Impact Limiter Design for a Lightweight Tritium Hydride Vessel Transport Container*

D.C. Harding, D.B. Longcope, M.K. Neilsen
Sandia National Laboratories

INTRODUCTION

Sandia National Laboratories (SNL) has designed an impact-limiting system for a small, lightweight radioactive material shipping container. The Westinghouse Savannah River Company (WSRC) is developing this Type B package for the shipment of tritium, replacing the outdated LP-50 shipping container. Regulatory accident resistance requirements for Type B packages, including this new tritium package, are specified in 10 CFR 71 (NRC 1983). The regulatory requirements include a 9-meter free drop onto an unyielding target, a 1-meter drop onto a mild steel punch, and a 30-minute 800° C fire test. Impact limiters are used to protect the package in the free-drop accident condition in any impact orientation without hindering the package's resistance to the thermal accident condition.

The overall design of the new package is based on a modular concept using separate thermal shielding and impact mitigating components in an attempt to simplify the design, analysis, test, and certification process. Performance requirements for the tritium package's limiting system are based on preliminary estimates provided by WSRC. The current tritium hydride vessel (THV) to be transported has relatively delicate valving assemblies and should not experience acceleration levels greater than approximately 200 g. A thermal overpack and outer stainless steel shell, to be designed by WSRC, will form the inner boundary of the impact-limiting system (see Figure 1). The mass of the package, including cargo, inner container, thermal overpack, and outer stainless steel shell (not including impact limiters) should be approximately 68 kg. Consistent with the modular design philosophy, the combined thermal overpack and containment system should be considered essentially rigid, with the impact limiters incurring all deformation. The outer overpack shell (punch resistant 3.2-mm 304 stainless steel sheet) should be the surface at which the 200 g deceleration design constraint for impact limiters is applied.

---

* This work was supported by the U. S. Department of Energy under contract number DE-AC04-94AL85000.

Impact-limiting materials considered for use with the new lightweight tritium package include uniaxial aluminum honeycomb, biaxial aluminum honeycomb, polyurethane foam, and aluminum wire mesh. Based upon cost and performance in simplified end-on impacts (Harding and Neilsen 1994), low-density rigid polyurethane foam (covered by a thin protective stainless steel skin) was chosen as an excellent impact limiting material. The polyurethane foam is much more isotropic than the aluminium honeycomb, which has a much lower compressive strength in a direction normal to the cell axis than along it. Even biaxial honeycomb requires wedge-shaped fabrication to ensure proper orientation. This paper presents finite element analysis results predicting the impact limiter's performance during end-on, side-on, and c.g.-over-corner impact accident conditions.

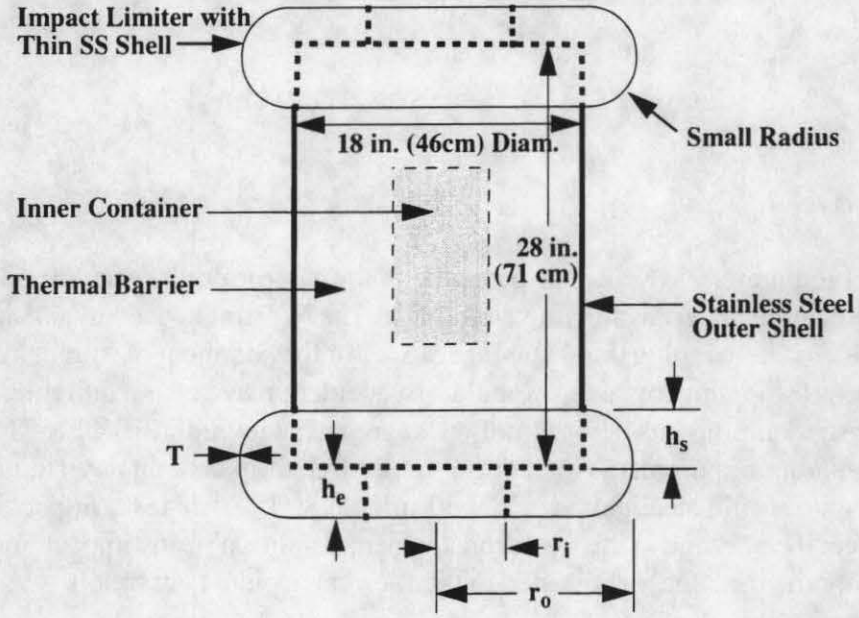

Figure 1. Conceptual Design of Generic Impact Limiters

IMPACT LIMITER SYSTEM ANALYSES

Preliminary detailed finite element analyses (FEAs) were used to develop a conceptual design to protect the container in randomly oriented impacts, yet cover minimal container surface area, thus promoting convection of internal heat generation. The conceptual impact limiter consists of 48 kg/m^3 (3 lb/ft^3) polyurethane foam enclosed by a thin stainless steel shell. Initial impact limiter dimensions were estimated using both energy methods and FEAs performed previously (Harding and Neilsen 1994). Final limiter dimensions were determined using trial and error FEAs to optimize performance in end, side, and c.g.-over-corner impacts. The analyses utilized the transient dynamic finite element codes PRONTO 2D (Taylor and Flanagan 1987) and PRONTO 3D (Taylor and Flanagan 1989) to model the package, limiter shell, and foam. The foam was represented with an orthotropic crush model and contact surfaces were used between the foam/shell and shell/package, where feasible. Approximate rigid-body decelerations were obtained by filtering raw FEA decelerations using a 1 kHz fifth-order low-pass Butterworth filter, which allows for moderate frequency acceleration pulses to remain intact. Higher-frequency acceleration pulses may be present during impact; however, damping of high-frequency pulses will occur within the thermal overpack material surrounding the THV, thus protecting delicate valving assemblies within it.

Material Properties

The impact absorbing material is polyurethane foam with a density of 48 kg/m^3 (3 lb/ft^3) (General Plastics 1992). The foam rise direction is assumed to be parallel to the axis of the cylindrical container, as would be expected if the foam were poured into empty limiter shells from either end. In this geometry, the foam is transversely isotropic with the higher compressive strength in the direction parallel to the container axis and the lower strength in any direction in a plane perpendicular to the container axis. The foam is represented by an orthotropic crush model having initial elastic behavior followed by crush strength that increases with volumetric crush strain, and finally isotropic elastic - perfectly plastic behavior when full compaction is reached. Dynamic strength versus volume strain values are used, which are about 32 percent higher than corresponding static values. Extrapolation of data for 48 kg/m^3 foam beyond 60% strain was necessary since these data were only available for 80 kg/m^3 foam. Strength properties for the lighter foam were based upon high-strain crush data for the 80 kg/m^3 foam reduced by the ratio of the two crush strengths at lower strains. A comparison of the 48 kg/m^3 foam properties parallel and perpendicular to the foam rise direction is shown in Figure 2.

The thin shell enclosing the polyurethane foam is 304 L annealed stainless steel which has high ductility. Its response was represented by an elastic-plastic model with isotropic strain hardening. The container was modeled as an elastic material with a Young's modulus of steel. The density was selected to give a mass of 68 kg for the geometry of the PRONTO model, which has the outer dimensions shown in Figure 1 and a 10 cm radius axial hole to reduce the number of elements required for the model.

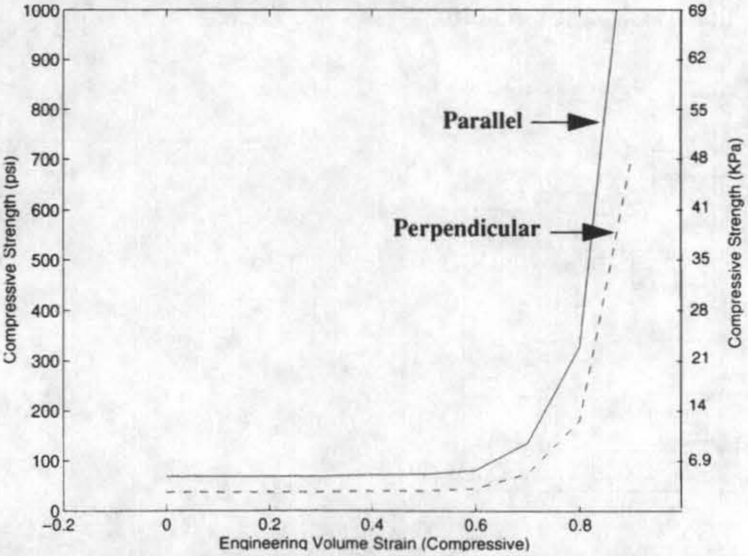

Figure 2. Dynamic Crush Strength of 48 kg/m^3 Polyurethane Foam, Parallel and Perpendicular to the Direction of Foam Rise

End Impact Modeling

Using the geometry of the initial impact limiter design, a series of end-impact analyses were performed with PRONTO 2D. These analyses served to (1) demonstrate the performance of various portions of the impact limiter; (2) evaluate the complexity of the model required to accurately determine the container acceleration; and (3) revise the impact limiter geometry so that the acceleration would not exceed 200 g. In each of these axisymmetric analyses, the container and impact limiters were given an initial velocity of 13.4 m/sec in the axial direction before impacting the rigid surface.

The end impact of an impact limiter enclosed by a 0.38 mm (0.015 in.) thick 304 L annealed stainless steel shell was modeled using shell and continuum elements, as shown in Figure 3. Contact surfaces with frictionless slip were modeled at the container/shell and shell/foam interfaces. Initial modeling was performed using bare polyurethane foam; however, resultant container decelerations increased dramatically with the inclusion of the thin protective shell. The shell provides a load path to the foam alongside the container causing it to contribute to the axial resistance against the container. Significant deformation near the top of the limiter is being initiated through tension in the stainless steel shell during impact.

Initially, the shell was modeled with only one 4-node axisymmetric quadrilateral element through the thickness to reduce the total number of elements in a problem where bending energy was likely negligible and membrane (tensile) behavior dominated. The number of elements used through the shell thickness is critical to reducing the computation (CPU) time, since the time step in PRONTO is proportional to the minimum element dimension. Subsequent shell modeling with two elements through the thickness produced negligible acceleration history changes in the results, and was thus shown to be unnecessary. Model accuracy was also verified by increasing the number of elements and observing insignificant changes in the acceleration results.

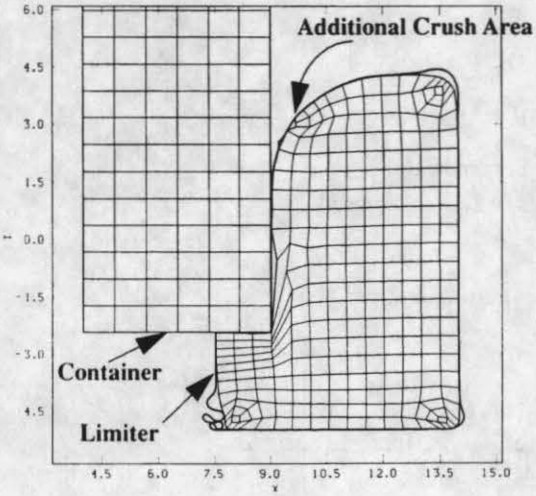

Figure 3. Maximum Crush of Shell/ Foam Limiter in End Impact

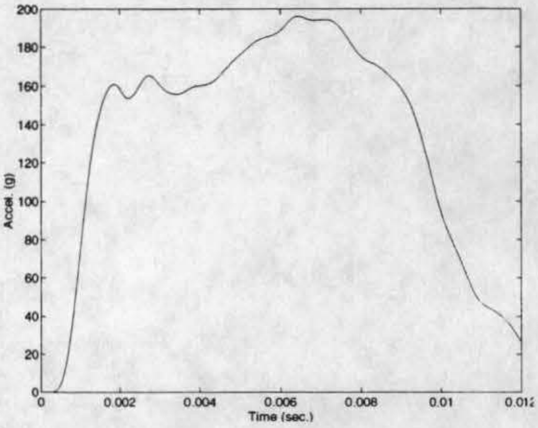

Figure 4. Container Acceleration in End Impact

To reduce the peak acceleration below the 200 g limit, the initial limiter geometry was changed by increasing the hole radius r_i to 19 cm (7.5 in.), reducing the outer radius r_o to 35.6 cm (14 in.), increasing the side height h_s to 12.7 cm (5 in.), increasing the end height h_e to 12.7 cm (5 in.), and reducing the shell thickness T to 0.38 mm (0.015 in.). The limiter corner modeling was also made less stiff by representing it as curved corner with a radius of 1.3 cm (0.5 in.). The container and impact limiter at the time of maximum crush during the end impact with this revised geometry are shown in Figure 3. The container acceleration shown in Figure 4 satisfies the 200 g limit with a maximum of 195 g.

A simplification of tying the limiter shell and foam together so there is no relative motion at their interface (no contact surface) was considered in anticipation of performing the side and c.g.-over-corner impact analyses, which are three-dimensional and require an order of magnitude more finite elements than the end impact analysis. With tied contact specified between the shell and foam, the limiter shell can be modeled with actual shell elements which can have dimensions and solution time steps an order of magnitude greater than thin continuum elements. Shell elements in PRONTO are allowed to have relative motion during contact on only one side. Relative motion was thus allowed across the limiter shell/container interfaces. Resultant container peak acceleration was approximately 35% higher due to increased stiffness in the shell buckling. Although some bonding between poured foam and the protective shell could occur during fabrication, this bond would likely fail during impact and accelerations would thus be more accurately represented by the former, 195 g results.

Side Impact Modeling

The side impact simulation was performed for the container and impact limiter geometry determined in the previous section. The side-on impact orientation required a three-dimensional model and the use of PRONTO 3D, but two symmetry planes allowed the use of a model consisting of one-quarter of the actual geometry. Relative motion was allowed across the limiter shell/container interface, but the limiter shell was represented with shell elements tied to the foam. The container and impact limiter are shown in Figure 5 at the time of maximum crush of the foam. The maximum container displacement is about 7.1 cm (2.8 in.), corresponding to a maximum average strain over the foam thickness of 56 percent, safely less than the 70 percent "lockup" strain shown in Figure 2 where small increases in deformation result in large acceleration force increases. The container acceleration history is shown in Figure 6, and its peak value falls below the 200 g limit.

C.G.-Over-Corner Impact Modeling

For the c.g.-over-corner impact, the impact velocity vector was assumed parallel to a line through the impacting corner and the container center of gravity. Symmetry about a plane through the container axis allowed for a model which represented only one-half of the actual geometry. Shell elements representing the limiter shell were tied to the foam. Contact surfaces were used between the shell and container. The PRONTO 3D model contained about 18,000 elements and ran for 20 hours of Cray Y-MP CPU time to reach the deformed configuration shown in Figure 7. At this time the limiter had almost reached maximum crush, but there was still about 13 percent of the initial kinetic energy remaining. Large deformations, contact surfaces, small shell elements, and a large total number of degrees of freedom made this analysis extremely challenging. The maximum distance of crush toward the container corner is estimated to be 12 cm (4.7 in.), which would still be about 6.1 cm (2.4 in.) from the container corner. The container acceleration is shown in Figure 8, and one peak exceeds the 200 g limit, reaching about 230 g. Judging by the results for the end impact analyses, the use of a more realistic slip condition across the foam/shell interface in place of the tied contact condition should reduce the peak acceleration below the 200 g limit.

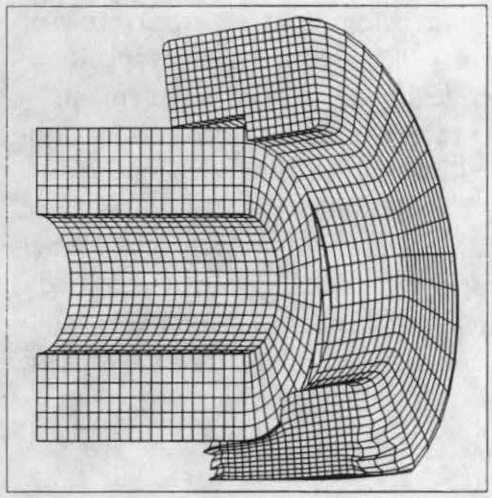

Figure 5. Side Impact Finite Element Model at Maximum Crush

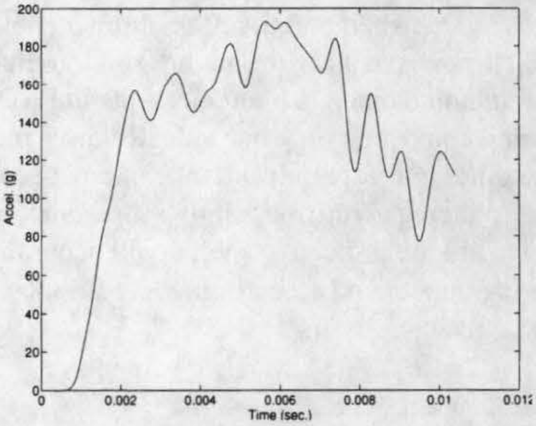

Figure 6. Side Impact Container Acceleration History

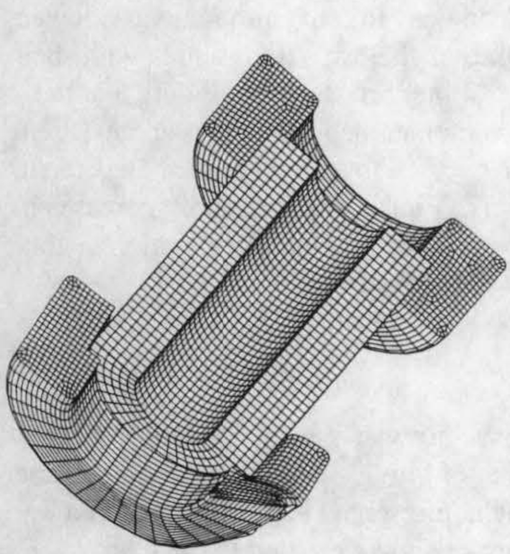

Figure 7. CG-Over-Corner Impact Model Near Maximum Crush

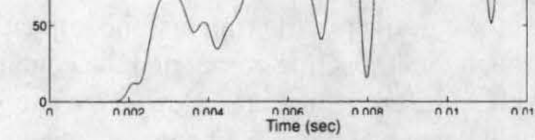

Figure 8. CG-Over-Corner Impact Container Acceleration History

DESIGN RECOMMENDATIONS AND CONCLUSIONS

Due to its balanced cost and performance low-density rigid polyurethane foam, FR-3703 (48 kg/m^3 or 3 lb/ft^3), is recommended as the impact limiting material for WSRC's new tritium package. It has well-characterized material properties, which provide excellent impact resistance, based upon WSRC's 200-g peak deceleration requirement. Also, the material may be neglected in a thermal accident condition environment, with adequate ventilation. Four 1-cm holes with plastic plugs around the diameter and on the end of each impact limiter would provide adequate venting of gasses away from the tritium package during a fire (General Plastics 1992).

Detailed two- and three-dimensional large-deformation finite element analyses have been conducted using Sandia National Labs' PRONTO2D and PRONTO3D explicit dynamic codes to design an impact limiting system for WSRC's new tritium package. End-on, side-on, and c.g.-over-corner impacts onto unyielding targets were analyzed during determination of limiter thicknesses to reduce outer container acceleration levels below 200 g. The recommended foam and 304 stainless steel outer skin geometry, based upon variables defined in Figure 1, is as follows: r_i = 19 cm (7.5 in.), r_o = 35.6 cm (14 in.), h_e = 12.7 cm (5 in.), h_s = 12.7 cm (5 in.), and T = 0.38 mm (0.015 in.). The mass of each impact limiter is approximately 7.3 kg (16.2 lb), yielding a total package mass of about 83 kg (182 lb) neglecting limiter attachment hardware. However, higher g-loads may be experienced by the outer container shell if the contents weigh less than or greater than 68 kg.

Although the c.g.-over-corner impact analysis produced a peak acceleration of slightly greater than 200 g, the conservative modeling technique was likely the cause of this result. As shown in the end-on analyses, which compared solid elements for the stainless steel skin versus tied shell elements, a 35 percent increase in peak acceleration was produced using tied shell elements. In reality, the foam may be partially bonded to the skin after the foaming process, but this bond would likely de-couple almost immediately during a high-shock impact event. Thus, assuming bonded or tied shell elements would overestimate the actual accelerations. Also, significant damping would likely occur in the ceramic fiber thermal overpack layer (depending upon its design), further reducing the acceleration forces seen by the internal tritium hydride vessel.

Any changes in the assumed design of the container, its contents, or applied boundary conditions could affect the accelerations and thus forces on internal components. If proposed 10 CFR 71 changes, including a dynamic crush criterion for lightweight packages are enacted, the tritium package impact limiter would require additional higher-density foam to absorb the significantly increased energy. An increase in container mass would result in additional foam crush depth, possible lockup, and much higher decelerative forces. Additional analyses could be necessary after final design of the tritium package is complete, especially with regard to inclusion of impact limiter attachment methods and fabrication of the thin protective foam shell. Since finite element analyses only approximate the behavior of these composite materials under extreme loading conditions, benchmarking of these analyses should be performed by free-drop impact testing of prototype hardware.

REFERENCES

General Plastics Manufacturing Company, *General Plastics LAST-A-FOAM FR-3700 for Crash and Fire Protection of Nuclear Material Shipping Containers*, Tacoma, WA (1992).

Harding, D. C., and Neilsen, M. K., *Impact-Limiting Materials for a Tritium Hydride Vessel Transport Container*, White paper to Westinghouse Savannah River Company (1994).

Taylor, L. M., and Flanagan, D. P., *PRONTO 2D: A Two-Dimensional Transient Solid Dynamics Program*, SAND86-0594, Sandia National Laboratories, Albuquerque, NM (1987).

Taylor, L.M., and Flanagan, D.P., *PRONTO-3D, A Three Dimensional Transient Solid Dynamics Program*, SAND87-1912, Sandia National Laboratories, Albuquerque, NM (1989).

U.S. Nuclear Regulatory Commission (NRC), *Title 10, Code of Federal Regulations, Part 71*, Washington, DC (1983).

ACKNOWLEDGMENT

The Department of Energy Office of Environmental Restoration and Waste Management Transportation Management Division provided funding for this work.