Table 3.II.2.3: HI-TRAC Version MS Weight and Dimension Data		
Item	Data (in inch or pounds)	Comment
Ref radial width of lead in the cask's annulus	4"	The data in this table corresponds to the Licensing drawing where the cask cavity height is set by the "reference PWR fuel". The radial thickness of lead and water jacket cavity are as listed in this table. These shielding material thicknesses may be adjusted to optimize shielding within the constraint of the cask laydown space in the Fuel Building and the capacity of the cask crane. The tornado missile analysis in Section 3.II.4 uses the reference data from this table.
Minimum radial width of lead in the cask's annulus	2 3/4"	
Ref radial width of water jacket in the cask body	4 3/4"	
Minimum radial width of water jacket in the cask body	3 7/8"	
Weight of empty cask with bottom lid attached (empty water jacket)	120,000	
Weight of Water in HI-TRAC Water Jacket	8,100	
HI-TRAC weight with MPC in the pool, water jacket *full* without accounting for buoyancy effects	230,000	
HI-TRAC weight with MPC in the pool, water jacket *empty* without accounting for buoyancy effects	222,000	
HI-TRAC weight with "loaded, welded and prepped" MPC (Includes 5% adder for fabrication tolerances)	215,000	

Table 3.II.2.4: Weight Data on HI-STORM 100S Version E Overpack			
Ref. Concrete density	Weight of cask body with MPC in kips (including lid)	Weight of top lid in kips	Comments
175 pcf	336,100	29,000	The weight data corresponds to the Licensing drawing
225 pcf	392,100	34,000	

the HI-TRAC Version MS main outer shell.

- For missile strikes on the side and top lid of the overpack, the analysis credits the structural resistance in compression offered by the concrete material that backs the outer shell and the lid.

- The resistance from the concrete is conservatively assumed to act over an area equal to the target area of impact. In other words, no diffusion of the load is assumed to occur through the concrete.

The analyses documented in [3.II.24] shows that the depth of penetration of the small missile is less than the thinnest section of material on the exterior surface of the HI-STORM 100S Version E or the HI-TRAC Version MS. Therefore, the small missile will dent, but not penetrate, the cask. Likewise, the 1-inch missile cannot enter the air inlet/outlet vents in the HI-STORM 100S Version E overpack. The penetration results for the small and intermediate missile are summarized in Table 3.II.4.11 per [3.II.24].

For the intermediate missile, the analyses documented in [3.II.24] show that there will be no penetration through the concrete surrounding the inner shell of the storage overpack or penetration of the top lid. Likewise, the intermediate missile will not penetrate the lead surrounding the HI-TRAC Version MS inner shell. Therefore, there will be no impairment to the Confinement Boundary due to tornado-borne missile strikes. Furthermore, since the HI-STORM 100S Version E and HI-TRAC Version MS inner shells are not compromised by the missile strike, there will be no permanent deformation of the inner shells and ready retrievability of the MPC will be assured.

(ii) Loading Case M-2; Vertical Free fall of Loaded cask:

Since the lifting devices and the cask appurtenances (lifting attachments on the cask) are designed to meet the sing-failure proof criteria as per section 2.II.2.7, the vertical free fall of the HI-STORM cask and the horizontal fall of the HI-TRAC is not credible. If the lifting devices fail to meet the single failure proof criteria as per section 2.II.2.7, the postulated drops shall be addressed as part of the 10CFR72.212 evaluations. Such site-specific evaluation (if warranted) shall use the identical structural (finite element) models or evaluation methodologies as discussed in the following.

(iii) Loading Case M-4; Non-Mechanistic Tip-Over:

As discussed in Section 2.II.2.2, the non-mechanistic tip-over event applies to a loaded HI-STORM Version E module that is not anchored (or otherwise constrained from overturning on the ISFSI pad). The cask tip-over is not postulated as an outcome of any environmental phenomenon or accident condition. The cask tip-over is a non-mechanistic event, which is analyzed to comply with the guidance in NUREG-1536 [2.1.5]. The objective of the analysis is to demonstrate that the plastic deformation in the fuel basket is limited to the value at which the criticality safety is maintained, retrieval of the fuel by normal means is assured, and that there is no significant loss of radiation shielding in the storage system.

The tip over event is an artificial construct wherein the HI-STORM 100S Version E overpack is assumed to be perched on its edge with its C.G. directly over the pivot point A (Figure 3.II.4.6)). In this orientation, the overpack begins its downward rotation with zero initial velocity. Towards the end of the tip-over, the overpack is horizontal with its downward velocity ranging from zero at the pivot point (point A) to a maximum at the farthest point of impact. The angular velocity at the instant of impact defines the downward velocity distribution along the contact line.

$$\dot{\theta}_1(t_B) = 1.48 \text{ rad/sec.}$$

The LS-DYNA finite element model is developed to simulate the postulated tip-over event of HI-STORM Version E storage cask with loaded MPC containing Metamic (MPC-32M) basket. The LS-DYNA model is constructed according to the dimensions specified in the licensing drawings included in Section 1.5. Because of geometric and loading symmetries, a half model of the loaded cask and impact target (i.e., the ISFSI pad) is considered in the analysis.

The ISFSI pad LS-DYNA model, which consists of a 320”×100”×36” concrete pad and the underlying subgrade (800”×275”×470” in size) with non-reflective lateral and bottom surface boundaries, is identical to that used in the HI-STORM 100 tip-over analysis documented in the HI-STORM 100 FSAR [3.1.3]. All structural members of the loaded cask are explicitly modeled so that any violation of the acceptance criteria can be found by examining the LS-DYNA simulation results (note: the fuel assembly, which is not expected to fail in a tip-over event, is modeled as an elastic rectangular body). This is an improvement compared with the approach taken in the HI-STORM 100 tip-over analysis, where the loaded MPC was modeled as a cylinder and therefore the structural integrity of the MPC and fuel basket had to be analyzed separately based on the rigid body deceleration result of the cask. Except for the fuel basket, which is divided into four parts based on the temperature distribution of the basket, each structural member of the cask is modeled as an independent part in the LS-DYNA model. Note that the critical weld connection between the MPC shell and the MPC lid is treated as a separate part and is modeled with solid elements. LS-DYNA model consists of twenty-nine parts, which are discretized with sufficiently high mesh density; very fine grids are used in modeling the MPC enclosure vessel, especially in the areas where high stress gradients are expected (e.g., initial impact location with the overpack). To ensure numerical accuracy, full integration thin shell and thick shell elements with 10 though-thickness integration points or multi-layer solid elements are used. The LS-DYNA tip-over model consists of over 690,995 nodes and 469,354 elements for HI-STORM Version E with loaded MPC-32M.

The ISFSI concrete pad material model used for the HI-STORM Version E tip-over analysis is identical to the one used for HI-STORM FW tip-over analysis [3.II.25]. Specifically, the concrete pad behavior is characterized using the same LS-DYNA material model (i.e., MAT_PSEUDO_TENSOR or MAT_016). Similarly, the subgrade is also conservatively modeled as an elastic material identical to the subgrade material used in HI-STORM FW tip-over analysis [3.II.25]. Note that this ISFSI pad material modeling approach was originally considered in the USNRC approved storage cask tip-over LS-DYNA analyses [3.II.31] where a very good agreement was obtained between the analysis results and the test results.

To assess the potential damage of the cask caused by the tip-over accident, a LS-DYNA nonlinear material model with strain rate effect is used to model the responses of all HI-STORM Version E cask structural members based on the true stress-strain curves of the corresponding materials. Note that the strain rate effect for the fuel basket material, i.e., Metamic HT, is not considered for conservatism.

Figures 3.II.4.8 to 3.II.4.21 depict the finite-element tip-over analysis model developed for the bounding HI-STORM Version E cask configuration with loaded MPC-32M. The orientation of the MPC-32M fuel basket in the tip-over analysis model (see Figure 3.II.4.8) is the so-called 0 degree orientation. The reason why the 0-degree orientation is most limiting for Metamic-HT baskets, including the MPC-68M and the MPC-32M, is explained in Subsection 3.III.4.4.3.1 of Supplement 3.III.

As shown in Figure 3.II.4.14, the fuel basket does not experience significant plastic deformation in the active fuel region to exceed the acceptable limits; plastic deformation is essentially limited locally in cells near the top of the basket beyond the active fuel region for MPC-32M basket. Note that the basket corner welds are not considered in the tip-over analysis for conservatism. The fuel basket is considered to be structurally safe since it can continue maintaining appropriate spacing between fuel assemblies after the tip-over event. The MPC enclosure vessel experiences minor plastic deformation at the impact locations with the overpack guide tubes; the maximum local plastic strain (30.4%, see Figure 3.II.4.15) is well below the failure strain of the material. Similarly, local plastic deformation occurs in the overpack MPC support guides plate near the MPC base plate impact location (see Figure 3.II.4.16), overpack lid (see Figure 3.II.4.19), and the MPC guide tubes attached to the inner shell of the overpack are locally crushed by the MPC (see Figure 3.II.4.18). However, the shielding capacity of overpack will not be compromised by the tip-over accident and there is no gross plastic deformation in the overpack inner shell to affect the retrievablilty of the MPC. In addition, the cask closure lid bolts are demonstrated to be structurally safe after the tip-over event, only a negligibly small plastic strain is observed in the bolt near the impact location (see Figure 3.II.4.17). Therefore, the cask lid will not dislodge after the tip-over event. Finally, the vertical displacement time history of the ISFSI concrete pad due to the impact of a loaded HI-STORM in the tip-over accident is shown in Figure 3.II.4.20; the impact will result in a maximum displacement of about 3.19 inches in the concrete pad. The maximum rigid body decelerations of the top of fuel assembly is shown in Figure 3.II.4.21; that to be 81.6 g's in the vertical direction. Note that the deceleration time histories are filtered using the LS-DYNA built-in Butterworth filter with a cut-off frequency of 350 Hz; the same filter was used for the HI-STORM 100 non-mechanistic tip-over analysis [3.II.3]. Table 3.II.4.12 per [3.II.26], summarizes the maximum plastic strain results, along with the corresponding material allowable stain.

Separately, a comparative assessment for the Version 1 Alloy X baskets is performed in [3.II.23] to arrive at the conclusion that the MPC-32 basket design is limiting in terms both of the load (demand) and the capacity. It is therefore ensured that the MPC-68 Version 1 basket essentially will have larger safety margins than the limiting MPC-32 Version 1 basket design. Based on this assessment, an explicit dynamic analysis is performed for the MPC 32 Version 1 basket. Figures 3.II.4.28 and 3.II.4.29 show the two limiting basket orientation which are critical in this safety determination. The analysis considers a bounding inertial load (deceleration), as depicted in Figure 3.II.4.30, applied to the Version 1 MPC 32 enclosure and its contents. The bounding stress intensity is noted at mid length of panel (2*27.95 ksi=55.9 ksi), as depicted in Figure 3.II.4.31, applied to the MPC 32Version 1 enclosure and its contents. The applicable stress allowable from Table 2.II.2.3 of this supplement are used for the structural qualification of the Version 1 Alloy X baskets. Based on this bounding analysis, it is concluded that Version 1 Alloy X baskets and the corresponding welds are structurally adequate to sustain the loads due to the cask Non-mechanistic Tip-over event.

Table 3.II.4.13 per [3.II.26], summarizes the safety factor results, along with the corresponding material allowable stress.

(iv) Loading Case M-5; Design Basis Earthquake: This loading case and corresponding acceptance criteria is defined in Paragraph 2.II.2.2.

For a "low intensity" Design Basis earthquake, the two inequalities in Paragraph 2.II.2.2(c) provide the acceptance criteria.

Table 3.II.4.12: Maximum Local True Plastic Strain Results		
Part	**MPC-32M**	**Failure Strain**
Fuel Basket	9.798×10^{-2}	1.97×10^{-1}
MPC Enclosure Vessel	3.04×10^{-1}	1.05×10^{0}
Cask Overpack (without Lid)	1.097×10^{-1}	3.72×10^{-1}
Cask Lid Bolts	1.32×10^{-1}	6.1×10^{-1}