Transportation Accident Response of a High-Capacity Truck Cask for Spent Fuel*

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INTRODUCTION

The recent GA-4 cask design was developed by General Atomics (GA 1994) as part of the DOE-OCRWM's Cask System Development Program for high-capacity shipping casks. The GA-4 design differs from earlier truck cask designs in its high capacity and non-cylindrical cross section as well as in other design details and material choices. Several earlier studies [in particular NRC (1977) Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes and (Fischer 1986) (referred to as the Modal Study)] examined the performance of spent nuclear fuel transportation casks in a wide range of potential transportation accidents. The earlier studies addressed the possibility that some parameter values of real accidents might exceed those values prescribed for design-basis accidents in regulations (10 CFR 71). The present study analyzes the response of the GA-4 truck cask for a similar range of potential accidents.

Two of the primary goals of this study were (i) to check the structural and thermal performance of the GA-4 cask in a broad range of accidents and (ii) to carry out a severe-accidents analysis as had been addressed in the Modal Study but now using a specific recent cask design and using current-generation computer models and capabilities. At the same time, it was desired to compare the accident performance of the GA-4 cask to that of the generic truck cask analyzed in the Modal Study.

The same range of impact and fire accidents developed in the Modal Study was adopted for this study. The accident-description data base of the Modal Study categorizes accidents into types of collisions with mobile or fixed objects, non-collision accidents, and fires.

The mechanical modes of damage may be via crushing, impact, or puncture. After screening and detailed analysis, the Modal Study found that the potentially cask-damaging mechanical modes are impacts with massive fixed objects such as tunnel abutments, rock, soil, and roadways below overpasses; and truck-train collisions at grade crossings. In its analysis the Modal Study deliberately ignored the energy-absorbing potential of the truck cab, trailer frame, and cask tie-down frame. We analyze the same significant impact scenarios and compare results to those of the Modal Study's generic truck cask. End-first and side-first impact analyses are supplemented by 15-degree slap-down impact analyses. The analyses are done using the inelastic finite-element program DYNA3D (Whirley 1991).

The fire occurrences in the Modal Study data are based on truck accident statistics. The fire types are taken to be pool fires of petroleum products from fuel tanks and/or cargoes. The cask may be engulfed or be at a

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standoff distance from the pool, depending on accident details. The flame temperature is assumed to apply for the duration of the fire. The Modal Study's accident statistics and cask response analyses found that most fire incidents do not have significant collision damage in the same accident. Thus as described below, we focused initial attention on the midsection of the cask. We analyzed this section in engulfing and standoff fires using a 2-D cross section model and the heat transfer program TOPAZ2D (Shapiro 1990). An axial-model analysis was done to check the heat transfer at the ends as compared to the midlength. The axial model includes a partially crushed impact limiter as would be produced in a design basis collision.

STRUCTURAL ANALYSIS

Material models. The analysis uses the geometry, materials, and operating temperatures specific to the GA-4 cask. The XM-19 stainless steel is modeled as elastic-plastic with nonlinear isotropic hardening behavior expressed as a power law. Depleted uranium (DU) with 0.2% molybdenum is used for the gamma-ray shield. The material properties of DU are dependent on processing history and temperature (Rack 1978). A concern with DU is that under some conditions, its tensile ductility can be very low. The DU is also modeled as elastic-plastic with nonlinear isotropic hardening behavior expressed as a power law. Model finite elements are permitted to "fail" during the calculation. Two failure criteria are used for a DU element: if the element reaches tensile pressure of 1,000 psi or plastic strain of 0.2. After failure, the element no longer supports tensile pressure or deviatoric stress.

The GA-4 cask uses impact limiters (ILs) comprised mainly of aluminum honeycomb. Their heterogeneous structure is oriented to absorb an appropriate amount of energy for any cask impact direction. This study models the ILs using a crushable foam material model, with the properties carefully selected so that the load-deflection characteristics of the ILs match the data provided by the manufacturer. The model includes the phenomenon of "lock-up" when the IL elements crush to 20% of their initial volume. What happens to the ILs after the onset of lockup is not known, as this is not within the concerns of the designers. In the model the material deforms further, but its stiffness rapidly approaches that of solid aluminum.

Main response parameter. In the presentation of results we focus on the cask's peak inelastic strain in its containment boundary components. The cask's strain level is a measure of the severity of the accident's structural response. For accident levels up to the design basis accidents and somewhat beyond, the cask impact limiters absorb most of the accident kinetic energy. For accidents beyond those levels, the cask body absorbs some of this kinetic energy through inelastic strain over a portion of the material in the cask body. The impacted object also absorbs some of this energy. The cask body, of XM-19 stainless steel, accommodates up to 30% strain without rupture. The limit of strain before a breach of containment may be considerably less if this strain is located in weld regions or in the closure seal region.

Finite element models. Three-dimensional models are needed for all the impact cases because of the non-cylindrical shape of the cask. Planes of symmetry are used where possible to reduce the number of elements. Models are developed for side impacts with the rounded corner or flat side toward the impacted surface, and for end impacts. For end impacts against massive surfaces, such as roadbeds and rock and soil masses, the impacted object is also modeled with finite elements.

The cask body, closure, gamma shield, basket liner, and impact limiters are included in the model. In the closure region, the compressed surface near the bolts and inside them is modeled as a fused solid. The surface outside the ring of bolts and the side surfaces are modeled with slide surfaces. The bolts are not modeled. The mass of the spent fuel is included on the end or sides toward the impact. The DU gamma shield model is separated into five sections with lap joints between sections. The gamma shield and cask body components are separated by 0.020-inch clearances. Frictionless sliding interfaces are used between components when they are in contact. The impact limiter support structure is modeled with shell elements and is attached to the cask body. The neutron shield is made of plastic blocks. For end impacts their mass but not structure is included. For side drops, they are modeled as a free-standing layer so that they are crushable but provide no structural support to the cask body.

End impact analyses. The end impact analyses consider a cask with an initial velocity impacting a flat target at its closure end. Velocities of 30, 45, 60, 75, and 90 mph were considered for a rigid target. The 30 mph impact corresponds closely to the required regulatory 30-foot drop case. The full capacity of the ILs (defined as crushing up to lockup) is reached during an end impact at about 45-50 mph.

End impacts were also considered against surfaces of hard rock, soft rock or concrete, and hard soil. Cask response was determined for impact velocities of 75 and 90 mph for these three deformable targets. Impact velocities below 75 mph are not considered because "damage" was absent at these velocities for the rigid target. Figure 1 shows the deformed cask model at the conclusion of the 90-mph end impact against soft rock. The location of peak strain in the cask containment boundary is near the forward end of the cask wall. This is consistent with findings presented in the Modal Study. A summary of cask response to end impacts is given in Figure 2.

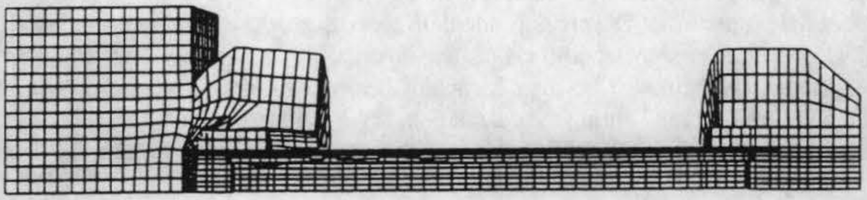

Figure 1. Finite element mesh of the cask at the conclusion of the 90-mph end impact against soft rock. Only the close-in portion of the soil FE mesh is pictured.

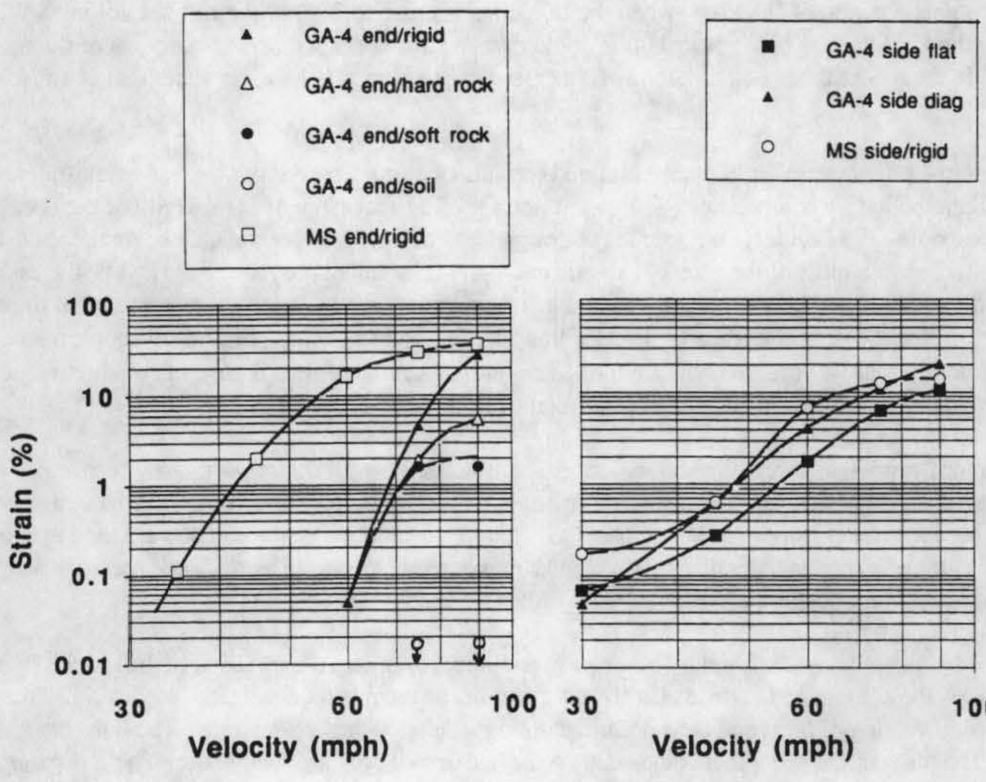

Figure 2. Peak strain in the GA-4 cask containment boundary as a function of impact velocity. On the left: end impacts. The highest curve is for the Modal Study's generic cask impacting on a rigid surface. The other curves are for GA-4 cask impacts on rigid and deformable surfaces. On the right: side impacts on a rigid surface. The highest curve is for the Modal Study's generic cask. The other curves are for GA-4 cask impacts with two cask rotational orientations.

Side impact analyses. The side impact analyses consider a cask oriented with its long axis parallel to the impacted surface, and its initial velocity directed toward this surface. Velocities of 30, 45, 60, 75, and 90 mph are considered for two cask orientations about its long axis: flat side facing the surface and rounded corner facing the surface. Again, the 30-mph impact corresponds closely to the required regulatory 30-foot drop case. The full capacity of the ILs during a side impact is reached at about 45 mph. At higher initial velocities, some elements of the ILs compress severely. As a check on their net effect, the 90-mph impact case was run twice. In the first run the ILs were included throughout the impact. In the second, when some IL elements reached severe compression, the ILs were removed from the model and the impact was allowed to proceed. The response in the second model agreed closely with that of the first.

In side impacts with rounded corner or flat side facing the target, the peak strain in the containment boundary is located near the center of the cask. This is consistent with findings presented in the Modal Study. Figure 2 shows a summary of GA-4 side impacts against a rigid surface. The figure also compares the GA-4 cask end and side impact results with the corresponding results for the Modal Study's generic truck cask (Fischer 1986).

Table 1. Peak strain in the cask containment boundary versus impact velocity and cask angle, for the cask orientation of corner-forward in the non-90-degree cask-angle cases.

Angle:	0° (side)	15° (slap-down)	90° (end)
Velocity (mph)			
30	0.05	N/A	0.
45	0.6	N/A	0.
60	4.2	3.7	0.05
75	11.	13.	4.7
90	21.	21.	29.

Slap-down impacts. Fifteen-degree slap-down impacts were analyzed with the cask orientation of corner-forward. The results are close to those for zero-degree impacts, both in location and amplitude of the peak strain in the containment boundary. The results are summarized in Table 1.

Locomotive impacts. The response from train locomotive impacts on a truck cask were analyzed. The locomotive was modeled as a plate frame at the elevation of the locomotive sill (Eggers 1983) with other masses of the locomotive added to the sill. This is similar to the model in the Modal Study. Contacts of other components on the front of the locomotive with the truck frame were left out. The analysis was done assuming a worst-case impact elevation, where the sill impacts on the centerline of the cask. Normally the train sill is at the elevation of the truck frame or the lower edge of the cask. A higher alignment could conceivably occur at a single-track crossing if the track is at a higher elevation than most of the road and the truck trailer just spans the rail track. The deformed finite element model at the end of a 30-mph impact is shown in Figure 3. The maximum strain occurs in the cask wall near the corners of the train sill. The maximum strain is 12%. A summary and comparison with the Modal Study's generic truck cask is shown in Figure 4. The strains in the outer wall of the two casks are close. In the Modal Study's cask, the inner wall is part of the containment boundary. For the GA-4 cask, the outer wall serves as part of the containment boundary. In an experimental train-truck collision (Yoshimura 1978) using a cask with external cooling fins, the train body and the displacement of the cask absorbed much of the impact energy. Dents were found in the cask's cooling fins due to the train sill contact.

THERMAL ANALYSIS

The Modal Study's accident statistics and cask response analyses found that most fire incidents did not have significant collision damage. For example, truck-truck collisions did not cause cask strains above 0.2%, but contributed to fires. About half of the fires were incidents where fire was reported as the only damaging event. Without major structural damage, the impact limiters and the polyethylene neutron-shielding blocks are likely to remain in place. Then the midsection of the cask, not covered by the impact limiters, is most subject to heat load from the fire. For this study we analyzed the cask midsection in engulfing and standoff fires over a range of flame temperatures and durations. An axial-model analysis was done to check the heat transfer at the ends as compared to the midlength.

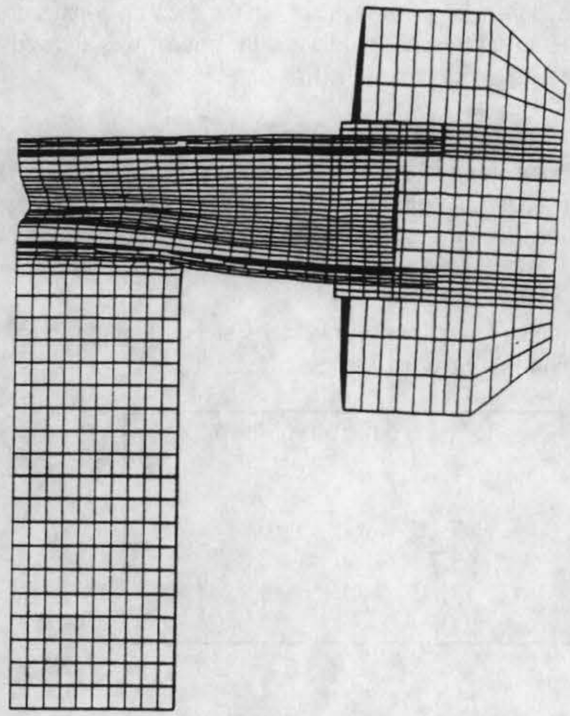

Figure 3. Finite element mesh of the cask and the train sill, utilizing vertical and a horizontal planes of symmetry, at the conclusion of a center-aligned collision with the train sill going 30 mph.

The fire load on the midsection of the cask is modeled using a 2-D cross-section model. Helium gaps between components are included where expected. A spent-fuel assembly has a composite conductivity and internal heat generation from radioactive decay. The model of the neutron-shielding blocks' heat transfer includes phase changes in the plastic material. For fires at offset locations, the model includes the fire sheet heat source, ground and sky heat sinks. Hot-day initial conditions are used. Results are documented as temperature-time histories and as temperature profiles across the cask at important times after ignition.

Fire environment parameters spanning the expectaccident range given in the Modal Study were investigated. Fire durations longer than 90 minutes have significant probability only for truck-truck collisions followed by fire and truck-locomotive collisions followed by fire. The analyzed flame temperature range up to 2,400°F provides for a potential torch fire and uncertainties. An early pool-fire test facility found 5-minute flame temperatures ranging up to 2,200°F (Bader 1965). Recent pool-fire

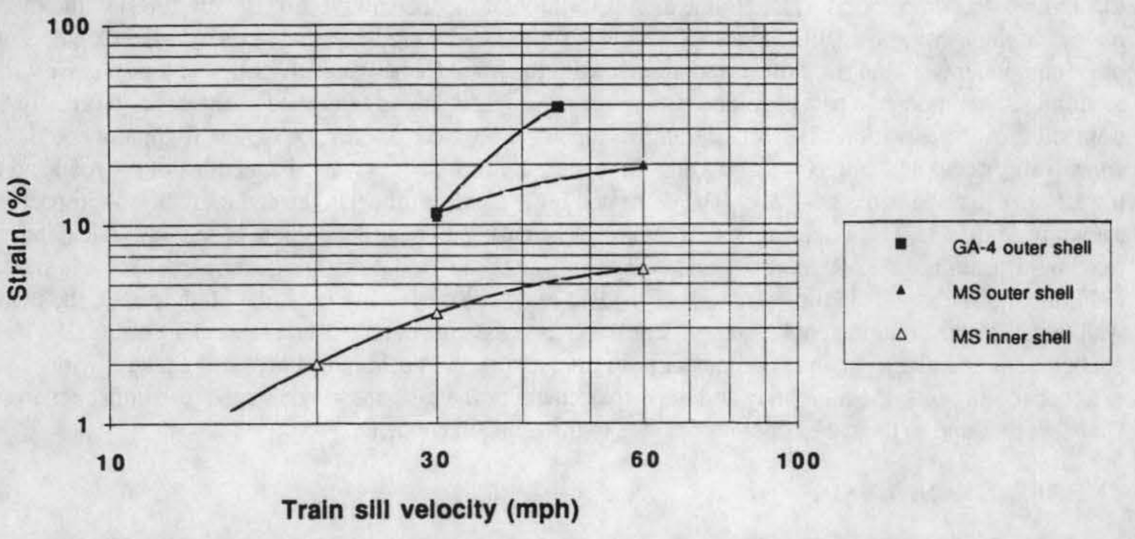

Figure 4. Summary comparison of peak strains in the GA-4 cask and the Modal Study's generic cask after center-aligned train locomotive impacts. The strains in the outer cask wall are fairly close in the two casks. The Modal Study design has an inner wall with lead shielding between the two walls.

facility tests (Gregory 1989) found short-duration temperatures on one side of a cask ranging up to 1,100°C (2,012°F), and sustained 30-minute average temperature at one point ranging up to 1,047°C (1,917°F). Another facility (Fry 1989) reported flame temperatures in the center of a fire (with no cask) averaging1,150°C (2,102°F) for a 13-minute fire. Another series of eight tests (Nitsche 1992) had average flame temperatures from 951°C (1,744°F) to 1,170°C (2,138°F) for fires of 5 to 16 minutes duration. Thus, average temperatures in the upper part of the range included in the Modal Study, 2,200–2,400°F, remain hypothetical.

Main response parameter. In the presentation of results we focus on the temperature at the mid-thickness of the DU gamma shielding shell, at a corner and on the flat side. Temperatures at these locations are used as a measure of the accident's thermal severity. The DU temperature is slightly above the temperature of the spent fuel closest to the edge of the basket and is above or near the temperature of the sealing gasket at the cask closure. The accuracy of the latter assumption is checked by analyses using an axial model for some engulfing fires.

Neutron shield thermal properties. The neutron-shielding layer is made of plastic blocks with metal tube inserts, enclosed in thin stainless steel shells. The blocks are arranged in an overlapping geometry. A series of analyses spanning different fire temperatures, durations, and locations was done using a cask design which included an interim design of this plastic and metal-tube composite layer. A change from the interim design of the neutron-shielding layer to the final design resulted in a lower thermal conductivity of this layer, due principally to a change in the metal tubes from copper to aluminum alloy. This change gives higher steady-state operating temperatures inside the cask, although still well below design limits, and more thermal resistance to fire heating of the gamma shield and the spent fuel contents. The fire durations required before the DU reaches specified thresholds of temperature are extended by approximately 10 to 15%, as will be discussed below. The suite of analyses with the interim properties is used below to show the dependence on the different fire environment parameters.

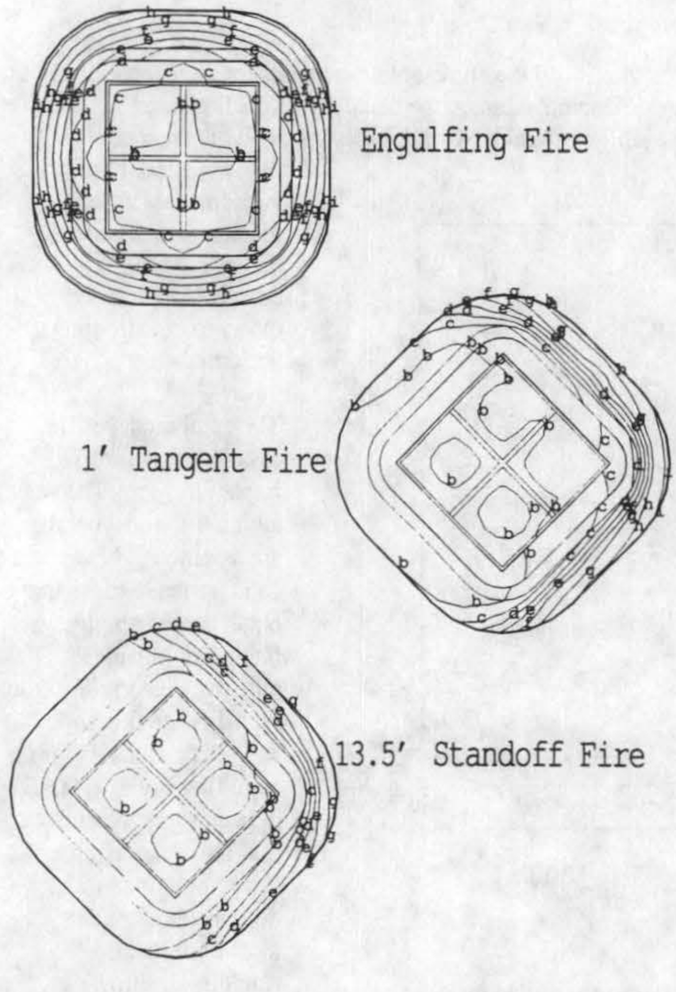

Figure 5. Contours of cask internal temperatures from fires at three locations, at the end of 90 minutes of 1,900°F flames. Contours (a) to (k) are for temperatures of 100 to 2,100°F in steps of 200°F.

Fire analyses. Figure 5 shows contours of internal temperatures from an engulfing fire and standoff fires at two distances, at the end of 90 minutes of 1,900°F flames. For the standoff fires the heating of the cask's internals is of lesser amplitude and spatial extent than in an engulfing fire.

Figure 6 compares the DU temperature at the cessation of the flames and at the post-fire peak value, for engulfing fires

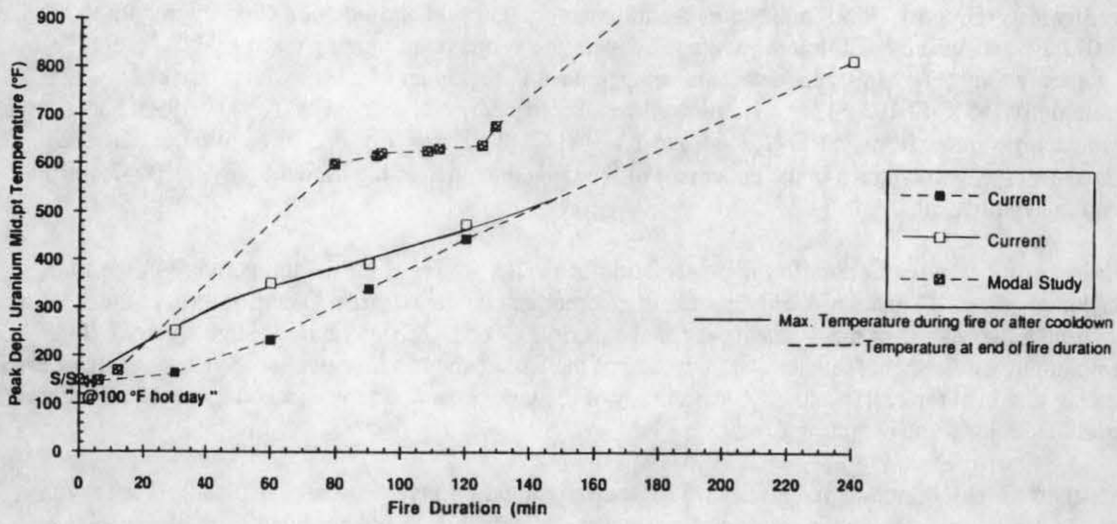

Figure 6. DU temperatures for fires of several durations, for engulfing fires at 1,475°F, both at the cessation of the flames and at the post-fire peak value for the GA-4 cask, and at the cessation of the flames for the Modal Study's generic truck cask.

at 1,475°F with several durations. It compares these with the corresponding results for the Modal Study's generic truck cask. The difference between the DU temperature at the cessation of the flames and at the true peak condition becomes smaller for more severe fires. The GA-4 cask heats up significantly more slowly than the Modal Study's cask for fires at this temperature. For fires above 1,900°F, the comparison of casks lies closer to equality in performance.

The axial model of the cask has a compressed impact limiter. The aluminum honeycombs are assumed to be aligned so that the air space in the honeycombs provides a line-of-sight path for radiative heat transfer from the IL outer skin to its base. The analysis for an engulfing fire at 1900°F indicates that the closure seal region heats up at about the same rate as does the axial midlength location in the DU shielding layer. This supports the use of the center of the DU at midlength as a key temperature location for

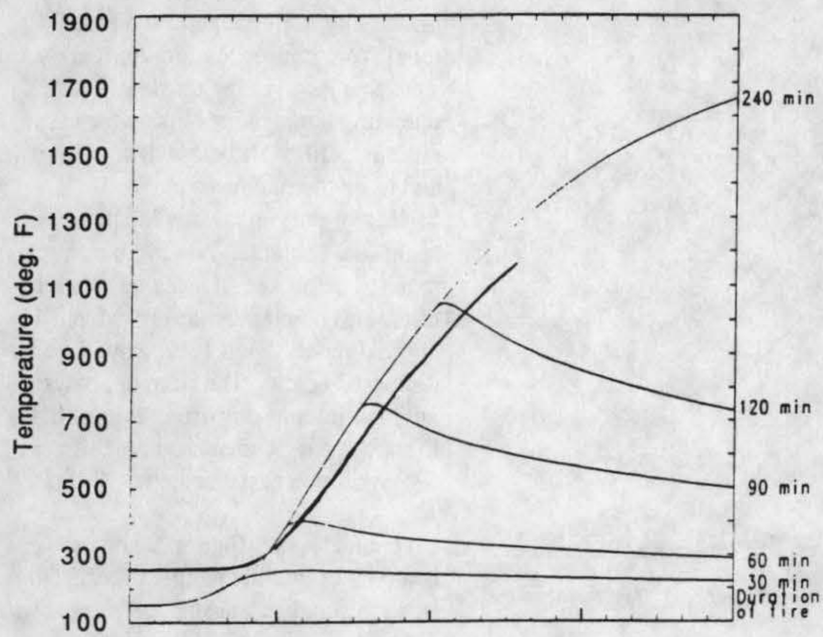

Figure 7. Temperature histories in the DU gamma-ray shielding layer at a corner midpoint for engulfing fires at 1900°F. Heavy curve: a 2.5-hour-long heatup analysis with the final design of the plastic-composite neutron shielding layer. Light curves: a 4-hour-long heatup analysis and four heatup-cooldown analyses with the interim neutron shielding layer design.

summarizing the cask's thermal response.

Figure 7 shows the DU temperature history for a heatup analysis with the final design of the plastic-composite neutron shielding layer superimposed on a 4-hr-long heatup analysis and four heatup-cooldown analyses with the interim design. With the former, the initial conditions are higher and the heatup is slower. Times of fire duration required to reach a given threshold temperature within the range 500-900°F are increased about 10 to 15% in the final design.

CONCLUSIONS

The mechanical and thermal response of the GA-4 cask was analyzed for a broad range of possible accidents. It was found to be comparable with, and in some respects better than, that predicted for the Modal Study's generic truck cask, using similar scenario-framing assumptions. Both the GA-4 cask and the Modal Study's conceptual cask were designed subject to the design basis accidents prescribed in 10 CFR 71. The design provides a substantial reserve margin in the GA-4 cask in terms of impact energy and thermal load beyond that of the design-basis accident before any significant damage can occur to the cask. For hypothetical accidents extending well beyond this reserve margin, the cask's performance declines gradually. The comparisons of results with those in the Modal Study indicates that the analysis methods used in the Modal Study nine years ago were reasonable.

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