividends in cost, time, quality assurance including the assurance of passing qualification tests, and, not least, peace of mind.

The fire retardant characteristics of polyurethane foams, including intumescent char, are achieved with special additives. Strength properties are primarily determined by foam density. Even if there is a good understanding of the required chemical composition needed to achieve all the properties necessary for a high-performance package, these properties can be compromised by poor processing techniques.

The package designer/user can obtain the greatest assurance of top quality foam work in his package by focusing on specifications which require strict adherence to physical properties testing. It may also be advisable to specify some process steps such as temperature bounds for in situ foaming, cleanliness and dryness of the cavity to be foamed, inspection hold points during foaming, etc. The least effective method of assuring quality foaming work is to only specify liquid formulations (or, even worse, to provide a recipe). When this happens inexperienced fabricators can be lulled into attempting to foam fill containers with insufficient preparation and poor production practices. There are numerous examples of poor foam specifications resulting in higher costs, schedule delays, and failed qualification tests.

SUMMARY:

Properly formulated rigid polyurethane foams can provide both impact and fire protection in nuclear material transportation containers. Impact protection depends on sufficient crushing distance and foam density to absorb the impact energy. Fire protection is primarily accomplished by the ablative effect of converting the foam to char. In order to preclude the possibility of a smoldering internal fire the foam must be capable of developing an intumescent char.