CHAPTER 3: STRUCTURAL EVALUATION†

3.0 OVERVIEW

In this chapter, the structural components of the HI-STORM FW system subject to certification by the USNRC are identified and described. The objective of the structural analyses is to ensure that the integrity of the HI-STORM FW system is maintained under all credible loadings under normal, off-normal and extreme environmental conditions as well all credible accident events. The results of the structural analyses, summarized in this FSAR, support the conclusion that the confinement, criticality control, radiation shielding, and retrievability criteria set forth under 10CFR72.236(l), 10CFR72.124(a), 10CFR72.104, 10CFR72.106, and 10CFR72.122(l) shall be met by the storage system. In particular, the design basis information contained in the previous two chapters and in this chapter provides the necessary data to permit all needed structural evaluations for demonstrating compliance with the requirements of 10CFR72.236(a), (b), (d) (e), (f), (g),and (1). To facilitate regulatory review, the assumptions and conservatisms inherent in the analyses are identified along with a concise description of the analytical methods, models, and acceptance criteria. A summary of the system's ability to maintain its structural integrity under other slow acting (degenerative) or precipitous (sudden) effects that may contribute to structural failure, such as, corrosion, fatigue, buckling, and non-ductile fracture is also provided. The information presented herein is intended to comply with the guidelines of NUREG-1536 and ISG-21 pertaining to use of finite element codes.

In particular, every Computational Modeling Software (CMS) deployed to perform the structural analyses is identified and its implementation appropriately justified as suggested in ISG-21. The information on benchmarking and validation of each Computational Modeling Software is also provided (in Subsection 3.6.2).

Where appropriate, the structural analyses have been performed using classical strength materials solution. Such calculations are presented in this FSAR in transparent detail.

Furthermore, the input data and analyses using Computational Modeling Software (CMS) are described in sufficient detail to enable an independent evaluation of safety conclusions reached in this chapter.

† This chapter has been prepared in the format and section organization set forth in Regulatory Guide 3.61. However, the material content of this chapter also fulfills the requirements of NUREG-1536. Pagination and numbering of sections, figures, and tables are consistent with the convention set down in Chapter 1, Section 1.0, herein. Finally, all terms-of-art used in this chapter are consistent with the terminology of the Glossary.

The safety analyses summarized in this chapter demonstrate acceptable margins to the allowable limits under all design basis loading conditions and operational modes. Minor changes to the design parameters that inevitably occur during the product's life cycle which are treated within the purview of 10CFR72.48 and are ascertained to have an insignificant effect on the computed safety factors may not prompt a formal reanalysis and revision of the results and associated data in the tables of this chapter unless the cumulative effect of all such unquantified changes on the reduction of any of the computed safety margins cannot be deemed to be insignificant. For purposes of this determination, an insignificant loss of safety margin with reference to an acceptance criterion is defined as the estimated reduction that is no more than one order of magnitude below the available margin reported in the FSAR. To ensure rigorous configuration control, the information in the Licensing drawings in Section 1.5 should be treated as the authoritative source for numerical analysis at all times. Reliance on the input data and associated results in this chapter for additional mathematical computations may not be appropriate as they serve the sole purpose of establishing safety compliance in accordance with the acceptance criteria set down in Chapter 2 and in this chapter.

3.1 STRUCTURAL DESIGN

3.1.1 Discussion

The HI-STORM FW system consists of the Multi-Purpose Canister (MPC) and the storage overpack (Figure 1.1.1). The components subject to certification on this docket consist of the HI-STORM FW system components and the HI-TRAC VW transfer cask (please see Table 1.0.1). A complete description of the design details of these three components are provided in Section 1.2. This section discusses the structural aspects of the MPC, the storage overpack, and the HI-TRAC VW transfer cask. Detailed licensing drawings for each component are provided in Section 1.5.

(i) The Multi-Purpose Canister (MPC)

The design of the MPC seeks to attain three objectives that are central to its functional adequacy:

- Ability to Dissipate Heat: The thermal energy produced by the stored spent fuel must be transported to the outside surface of the MPC to maintain the fuel cladding and fuel basket metal walls below the regulatory temperature limits.

- Ability to Withstand Large Impact Loads: The MPC, with its payload of nuclear fuel, must withstand the large impact loads associated with the non-mechanistic tipover event.

- Restraint of Free End Expansion: The MPC structure is designed so that membrane and bending (primary) stresses produced by constrained thermal expansion of the fuel basket do not arise.

As stated in Chapter 1, the MPC Enclosure Vessel is a confinement vessel designed to meet the stress limits in ASME Code, Section III, Subsection NB. The enveloping canister shell, baseplate, and the lid system form a complete Confinement Boundary for the stored fuel that is referred to as the "Enclosure Vessel". Within this cylindrical shell confinement vessel is an egg-crate assemblage of Metamic-HT plates that form prismatic cells with square cross sectional openings for fuel storage, referred to as the fuel basket. All multi-purpose canisters designed for deployment in the HI-STORM FW have identical external diameters. The essential difference between the different MPCs lies in the fuel baskets, each of which is designed to house different types of fuel assemblies. All fuel basket designs are configured to maximize structural integrity through extensive inter-cell connectivity. Although all fuel basket designs are structurally similar, analyses for each of the MPC types is carried out separately to ensure structural compliance.

The design criteria of components in the HI-STORM FW system important to safety are defined in Chapter 2.

The principal structural functions of the MPC in storage mode are:

i. To position the fuel in a subcritical configuration, and

ii. To provide a leak tight Confinement Boundary.

The key structural functions of the overpack during storage are:

i. To serve as a missile barrier for the MPC,

ii. To provide flow paths for natural convection,

iii. To provide a kinematically stable SNF storage configuration,

iv. To provide fixed and reliable radiation shielding, and

v. To allow safe translocation of the overpack with a loaded MPC inside.

Some structural features of the MPCs that allow the system to perform these functions are summarized below:

- There are no gasketed ports or openings in the MPC. The MPC does not rely on any mechanical sealing arrangement except welding. The absence of any gasketed or flanged joints makes the MPC structure immune from joint leaks. The Confinement Boundary contains no valves or other pressure relief devices.

- The closure system for the MPCs consists of two components, namely, the MPC lid and the closure ring. The MPC lid can be either a single thick circular plate continuously welded to the MPC shell along its circumference or a two-piece lid, dual lids welded around their common periphery. When using a two piece lid only the top portion of the lid is considered as part of the closure system, the bottomportion is only for shielding purposes. The MPC closure system is shown in the licensing drawings in Section 1.5. The MPC lid is equipped with vent and drain ports, which are used both for evacuating moisture and air from the MPC following fuel loading and subsequent backfilling with an inert gas (helium) at a specified mass. The vent and drain ports are covered by a cover plate and welded before the closure ring is installed. The closure ring is a circular annular plate edge-welded to the MPC lid and shell. The two closure members are interconnected by welding around the inner diameter of the ring. Lift points for the MPC are provided on the MPC lid.

- The MPC fuel baskets consist of an array of interconnecting plates. The number of storage cells formed by this interconnection process varies depending on the type of fuel being stored. Basket configurations designed for both PWR and BWR fuel are explained in detail in Section 1.2. All baskets are designed to fit into the same MPC shell.

- The MPC basket is separated from its lateral supports (basket shims) by a small, calibrated gap designed to prevent thermal stressing associated with the thermal expansion mismatches between the fuel basket and the basket support structure. The gap is designed to ensure that the basket remains unconstrained when subjected to the thermal heat generated by the spent nuclear fuel.

The MPC fuel basket maintains the spent nuclear fuel in a subcritical arrangement. Its safe operation is assured by maintaining the physical configuration of the storage cell cavities intact in the aftermath of a non-mechanistic tipover event. This requirement is satisfied if the MPC fuel basket plates undergo a minimal deflection (see Table 2.2.11). The fuel basket strains are shown in Subsection 3.4.4.1.4 to remain essentially elastic, and, therefore, there is no impairment in the recoverability or retrievability of the fuel and the subcriticality of the stored fuel is unchallenged.

The MPC Confinement Boundary contains no valves or other pressure relief devices. In addition, the analyses presented in Subsections 3.4.3, 3.4.4.1.5, and 3.4.4.1.6 show that the MPC Enclosure Vessel meets the stress intensity criteria of the ASME Code, Section III, Subsection NB for all service conditions. Therefore, the demonstration that the MPC Enclosure Vessel meets Subsection NB stress limits ensures that there will be no discernible release of radioactive materials from the MPC.

(ii) Storage Overpack

The HI-STORM FW storage overpack is a steel cylindrical structure consisting of inner and outer low carbon steel shells, a lid, and a baseplate. Between the two shells is a thick cylinder of un-reinforced (plain) concrete. Plain concrete is also installed in the lid to minimize skyshine. The storage overpack serves as a missile and radiation barrier, provides flow paths for natural convection, provides kinematic stability to the system, and acts as a shock absorber for the MPC in the event of a postulated tipover accident. The storage overpack is not a pressure vessel since it contains cooling vents. The structural steel weldment of the HI-STORM FW overpack is designed to meet the stress limits of the ASME Code, Section III, Subsection NF, Class 3 for normal and off-normal loading conditions and Regulatory Guide 3.61 for handling conditions.

As discussed in Chapters 1 and 2, the principal shielding material utilized in the HI-STORM FW overpack is plain concrete. The plain concrete in the HI-STORM FW serves a structural function only to the extent that it may participate in supporting direct compressive or punching loads. The allowable compression/bearing resistance is defined and quantified in ACI -318-05 [3.3.5]. Strength analyses of the HI-STORM FW overpack and its confined concrete have been carried out in Subsections 3.4.4.1.3 and 3.4.4.1.4 to show that the concrete is able to perform its radiation protection function and that retrievability of the MPC subsequent to any postulated accident condition of storage or handling is maintained.

(iii) Transfer Cask

The HI-TRAC VW transfer cask is the third component type subject to certification. Strictly speaking, the transfer cask is an ancillary equipment which serves to enable the *short term operations* to be carried out safely and ALARA. Specifically, the transfer cask provides a missile and radiation barrier during transport of the MPC from the fuel pool to the HI-STORM FW overpack. Because of its critical role in insuring a safe dry storage implementation, the transfer cask is subject to certification under 10CFR 72 even though it is not a device for storing spent fuel.

The HI-TRAC VW body is a double-walled steel cylinder that constitutes its structural system. Contained between the two steel shells is an intermediate lead cylinder. Integral to the exterior of the HI-TRAC VW body outer shell is a water jacket that acts as a radiation barrier. The HI-TRAC VW is not a pressure vessel since it contains penetrations and openings. The structural steel components of the HI-TRAC VW are subject to the stress limits of the ASME Code, Section III, Subsection NF, Class 3 for normal and off-normal loading conditions.

Since the HI-TRAC VW may serve as an MPC carrier, its lifting attachments are designed to meet the design safety factor requirements of NUREG-0612 [3.1.1] and Regulatory Guide 3.61 [1.0.2] for single-failure-proof lifting equipment.

3.1.2 Design Criteria and Applicable Loads

Principal design criteria for normal, off-normal, and accident/environmental events are discussed in Section 2.2. In this section, the loads, load combinations, and the structural performance of the HI-STORM FW system under the required loading events are presented.

Consistent with the provisions of NUREG-1536, the central objective of the structural analysis presented in this chapter is to ensure that the HI-STORM FW system possesses sufficient structural capability to withstand normal and off-normal loads and the worst case loads under natural phenomenon or accident events. Withstanding such loadings implies that the HI-STORM FW system will successfully preclude the following:

- unacceptable risk of criticality
- unacceptable release of radioactive materials
- unacceptable radiation levels
- impairment of ready retrievability of the SNF

The above design objectives for the HI-STORM FW system can be particularized for individual components as follows:

- The objectives of the structural analysis of the MPC are to demonstrate that:

  i. Confinement of radioactive material is maintained under normal, off-normal, accident conditions, and natural phenomenon events.

  ii. The MPC basket does not deform under credible loading conditions such that the subcriticality or retrievability of the SNF is jeopardized.

- The objectives of the structural analysis of the storage overpack are to demonstrate that:

  i. Large energetic missiles such as tornado-generated missiles do not compromise the integrity of the MPC Confinement Boundary.

  ii. The radiation shielding remains properly positioned in the case of any normal, off-normal, or natural phenomenon or accident event.

  iii. The flow path for the cooling airflow shall remain available under normal and off-normal conditions of storage and after a natural phenomenon or accident event.

  iv. The loads arising from normal, off-normal, and accident level conditions exerted on the contained MPC do not violate the structural design criteria of the MPC.

  v. No geometry changes occur under any normal, off-normal, and accident level conditions of storage that preclude ready retrievability of the contained MPC.

  vi. A freestanding storage overpack loaded with a MPC can safely withstand a non-mechanistic tip-over event.

  vii. The inter-cask transfer of a loaded MPC can be carried out without exceeding the structural capacity of the HI-STORM FW overpack, provided all required auxiliary equipment and components specific to an ISFSI site comply with their design criteria set forth in this FSAR and the handling operations are in full compliance with operational limits and controls prescribed in this FSAR.

- The objective of the structural analysis of the HI-TRAC VW transfer cask is to demonstrate that:

    i. Tornado generated missiles do not compromise the integrity of the MPC Confinement Boundary while the MPC is contained within HI-TRAC VW.

    ii. No geometry changes occur under any postulated handling or storage conditions that may preclude ready retrievability of the contained MPC.

    iii. The structural components perform their intended function during lifting and handling with the loaded MPC.

    iv. The radiation shielding remains properly positioned under all applicable handling service conditions for HI-TRAC VW.

The above design objectives are deemed to be satisfied for the MPC, the overpack, and the HI-TRAC VW, if stresses (or stress intensities or strains, as applicable) calculated by the appropriate structural analyses are less than the allowables defined in Subsection 3.1.2.3, and if the diametral change in the storage overpack (or HI-TRAC VW), if any, after any event of structural consequence to the overpack (or transfer cask), does not preclude ready retrievability of the contained MPC.

Stresses arise in the components of the HI-STORM FW system due to various loads that originate under normal, off-normal, or accident conditions. These individual loads are combined to form load combinations. Stresses, strains, displacements, and stress intensities, as applicable, resulting from the load combinations are compared to their respective allowable limits. The following subsections present loads, load combinations, and the allowable limits germane to them for use in the structural analyses of the MPC, the overpack, and the HI-TRAC VW transfer cask.

3.1.2.1 Applicable Loadings

The individual loads applicable to the HI-STORM FW system and the HI-TRAC VW cask are defined in Section 2.2 of this FSAR. Load combinations are developed by assembling the individual loads that may act concurrently, and possibly, synergistically. In this subsection, the individual loads are further clarified as appropriate and the required load combinations are identified. Table 3.1.1 contains the governing load cases and the affected components. Loadings are applied to the mathematical models of the MPCs, the overpack, and the HI-TRAC VW. Results of the analyses carried out under bounding load combinations are compared with their respective allowable limits. The analysis results from the bounding load combinations are also evaluated to ensure satisfaction of the functional performance criteria discussed in the foregoing.

The individual loads that address each design criterion applicable to the structural design of the HI-STORM FW system are cataloged in Tables 2.2.6, 2.2.7, and 2.2.13 for the handling, normal, off-normal, and accident (Design Basis Loads) conditions, respectively. The magnitude of loadings

associated with accident condition and natural phenomena-induced events, in general, do not have a regulatory limit. For example, the impact load from a tornado-borne missile, or the overturning load under flood or tsunami, cannot be prescribed as design basis values with absolute certainty that all ISFSI sites will be covered. Therefore, as applicable, representative magnitudes of such loadings are drawn from regulatory and industry documents (such as for tornado missiles and wind from Reg. Guide 1.76). In the following, the essential characteristics of both credible and non-credible loadings analyzed in this FSAR are explained.

a. Tip-Over

The freestanding HI-STORM FW storage overpack, containing a loaded MPC, must not tip over as a result of postulated natural phenomenon events, including tornado wind, a tornado-generated missile, a seismic or a hydrological event (flood). However, to demonstrate the defense-in-depth features of the design, a *non-mechanistic* tip-over scenario per NUREG-1536 is analyzed (Subsection 2.2.3) in this chapter. For MPC transfers that will occur outside of a Part 50 controlled structure, the potential of the HI-STORM FW overpack tipping over during the lowering (or raising) of the loaded MPC from (or into) the mounted HI-TRAC VW cask is ruled out because of the safeguards and devices mandated by this FSAR for such operations (Subsection 2.3.3). The physical and procedural barriers imposed during MPC handling operations, as described in this FSAR, prevent overturning of the HI-STORM/HI-TRAC assemblage with an extremely high level of certainty. Among the physical barriers to prevent the overturning of the HI-STORM/HI-TRAC stack during MPC transfer is the use of the Canister Transfer Facility illustrated in Figure 1.1.2 which secures the HI-STORM FW inside an engineered pit.

b. Handling Accident

The handling of all heavy loads that are within Part 72 jurisdiction must be carried out using single failure-proof equipment and lifting devices that comply with the stress limits of ANSI N14.6 to render an uncontrolled lowering of the payload non-credible (please see Subsection 2.2.3).

c. Flood

Flood at an ISFSI is designated as an extreme environmental event and is described in Subsection 2.2.3 (f).

The postulated flood event has two discrete potential structural consequences; namely,

i. stability of the HI-STORM FW system due to flood water velocity, and
ii. structural effects of hydrostatic pressure and water velocity induced lateral pressure.

The maximum hydrostatic pressure on the cask in a flood where the water level is conservatively set per Table 2.2.8 is calculated as follows:

Using p = the maximum hydrostatic pressure on the system (psi),
γ = weight density of water = 62.4 lb/ft^3,
h = the height of the water level = 125 ft;

The maximum hydrostatic pressure is

$$p = \gamma h = (62.4 \text{ lb/ft}^3)(125 \text{ ft})(1 \text{ ft}^2/144 \text{ in}^2) = 54.2 \text{ psi}$$

It is noted that the accident condition design external pressure for the MPC (Table 2.2.1) bounds the maximum hydrostatic pressure exerted by the flood.

The maximum acceptable water velocity for a moving flood water scenario is computed using the procedure in Subsection 3.4.4.1.1.

d. Explosion

Explosion, by definition, is a transient event. Explosive materials (except for the short duration when a limited quantity of motive fuel for placing the loaded MPC on the ISFSI pad is present in the tow vehicle or transporter) are prohibited in the controlled area by specific stipulation in the HI-STORM FW Technical Specification. However, pressure waves emanating from explosions in areas outside the ISFSI are credible.

Pressure waves from an explosive blast in a property near the ISFSI site result in an impulsive aerodynamic loading on the stored HI-STORM FW overpacks. Depending on the rapidity of the pressure build-up, the inside and outside pressures on the HI-STORM FW METCON™ shell may not equalize, leading to a net lateral loading on the upright overpack as the pressure wave traverses the overpack. The magnitude of the dynamic pressure wave is conservatively set to a value below the magnitude of the pressure differential that would cause a tip-over of the cask if the pulse duration were set infinite.

The allowable pressure from explosion, p_e, can be computed from static equilibrium to prevent sliding or tipping of the cask. A simplified inequality to ensure that the cask will not slide is given by

$$p_e \, D \, L \leq \mu \, W$$

where:

D: diameter of the cask
L: height of the cask above the ISFSI pad
μ: limiting value of the interface friction coefficient
W: weight of the cask (lower bound weight, assuming that the MPC has only one fuel assembly)

$$p_e \leq \frac{\mu W}{DL} \qquad \text{(A)}$$

The inequality for protection against tipping is obtained by moment equilibrium.

$$p_e \; D \frac{L^2}{2} \; \leq \; \frac{W \; D}{2}$$

or $$p_e \leq \frac{W}{L^2} \qquad \text{(B)}$$

The allowable value of p_e must be lesser of the two values given by inequalities (A) and (B) above.

In contrast to the overpack, the MPC is a closed pressure vessel. Because of the enveloping overpack around it, the explosive pressure wave would manifest as an external pressure on the external surface of the MPC.

The maximum overpressure on the MPC resulting from an explosion is limited by the HI-STORM FW Technical Specification to be equal to or less than the accident condition design external pressure specified in Table 2.2.1.

e. Tornado

The tornado loading is described in Subsection 2.2.3 (e). The three components of a tornado load are:

1. pressure changes,
2. wind loads, and
3. tornado-generated missiles.

Reference values of wind speeds and tornado-induced pressure drop are specified in Table 2.2.4. Tornado missiles are listed in Table 2.2.5. A central functional objective of a storage overpack is to maintain the integrity of the “Confinement Boundary”, namely, the multi-purpose canister stored inside it. This operational imperative requires that the mechanical loadings associated with a tornado at the ISFSI do not jeopardize the physical integrity of the loaded MPC. Potential consequences of a tornado on the cask system are:

- Instability (tip-over) due to tornado missile impact plus either steady wind or impulse from the pressure drop

- Loadings applied on the MPC transmitted to the inside of the overpack through its openings or as a secondary effect of loading on the enveloping overpack structure.

- Excessive storage overpack permanent deformation that may prevent ready retrievability of the MPC.

- Excessive storage overpack permanent deformation that may significantly reduce the shielding effectiveness of the storage overpack.

Analyses must be performed to ensure that, due to the tornado-induced loadings:

- The overpack does not deform plastically such that the retrievability of the stored MPC is threatened.

- The MPC Confinement Boundary is not breached.

- The MPC fuel basket does not deform beyond the permitted limit (Table 2.2.11) to preserve its subcriticality margins (requires evaluation if the overpack tips over).

f. Earthquake

The earthquake loading and the associated acceptance criteria are presented in Subsection 2.2.3(g).

The Design Basis Earthquake for an ISFSI site shall be obtained *on the top surface of the pad* using an appropriate soil-structure interaction Code such as SHAKE2000 [3.1.7]. The seismic analysis methodology is provided in Subsection 3.4.4.1.2.

g. Lightning

The HI-STORM FW overpack contains over 50,000 lb of highly conductive carbon steel with over 700 square feet of external surface area. It is known from experience that such a large surface area and metal mass is adequate to dissipate any lightning that may strike the HI-STORM FW system. There are no combustible materials on the HI-STORM FW surface. Therefore, a postulated lightning strike event will not impair the structural performance of components of the HI-STORM FW system that are important-to-safety.

h. Fire

The fire event applicable to an ISFSI is described in Subsection 2.2.3(c) wherein the acceptance criteria are also presented.

i. 100% Fuel Rod Rupture

The sole effect of the postulated 100% fuel rod rupture is to increase the internal pressure in the MPC. Calculations in Chapter 4 show that the accident internal pressure limit set in Chapter 2 bounds the pressure from 100% fuel rod rupture. Therefore, 100% rod rupture does not define a new controlling loading event.

3.1.2.2 Design Basis Loads and Load Combinations

As discussed in Subsection 2.2.7, the number of discrete loadings for each situational condition (i.e., normal, off-normal, etc.) is consolidated by defining bounding loads for certain groups of loadings. Thus, the accident condition pressure P_o^* bounds the surface loadings arising from accident and extreme natural phenomenon events, namely, tornado wind W', flood F, and explosion E^*. These bounding loads are referred to as “Design Basis Loads”.

The Design Basis Loads are analyzed in combination with other permanent loads, i.e., loads that are present at all times. The permanent loads consist of:

- The dead load of weight of each component.
- Internal pressure in the MPC.

For conservatism, the upper or lower bound of the dead load, D, of a component is used for a DBL to maximize the response. Thus, the lower bound value of D is used in the stability of the HI-STORM FW system under flood. Likewise, the value of internal pressure in the MPC is represented by the Design Pressure (Table 2.2.1), which envelops the actual internal pressure under each service condition.

As noted previously, certain loads, namely earthquake E, flowing water under flood condition F, force from an explosion pressure pulse F*, and tornado missile M, act to destabilize a cask. Additionally, these loads act on the overpack and produce essentially localized stresses at the HI-STORM FW system to ISFSI interface. Table 3.1.1 provides the load combinations that are relevant to the stability analyses of freestanding casks.

The major constituents in the HI-STORM FW system are: (i) the fuel basket, (ii) the Enclosure Vessel, (iii) the HI-STORM FW overpack, and (iv) the HI-TRAC VW transfer cask. The fuel basket and the Enclosure Vessel (EV) together constitute the multi-purpose canister. A complete account of analyses and results for all applicable loadings for all four constituent parts is provided in Section 3.4 as suggested in Regulatory Guide 3.61.

In the following, the loadings listed as applicable for each situational condition are addressed in meaningful load combinations for the fuel basket, Enclosure Vessel, and the overpack. Each component is considered separately.

a. Fuel Basket

Table 3.1.1 summarizes the loading cases (derived from Tables 2.2.6, 2.2.7, and 2.2.13) that are germane to demonstrating compliance of the loaded fuel baskets inside the MPC Enclosure Vessel.

The fuel basket is not a pressure vessel; therefore, the pressure loadings are not meaningful loads for the basket. Further, the basket is physically disconnected from the Enclosure Vessel. The gap between the basket and the Enclosure Vessel is sized to ensure that no constraint of free-end thermal expansion of the basket occurs. The demonstration of the adequacy of the basket-to-Enclosure Vessel (EV) gap to ensure absence of interference due to differential thermal expansion is addressed in Chapter 4.

The normal handling of the MPC within the HI-STORM FW system or the HI-TRAC VW transfer cask does not produce any significant stresses in the fuel basket because the operating procedures preclude horizontal handling.

b. Enclosure Vessel

Table 3.1.1 summarizes all load cases that are applicable to structural analysis of the Enclosure Vessel to ensure integrity of the Confinement Boundary.

The Enclosure Vessel is a pressure retaining device consisting of a cylindrical shell, a thick circular baseplate at the bottom, and a thick circular lid at the top. This pressure vessel must be shown to meet the primary stress intensity limits per ASME Section III Class 1 at the design temperature and primary plus secondary stress intensity limits under the combined action of pressure plus thermal loads (Level A service condition in the Code).

Normal handling of the Enclosure Vessel is considered in Section 2.2; the handling loads are independent of whether the Enclosure Vessel is within the storage overpack or HI-TRAC VW cask.

c. Storage Overpack

Table 3.1.1 identifies the load cases to be considered for the overpack. The following acceptance criteria apply:

i. Normal Conditions

- The dead load of the HI-TRAC VW with the heaviest loaded MPC (dry) on top of the HI-STORM FW overpack must be shown to be able to be supported by the metal-concrete (METCON™) structure consisting of the two concentric steel shells and the radial ribs.

- The stress field in the steel structure of the overpack must meet Level A (Subsection NF) limits.

ii. Accident Conditions

- Maximum flood water velocity for the overpack with a near empty MPC (only one SNF stored) shall not cause sliding or tip-over of the cask.

- Tornado missile plus wind on an overpack (with an empty MPC) (see Table 2.2.4) must not lead to violation of the acceptance criteria in 3.1.2.1(e).

- Large or medium penetrant missiles (see Table 2.2.5) must not be able to access the MPC. The small missile must be shown not to penetrate the MPC pressure vessel boundary since, in principle, it can enter the overpack cavity through the (curvilinear) vent inlet vent passages.

- Under seismic conditions, a freestanding HI-STORM FW overpack must be demonstrated to not tip over under the DBE events. The maximum sliding of the overpack must demonstrate that casks will not impact each other.

- Under a non-mechanistic tip-over of a fully loaded, freestanding HI-STORM FW overpack, the overpack lid must not dislodge.

- Accident condition induced gross general deformations of the storage overpack must be limited to values that do not prevent ready retrievability of the MPC.

d. HI-TRAC VW Transfer Cask

Table 3.1.1 culled from Tables 2.2.6, 2.2.7 and 2.2.13 identifies load cases applicable to the HI-TRAC VW transfer cask.

The HI-TRAC VW transfer cask must provide radiation protection, must act as a handling cask when carrying a loaded MPC, and in the event of a postulated accident must not suffer permanent deformation to the extent that ready retrievability of the MPC is compromised.

3.1.2.3 Allowables

The important-to-safety (ITS) components of the HI-STORM FW system are identified on the drawings in Section 1.5. Allowable stresses, as appropriate, are tabulated for these components for all service conditions.

In Section 2.2, the applicable service level from the ASME Code for determination of allowables is listed. Tables 2.2.6, 2.2.7 and 2.2.13 (condensed in Table 3.1.1) provide a tabulation of loadings for normal, off-normal, and accident conditions and the applicable acceptance criteria.

Relationships for allowable stresses and stress intensities for NB and NF components are provided in Tables 2.2.10 and 2.2.12, respectively. Tables 3.1.2 through 3.1.8 contain numerical values of the allowable stresses/stress intensities for all MPC, overpack, and HI-TRAC VW load bearing Code materials as a function of temperature. The tabulated values for the allowable stresses/stress intensities are used in Subsections 3.4.3 and 3.4.4, as applicable, to compute factors of safety for the ITS components of the HI-STORM FW system for various loadings.

In all tables the terms S, S_m, S_y, and S_u, respectively, denote the design stress, design stress intensity, minimum yield strength, and the ultimate strength. Property values at intermediate temperatures that are not reported in the ASME Code are obtained by linear interpolation. Property values are not extrapolated beyond the limits of the Code in any structural calculation.

Additional terms relevant to the stress analysis of the HI-STORM FW system extracted from the ASME Code (see Figure NB-3222-1, for example) are listed in Table 3.1.10.

3.1.2.4 Brittle Fracture

Section 8.4.3 discusses the low temperature ductility of the HI-STORM FW system materials. Table 3.1.9 provides a summary of impact testing requirements to insure prevention of brittle fracture.

3.1.2.5 Fatigue

Fatigue is a consequence of a cyclic state of stress applied on a metal part. Failure from fatigue occurs if the combination of amplitude of the cyclic stress, σ_a, and the number of cycles, n_f, reaches a threshold value at which failure occurs. ASME Code, Section III, Subsection NCA provides the σ_a-n_f curves for a number of material types. At $n_f = 10^6$, the required σ_a is referred to as the "Endurance Limit". The Endurance Limit for stainless steel (the material used in the MPC) according to the ASME Code, Section III, Div. 1, Appendices, Table I.9.2, is approximately 28 ksi.

The causative factors for fatigue expenditure in a non-active system (i.e., no moving parts) such as the HI-STORM FW system may be:

i. rapid temperature changes
ii. significant pressure changes

The HI-STORM FW system is exposed to the fluctuating thermal state of the ambient environment. Effect of wind and relative humidity also play a role in affecting the temperature of the cask components. However, the most significant effects are the large thermal inertia of the system and the relatively low heat transfer coefficients that act to smooth out the daily temperature cycles. As a result, the amplitude of the cyclic stresses, to the extent that they are developed, remains orders of magnitude below the cask material's Endurance Limit.

The second causative factor, namely, pressure pulsation, is limited to the only pressure vessel in the system – the MPC. Pressure produces several types of stresses in the MPC (see Table 3.1.10), all of which are equally effective in causing fatigue expenditure in the metal. However, the amplitude of stress from the pressure cycling (due to the changes in the ambient conditions) is quite small and well below the endurance limit of the stainless steel material.

Therefore, failure from fatigue is not a credible concern for the HI-STORM FW system components.

3.1.2.6 Buckling

Buckling is caused by a compressive stress acting on a slender section. In the HI-STORM FW system, the steel weldment in the overpack is not slender; its height-to-diameter ratio being less than 2. There is no source of compressive stress except from the self-weight of the shell and the overpack weight of the HI-TRAC VW in the stacked condition, which produces a modest state of compressive stress. The state of a small compressive stress combined with a low slenderness ratio makes the HI-STORM FW overpack safe from the buckling mode of failure. The same statement also applies to the HI-TRAC VW transfer cask, which is a radially buttressed triple shell (in comparison to the dual shell construction in HI-STORM FW) structure.

The MPC Enclosure Vessel is protected from buckling of by the permanent tensile stress in both hoop and longitudinal directions due to internal pressure.

Finally, the fuel basket, which is an egg-crate structure, as shown in Figures 1.1.6 and1.1.7 (an intrinsically resistant structural form to buckling from axial compressive loads), is subject to minor compressive stresses from its own weight. The absence of buckling in the Metamic-HT fuel basket is based on the fact that there are no causative scenarios (normal or accident) that produce a significant in-plane compressive stress in the basket structure. A lower bound Euler Buckling strength for the Metamic-HT fuel basket can be obtained by assuming that the basket walls are fully continuous[1] over the entire height of the MPC fuel basket, neglecting the strengthening effect of the honeycomb completely, and treating the Metamic-HT basket wall as an end-loaded plate 199.5" high by 8.94" wide by 0.59" thick (corresponding to the maximum height MPC-37 fuel basket). The top and

1 In reality, the basket walls are not fully continuous in the vertical direction since the fuel basket is assembled by vertically stacking narrow width Metamic-HT panels in a honeycomb pattern (see drawing 6506 in Chapter 1 of HI-STORM FW SAR). For the above buckling strength evaluation, the assumption that the basket walls are continuous over the full height of the fuel basket is extremely conservative since the critical buckling load is inversely proportional to the square of the height.

bottom edges are assumed to be pinned and the lateral edges are assumed to be free to minimize the permissible buckling load (a particularly severe modeling artifice to minimize buckling strength). The Euler buckling load for this geometry is given by (see Timoshenko et al., "Theory of ElasticStability", 2nd Edition):

$$P_{cr} = \frac{\pi^2 EI}{h^2} = 125.2 lbf$$

where E = Young's Modulus of Metamic-HT at 500ºC = 3,300 ksi,
I = moment of inertia of 8.94" wide by 0.59" thick plate = 0.153 in^4,
h = maximum height of fuel basket = 199.5"

The corresponding compressive axial stress is given by:

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{125.2 lbf}{(8.94 in)(0.59 in)} = 23.7 \, psi$$

The factor of safety against buckling is given by (where σ_b is the compressive stress in the basket due to self weight):

$$SF = \frac{\sigma_{cr}}{\sigma_b} = \frac{23.7 \, psi}{19.5 \, psi} = 1.21$$

Thus, even with an exceedingly conservative model, the safety margin against buckling is more than 20%.

Therefore, buckling is ruled out as a credible failure mechanism in the HI-STORM FW system components. Nevertheless, a Design Basis Load consisting of external pressure is specified in Table 2.2.1 with the (evidently, non-mechanistic) conservative assumption that the internal pressure, which will counteract buckling behavior, is zero psig. (In reality, internal pressure cannot be zero because of the positive helium fill pressure established at the time of canister backfill.)

3.1.2.7 Consideration of Manufacturing and Material Deviations

Departure from the assumed values of material properties in the safety analyses clearly can have a significant effect on the computed margins. Likewise, the presence of deviations in manufacturing that inevitably occur in custom fabrication of capital equipment may detract from the safety factors reported in this chapter. In what follows, the method and measures adopted to insure that deviations in material properties or in the fabricated hardware will not undermine the structural safety conclusions are summarized.

That the yield and ultimate strengths of materials used in manufacturing the HI-STORM FW

components will be greater than that assumed in the structural analyses is insured by the requirement in the ASME Code which mandates all Code materials to meet the minimum certified property values set down in the Code tables. Holtec International requires the material supplier to provide a Certified Mill Test Report in the format specified in the Code to insure compliance of all physical properties of the supplied material with the specified Code minimums. The same protocol to insure that the actual property values are above the minimum specified values is followed in the manufacture of Metamic-HT (Section 1.2.1.4.1 and Subsection 10.1.3). An additional margin in the actual physical properties vis-à-vis the Code values exists in the case of the MPC Confinement Boundary material by virtue of the Alloy X definition (Appendix 1.A): The physical properties of Alloy X at each temperature are set down at the lowest of that property value in the Code from a group of austenitic stainless steels.

The above measures make the probability of an actual material strength property to be falling below the assumed value in the structural analysis in this chapter to be non-credible. On the contrary, Holtec's manufacturing experience suggests that the actual properties are likely to be uniformly and substantially greater than the assumed values.

A similarly conservative approach is used to insure that the fabrication processes do not degrade the computed safety margins. Towards this end, the fabrication documents (drawings, travelers and shop procedures) implement a number of pro-active measures to prevent all known sources of development of a strength-adverse condition, such as:

i. All welding procedures are qualified to yield better physical properties than the Code minimums. All essential variables that affect weld quality are tightly controlled.

ii. Only those craftsmen who have passed the welding skill criteria implemented in the shop are permitted to weld.

iii. A rigorous weld material quality overcheck program is employed to insure that every weld wire spool meets its respective Code specification.

iv. All welds are specified as minimums: In practice, most exceed the specified minimums significantly. All primary structural welds are subject to Q.C. overcheck and sign-off.

v. The Threaded Anchor Locations (TALs) are machined to a depth greater than the specified minimum. The stress analyses utilize the minimum thread depths/lengths per the licensing drawings.

In the event of a deviation that may depress the computed safety margin, a non-conformance report is prepared by the manufacturer and subject to a safety analysis by Holtec International's corporate engineering using the same methodology as that described in this FSAR. The item is accepted only if the safety evaluation musters part 72.48 acceptance criteria. A complete documentation of the life cycle of the NCR is archived in the Company's Permanent Filing System and shared with the designated system user.

The above processes and measures have been in place at the Holtec Manufacturing Division to insure that an unacceptable reduction in the safety factors due to variation in material properties and manufacturing processes does not occur. The manufacturing experience over the past 20 years corroborates the effectiveness of the above measures.

3.1.3 Stress Analysis Models

To evaluate the effect of loads on the HI-STORM FW system components, finite element models for stress and deformation analysis are developed. The essential attributes of the finite element models for the HI-STORM overpack and the MPC are presented in this subsection. These models are used to perform the structural analysis of the system components under the loadings listed in Tables 2.2.6, 2.2.7 and 2.2.13, and summarized in Table 3.1.1 herein for handling, normal, off-normal, and accident conditions, respectively. The HI-TRAC VW transfer cask, on the other hand, is conservatively analyzed using strength of materials principles, as described in Subsection 3.1.3.3.

All finite element models are three-dimensional and are prepared to the level of discretization appropriate to the problem to be solved. The models are suitable for implementation in ANSYS and LS-DYNA general purpose codes, which are described in Subsection 3.6.2.

In the following, the finite element models of the HI-STORM overpack (body and lid) and the MPC (Confinement Boundary and the fuel baskets) are presented. Pursuant to ISG-21, the description of the computational model for each component addresses the following areas:

- Description of the model, its key attributes and its conservative aspects
- Types of finite elements used and the rationale for their selection
- Material properties and applicable temperature ranges
- Modeling simplifications and their underlying logic

In subsequent subsections, where the finite element models are deployed to analyze the different load cases, the presentation includes the consideration of:

- Geometric compliance of the simulation with the physics of the problem
- Boundary conditions
- Effect of tolerances on the results
- Convergence (numerical) of the solutions reported in this FSAR

The input files prepared to implement the finite element solutions as well as detailed results are

archived in the Calculation Packages [3.4.11, 3.4.13] within the Company's Configuration Control System. Essential portions of the results for each loading case necessary to draw safety conclusions are extracted from the Calculation Packages and reported in this FSAR. Specifically, the results summarized from the finite element solutions in this chapter are self-contained to enable an independent assessment of the system's safety. Input data is provided in tabular form as suggested in ISG-21. For consistency, the following units are employed to document input data throughout this chapter:

- Time: second
- Mass: pound
- Length: inch

3.1.3.1 HI-STORM FW Overpack

The physical geometry and materials of construction of the HI-STORM FW overpack are provided in Sections 1.1 and 1.2 and the drawings in Section 1.5. The finite element simulation of the overpack consists of two discrete models, one for the overpack body and the other for the top lid.

The models are initially developed using the finite element code ANSYS [3.4.1], and then, depending on the load case, numerical simulations are performed either in ANSYS or in LS-DYNA [3.1.8]. For example, the handling loads (Load Case 9) and the snow load (Load Case 10) are simulated in ANSYS, and the non-mechanistic tipover event (Load Case 4) is simulated in LS-DYNA. For the non-mechanistic tipover analysis, two distinct finite element models are created: one for the HI-STORM FW overpack carrying the maximum length MPC-37 and one for the HI-STORM FW overpack carrying the maximum length MPC-89 (Figures 3.4.10A and 3.4.10B).

The key attributes of the HI-STORM FW overpack models (implemented in ANSYS) are:

i. The finite element discretization of the overpack is sufficiently detailed to accurately articulate the primary membrane and bending stresses as well as the secondary stresses at locations of gross structural discontinuity. The finite element layout of the HI-STORM FW overpack body and the top lid are pictorially illustrated in Figures 3.4.3 and 3.4.5, respectively. The overpack model consists of over 70,000 nodes and 50,000 elements, which exceed the number of nodes and elements in the HI-STORM 100 tipover model utilized in [3.1.4]. Table 3.1.11 summarizes the key input data that is used to create the finite element models of the HI-STORM FW overpack body and top lid.

ii. The overpack baseplate, anchor blocks, and the lid studs are modeled with SOLID45 elements. The overpack inner and outer shells, bottom vent shells, and the lifting ribs are modeled with SHELL63 elements. A combination of SOLID45, SHELL63, and SOLSH190 elements is used to model the steel components in the HI-STORM FW lid. These element types are well suited for the overpack geometry and loading conditions, and they have been

used successfully in previous cask licensing applications [3.1.10, 3.3.2].

iii. All overpack steel members are represented by their linear elastic material properties (at 300ºF) based on the data provided in Section 3.3. The concrete material in the overpack body is not explicitly modeled. Its mass, however, is accounted for by applying a uniformly distributed pressure on the baseplate annular area between the inner and outer shells (see Figure 3.4.26). The plain concrete in the HI-STORM FW lid is explicitly modeled in ANSYS using SOLID65 elements along with the input parameters listed in Table 3.1.12.

iv. To implement the ANSYS finite element model in LS-DYNA, the SOLID45, SHELL63, and SOLSH190 elements are converted to solid, shell, and thick shell elements, respectively, in LS-DYNA. The SOLID65 elements used to model the plain concrete in the HI-STORM FW lid are replaced by MAT_PSEUDO_TENSOR (or MAT_016) elements in LS-DYNA. The plain concrete in the overpack body is also modeled in LS-DYNA using MAT_PSEUDO_TENSOR elements.

v. In LS-DYNA, all overpack steel members are represented by their applicable nonlinear elastic-plastic true stress-strain relationships. The methodology used for obtaining a true stress-strain curve from a set of engineering stress-strain data (e.g., strength properties from [3.3.1]) is provided in [3.1.9], which utilizes the following power law relation to represent the flow curve of metal in the plastic deformation region:

$$\sigma = K\varepsilon^n$$

where n is the strain-hardening exponent and K is the strength coefficient. Table 3.1.13 provides the values of K and n that are used to model the behavior of the overpack steel materials in LS-DYNA. Further details of the development of the true stress-strain relations for these materials are found in [3.4.11]. The concrete material is modeled in LS-DYNA using a non-linear material model (i.e., MAT_PSEUDO_TENSOR or MAT_016) based on the properties listed in Section 3.3.

3.1.3.2 Multi-Purpose Canister (MPC)

The two constituent parts of the MPC, namely (i) the Enclosure Vessel and (ii) the Fuel Basket, are modeled separately. The model for the Enclosure Vessel is focused to quantify its stress and strain field under the various loading conditions. The model for the Fuel Basket is focused on characterizing its strain and displacement behavior during a non-mechanistic tipover event. For the non-mechanistic tipover analysis, two distinct finite element models are created: one for the maximum length MPC-37 and one for the maximum length MPC-89 (Figures 3.4.11 and 3.4.12).

The key attributes of the MPC finite element models (implemented in ANSYS) are:

i. The finite element layout of the Enclosure Vessel is pictorially illustrated in Figure 3.4.1. The finite element discretization of the Enclosure Vessel is sufficiently detailed to accurately

articulate the primary membrane and bending stresses as well as the secondary stresses at locations of gross structural discontinuity, particularly at the MPC shell to baseplate juncture. This has been confirmed by comparing the ANSYS stress results with the analytical solution provided in [3.4.16] (specifically Cases 4a and 4b of Table 31) for the discontinuity stress at the junction between a cylindrical shell and a flat circular plate under internal pressure (100 psig). The two solutions agree within 3% indicating that the finite element mesh for the Enclosure Vessel is adequately sized. Table 3.1.14 summarizes the key input data that is used to create the finite element model of the Enclosure Vessel.

ii. The Enclosure Vessel shell, baseplate, and upper and lower lids are meshed using SOLID185 elements. The MPC lid-to-shell weld and the reinforcing fillet weld at the shell-to-baseplate juncture are also explicitly modeled using SOLID185 elements (see Figure 3.4.1).

iii. Consistent with the drawings in Section 1.5, the MPC lid is modeled as two separate plates, which are joined together along their perimeter edge. The upper lid is conservatively modeled as 4.5” thick, which is less than the minimum thickness specified on the licensing drawing (see Section 1.5). “Surface-to-surface” contact is defined over the interior interface between the two lid plates using CONTA173 and TARGE170 contact elements.

iv. The materials used to represent the Enclosure Vessel are assumed to be isotropic and are assigned linear elastic material properties based on the Alloy X material data provided in Section 3.3. The Young’s modulus value varies throughout the model based on the applied temperature distribution, which is shown in Figure 3.4.27 and conservatively bounds the normal operating temperature distribution for the maximum length MPC-37 as determined by the thermal analyses in Chapter 4.

v. The fuel basket models (Figures 3.4.12A and 3.4.12B), which are implemented in LS-DYNA, are assembled from intersecting plates per the licensing drawings in Section 1.5, include all potential contacts and allow for relative rotations between intersecting plates. For conservatism, a bounding gap is assumed at contact interfaces between any two perpendicular basket plates to allow for impacts and, therefore, maximize the stress and deformation of the fuel basket plate. The fuel basket plates are modeled in LS-DYNA using thick shell elements, which behave like solid elements in contact, but can also accurately simulate the bending behavior of the fuel basket plates. To ensure numerical accuracy, full integration thick shell elements with 10 through-thickness integration points are used. This modeling approach is consistent with the approach taken in [3.1.10] to qualify the F-32 and F-37 fuel baskets.

vi. In LS-DYNA, the fuel basket plates are represented by their applicable nonlinear elastic-plastic true stress-strain relationships in the same manner as the steel members of the HI-STORM FW overpack (see Subsection 3.1.3.1). Table 3.1.13 provides the values of K and n that are used to model the behavior of the fuel basket plates in LS-DYNA. Details of the development of the true stress-strain relations are found in [3.4.11].

3.1.3.3 HI-TRAC VW Transfer Cask

The stress analysis of the transfer cask addresses three performance features that are of safety consequence. They are:

i. Performance of the water jacket as a pressure retaining enclosure under an accident condition leading to overheating of water.
ii. Performance of the threaded anchor locations in the HI-TRAC VW top flange under the maximum lifted load.
iii. Performance of the HI-TRAC VW bottom lid under its own self weight plus the weight of the heaviest MPC.

The above HI-TRAC VW components are analyzed separately using strength of materials formula, the details of which are provided in Subsections 3.4.3 and 3.4.4.

Table 3.1.1

GOVERNING CASES AND AFFECTED COMPONENTS

Case	Loading Case I.D. from Tables 2.2.6, 2.2.7 and 2.2.13	Loading Event	Affected Components			Objective of the Analysis	For additional discussion, refer to Subsection
			HI-STORM	MPC	HI-TRAC		
1	AD	Moving Flood Moving Floodwater with loaded HI-STORM on the pad.	X	—	—	Determine the flood velocity that will not overturn the overpack.	2.2.3
2.	AE	Design Basis Earthquake (DBE) Loaded HI-STORMs arrayed on the ISFSI pad subject to ISFSI's DBE	X	X	—	Determine the maximum magnitude of the earthquake that meets the acceptance criteria of 2.2.3(g).	2.2.3
3	AC	Tornado Missile A large, medium or small tornado missile strikes a loaded HI-STORM on the ISFSI pad or HI-TRAC.	X	X	X	Demonstrate that the acceptance criteria of 2.2.3(e) will be met.	2.2.3
4	AA	Non-Mechanistic Tip-Over A loaded HI-STORM is assumed to tip over and strike the pad.	X	X	—	Satisfy the acceptance criteria of 2.2.3(b).	2.2.3
5	NB	Design Internal Pressure MPC under the normal condition Design Internal Pressure	—	X	—	Demonstrate that the MPC meets "NB" stress intensity limits.	2.2.1
6	NB	Maximum Internal Pressure Under the Accident Condition MPC under the accident condition internal pressure (from Table 2.2.1)	—	X	—	Demonstrate that the Level D stress intensity limits are met.	2.2.1

Table 3.1.1 (continued)

GOVERNING CASES AND AFFECTED COMPONENTS

Case	**Loading Case I.D. from Tables 2.2.6, 2.2.7 and 2.2.13**	**Loading Event**	**Affected Components**			**Objective of the Analysis**	**For additional discussion, refer to Subsection**
7	AH	Design External Pressure MPC under the accident condition external pressure (from Table 2.2.1)	—	X	—	The Enclosure Vessel must not buckle.	2.2.3
8	AJ	HI-TRAC Non-Mechanistic Heat-Up Postulate the water jacket's internal pressure reaches the Design Pressure (defined in Table 2.2.1)	—	—	X	Demonstrate that the stresses in the water jacket meet the ASME Code Section III Subsection Class 3 limits for the Design Condition.	2.2.1
9.	HA, HB, and HC	Handling of Components	X	X	X	Demonstrate that the tapped anchor locations (TALs) meet the Regulatory Guide 3.61 and NUREG-0612 stress limits (as applicable).	2.2.1
10.	NA	Snow Load	X	—	—	Demonstrate that the top lid's steel structure meets "NF" stress limit for normal condition.	2.2.1
11.	NA	MPC Reflood Event	—	X	—	Demonstrate that there is no breach of the fuel rod cladding.	12.3.1

Table 3.1.2

DESIGN AND LEVEL A: STRESS

Reference Code: ASME NF
Material: SA36
Service Conditions: Design and Normal
Item: Stress

Temp. (Deg. F)	Classification and Value (ksi)		
	S	Membrane Stress	Membrane plus Bending Stress
-20 to 650	16.6	16.6	24.9
700	15.6	15.6	23.4

Notes:

1. S = Maximum allowable stress values from Table 1A of ASME Code, Section II, Part D.
2. Stress classification per Paragraph NF-3260.
3. Limits on values are presented in Table 2.2.12.

Table 3.1.3

LEVEL B: STRESS

Reference Code: ASME NF
Material: SA36
Service Conditions: Off-Normal
Item: Stress

Temp. (Deg. F)	Classification and Value (ksi)	
	Membrane Stress	**Membrane plus Bending Stress**
-20 to 650	22.1	33.1
700	20.7	31.1

Notes:

1. Limits on values are presented in Table 2.2.12 with allowables from Table 3.1.2.

Table 3.1.4

DESIGN AND LEVEL A SERVICE CONDITIONS: ALLOWABLE STRESS

Code:	ASME NF
Material:	SA516 (SA515) Grade 70, SA350-LF3 (SA350-LF2)
Service Conditions:	Design and Normal
Item:	Allowable Stress

Temp. (Deg. F)	**Classification and Value (ksi)**		
	S	**Membrane Stress**	**Membrane plus Bending Stress**
-20 to 400	20.0	20.0	30.0
500	19.6	19.6	29.4
600	18.4	18.4	27.6
650	17.8	17.8	26.7
700	17.2	17.2	25.8

Notes:

1. S = Maximum allowable stress values from Table 1A of ASME Code, Section II, Part D.
2. Stress classification per Paragraph NF-3260.
3. Limits on values are presented in Table 2.2.12.
4. Maximum allowable stress values are the lowest of all values for the candidate materials (SA516 (SA515) Grade 70, SA350-LF3 (SA350-LF2)) at corresponding temperature.

Table 3.1.5

LEVEL B: ALLOWABLE STRESS

Code: ASME NF
Material: SA516 (SA515) Grade 70, SA350-LF3 (SA350-LF2)
Service Conditions: Off-Normal
Item: Allowable Stress

Temp. (Deg. F)	**Classification and Value (ksi)**	
	Membrane Stress	**Membrane plus Bending Stress**
-20 to 400	26.6	39.9
500	26.1	39.1
600	24.5	36.7
650	23.7	35.5
700	22.9	34.3

Notes:

1. Limits on values are presented in Table 2.2.12 with allowables from Table 3.1.4.
2. Maximum allowable stress values are the lowest of all values for the candidate materials (SA516 (SA515) Grade 70, SA350-LF3 (SA350-LF2)) at corresponding temperature.

Table 3.1.6

LEVEL D: STRESS INTENSITY

Code:	ASME NF
Material:	SA516 (SA515) Grade 70
Service Conditions:	Accident
Item:	Stress Intensity

Temp. (Deg. F)	**Classification and Value (ksi)**		
	S_m	**P_m** AMAX ($1.2S_y$, $1.5S_m$), but < $0.7 S_u$	**$P_m + P_b$** 150% of P_m
-20 to 100	23.3	45.6	68.4
200	23.2	41.8	62.7
300	22.4	40.3	60.4
400	21.6	39.0	58.5
500	20.6	37.2	55.8
600	19.4	34.9	52.4
650	18.8	33.8	50.7
700	18.1	32.9	49.4

Notes:

1. Level D allowable stress intensities per Appendix F, Paragraph F-1332.
2. S_m = Stress intensity values per Table 2A of ASME, Section II, Part D.
3. P_m and P_b are defined in Table 3.1.10.

Table 3.1.7

DESIGN, LEVELS A AND B: STRESS INTENSITY

Code: ASME NB
Material: Alloy X
Service Conditions: Design, Levels A and B (Normal and Off-Normal)
Item: Stress Intensity

Temp. (Deg. F)	**Classification and Numerical Value**					
	$\mathbf{S_m}$	$\mathbf{P_m}^{\dagger}$	$\mathbf{P_L}^{\dagger}$	$\mathbf{P_L + P_b}^{\dagger}$	$\mathbf{P_L + P_b + Q}^{\dagger\dagger}$	$\mathbf{P_e}^{\dagger\dagger}$
-20 to 100	20.0	20.0	30.0	30.0	60.0	60.0
200	20.0	20.0	30.0	30.0	60.0	60.0
300	20.0	20.0	30.0	30.0	60.0	60.0
400	18.6	18.6	27.9	27.9	55.8	55.8
500	17.5	17.5	26.3	26.3	52.5	52.5
600	16.5	16.5	24.75	24.75	49.5	49.5
650	16.0	16.0	24.0	24.0	48.0	48.0
700	15.6	15.6	23.4	23.4	46.8	46.8
750	15.2	15.2	22.8	22.8	45.6	45.6
800	14.8	14.8	22.2	22.2	44.4	44.4

Notes:

1. S_m = Stress intensity values per Table 2A of ASME II, Part D.
2. Alloy X S_m values are the lowest values for each of the candidate materials at corresponding temperature.
3. Stress classification per NB-3220.
4. Limits on values are presented in Table 2.2.10.
5. P_m, P_L, P_b, Q, and P_e are defined in Table 3.1.10.

† Evaluation required for Design condition only.
†† Evaluation required for Levels A, B conditions only. P_e not applicable to vessels.

Table 3.1.8

LEVEL D: STRESS INTENSITY

Code: ASME NB
Material: Alloy X
Service Conditions: Level D (Accident)
Item: Stress Intensity

Temp. (Deg. F)	**Classification and Value (ksi)**		
	P_m	**P_L**	**$P_L + P_b$**
-20 to 100	48.0	72.0	72.0
200	48.0	72.0	72.0
300	46.3	69.45	69.45
400	44.6	66.9	66.9
500	42.0	63.0	63.0
600	39.6	59.4	59.4
650	38.4	57.6	57.6
700	37.4	56.1	56.1
750	36.5	54.8	54.8
800	35.5	53.25	53.25

Notes:

1. Level D stress intensities per ASME NB-3225 and Appendix F, Paragraph F-1331.
2. The average primary shear strength across a section loaded in pure shear may not exceed 0.42 S_u.
3. Limits on values are presented in Table 2.2.10.
4. P_m, P_L, and P_b are defined in Table 3.1.10.

Table 3.1.9

FRACTURE TOUGHNESS TEST REQUIREMENTS FOR HI-STORM FW OVERPACK

Material	Test Requirement	Test Temperature	Acceptance Criterion
Bolting (SA193 B7)	Not required per NF-2311(b)(13) and Note (e) to Figure NF-2311(b)-1	-	-
Material with a nominal section thickness of 5/8" and less	Not required per NF-2311(b)(1)	-	-
Normalized SA516 Gr. 70 (thicknesses 2-1/2" and less)	Not required per NF-2311(b)(10) for service temperatures greater than or equal to 0°F (i.e., handling operations), and per NF-2311(b)(7) for service temperatures less than 0°F and greater than or equal to -40°F (i.e., non-handling operations)	-	-
Normalized SA516 Gr. 70 used for HI-STORM FW base plate (thickness greater than 2-1/2")	Not required per NF-2311(b)(7)	-	-
As rolled SA516 Gr. 70 used for HI-STORM FW inner and outer shells, base plate, top plate, inlet shell plate, inlet vent top plate, gamma shield plate, lid lower shim plate, and lid gusset	Not required per NF-2311(b)(7)	-	-
SA36 (thickness greater than 5/8")	Not required per NF-2311(b)(7)	-	-
SA350-LF2 (thickness greater than 5/8") and as rolled SA516 Gr. 70 used for HI-STORM FW lifting rib	Per NF-2331	-40°F (Also must meet ASME Section IIA requirements)	Table NF-2331(a)-3 or Figure NF-2331(a)-2 (Also must meet ASME Section IIA requirements)
Weld material	Test per NF-2430 if: (1) either of the base materials of the production weld requires impact testing, or; (2) either of the base materials is SA516 Gr. 70 with nominal section thickness greater than 5/8".	-40°F	Per NF-2331

Table 3.1.9 (continued)

FRACTURE TOUGHNESS TEST REQUIREMENTS FOR HI-TRAC VW TRANSFER CASK

Material	**Test Requirement**	**Test Temperature**	**Acceptance Criterion**
Bolting (SA193 B8 Class 2)	Not required per NF-2311(b)(5)	-	-
Material with a nominal section thickness of 5/8" and less	Not required per NF-2311(b)(1)	-	-
Normalized SA516 Gr. 70 (thicknesses 2-1/2" and less)	Not required per NF-2311(b)(10)	-	-
Normalized SA516 Gr. 70 used for HI-TRAC VW bottom lid (thickness greater than 2-1/2")	Not required per NF-2311(b)(7)	-	-
As rolled SA516 Gr. 70 used for HI-TRAC VW inner and outer shells, bottom flange, extended rib, short rib, bolt recess cap, and bottom lid	Not required per NF-2311(b)(7)	-	-
SA36 (thickness greater than 5/8")	Not required per NF-2311(b)(7)	-	-
SA515 Gr. 70, SA106 Gr. C, and SA350-LF3 (thickness greater than 5/8")	Per NF-2331	0°F (Also must meet ASME Section IIA requirements)	Table NF-2331(a)-3 or Figure NF-2331(a)-2 (Also must meet ASME Section IIA requirements)
Weld material	Test per NF-2430 if: (1) either of the base materials of the production weld requires impact testing, or; (2) either of the base materials is SA516 Gr. 70 with nominal section thickness greater than 5/8".	0°F	Per NF-2331

Table 3.1.10

ORIGIN, TYPE AND SIGNIFICANCE OF STRESSES IN THE HI-STORM FW SYSEM

Symbol	Description	Notes
P_m	Primary membrane stress	Excludes effects of discontinuities and concentrations. Produced by pressure and mechanical loads. Primary membrane stress develops in the MPC Enclosure Vessel shell. Limits on P_m exist for normal (Level A), off-normal (Level B), and accident (Level D) service conditions.
P_L	Local membrane stress	Considers effects of discontinuities but not concentrations. Produced by pressure and mechanical loads, including earthquake inertial effects. P_L develops in the MPC Enclosure Vessel wall due to impact between the overpack guide tubes and the MPC (near the top of the MPC) under an earthquake (Level D condition) or non-mechanistic tip-over event. However, because there is no Code limit on P_L under Level D event, a limit on the local strain consistent with the approach in the HI-STORM 100 docket is used (see Subsection 3.4.4.1.4).
P_b	Primary bending stress	Component of primary stress proportional to the distance from the centroid of a solid section. Excludes the effects of discontinuities and concentrations. Produced by pressure and mechanical loads, including earthquake inertial effects. Primary bending stress develops in the top lid and baseplate of the MPC, which is a pressurized vessel. Lifting of the loaded MPC using the so-called "lift cleats" also produces primary bending stress in the MPC lid. Similarly, the top lid of the HI-STORM FW module, a plate-type structure, withstands the snow load (Table 2.2.8) by developing primary bending stress.
P_e	Secondary expansion stress	Stresses that result from the constraint of free-end displacement. Considers effects of discontinuities but not local stress concentration (not applicable to vessels). It is shown that there is no interference between component parts due to free thermal expansion. Therefore, P_e does not develop within any HI-STORM FW component.
Q	Secondary membrane plus bending stress	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at gross structural discontinuities. Can be caused by pressure, mechanical loads, or differential thermal expansion. The junction of MPC shell with the baseplate and top lid locations of gross structural discontinuity, where secondary stresses develop as a result of internal pressure. Secondary stresses would also develop at the two extremities of the MPC shell if a thermal gradient were to exist. However, because the top and bottom regions of the MPC cavity also serve as the top and bottom plenums, respectively, for the recirculating helium, the temperature field in the regions of gross discontinuity is essentially uniform, and as a result, the thermal stress adder is insignificant and neglected (see Paragraph 3.1.2.5).
F	Peak stress	Increment added to primary or secondary stress by a concentration (notch), or, certain thermal stresses that may cause fatigue but not distortion. Because fatigue is not a credible source of failure in a passive system with gradual temperature changes, fatigue damage is not computed for HI-STORM FW components.

Table 3.1.11 KEY INPUT DATA FOR FINITE ELEMENT MODEL OF HI-STORM FW OVERPACK	
Item	Value
Overall height of HI-STORM FW (including top lid)	221.5 in (for maximum length BWR fuel) 239.5 in (for maximum length PWR fuel)
Height of overpack body	199.25 (for maximum length BWR fuel) 217.25 in (for maximum length PWR fuel)
Height of top lid above top of overpack body	22.25 in
Top lid diameter	103 in
Inside diameter of HI-STORM FW storage cavity	81 in
Outside diameter of HI-STORM FW overpack	139 in
Inner shell thickness	0.75 in
Outer shell thickness	0.75 in
Lifting rib thickness	1 in
Baseplate thickness	3 in
Material	Various (see licensing drawings in Section 1.5)
Ref. temperature for material properties	300°F (implemented in ANSYS) Table 3.1.13 (implemented in LS-DYNA)
Concrete density	200 lbf/ft^3

Table 3.1.12 INPUT PARAMETERS FOR SOLID65 CONCRETE ELEMENTS USED IN HI-STORM FW LID MODEL	
Input Parameter	Value
Density	200 lbf/ft^3
Poisson's ratio	0.17
Compressive strength	3,000 psi
Young's modulus	3.122 x 10^6 psi
Shear transfer coefficient for open cracks	0.1
Shear transfer coefficient for closed cracks	0.3

Table 3.1.13

VALUES OF "K" AND "n" USED TO MODEL ELASTIC-PLASTIC BEHAVIOR OF HI-STORM SYSTEM COMPONENTS IN LS-DYNA

Component	Material	Ref. Temperature	K† (psi)	n†
Fuel Basket	Metamic-HT	365ºC	1.421×10^4	0.059
		350ºC	1.506×10^4	0.062
		325ºC	1.705×10^4	0.055
		300ºC	1.901×10^4	0.049
		250ºC	2.184×10^4	0.064
		200ºC	2.461×10^4	0.075
MPC Lid	Alloy X	500ºF	1.055×10^5	0.235
MPC Shell	Alloy X	450ºF	1.152×10^5	0.244
MPC Baseplate	Alloy X	350ºF	1.161×10^5	0.236
HI-STORM Anchor Block	SA-350 LF2	250ºF	1.160×10^5	0.189
HI-STORM Lid Stud	SA-193 B7	250ºF	1.399×10^5	0.082
HI-STORM Inlet Shield Pipe	SA-53	250ºF	9.464×10^4	0.161
HI-STORM Body††	SA-516 Gr. 70	300ºF	1.144×10^5	0.181
HI-STORM Lid	SA-516 Gr. 70	250ºF	1.139×10^5	0.179
HI-STORM Inlet Shell Plate, Inlet Vent Top Plate, & Lid	SA-36	250ºF	8.952×10^4	0.150

† K and n are defined in Subsection 3.1.3.1.

†† Includes all components in HI-STORM overpack body made from SA-516 Gr. 70 material (e.g., baseplate, inner and outer shells, lifting ribs, etc.).

Table 3.1.14

KEY INPUT DATA FOR ANSYS MODEL OF MPC ENCLOSURE VESSEL

Item	Value
Overall Height of MPC	195 in (for maximum length BWR fuel) 213 in (for maximum length PWR fuel)
Outside diameter of MPC	75.5 in
MPC upper lid thickness	4.5 in
MPC lower lid thickness	4.5 in
MPC shell thickness	0.5 in
MPC baseplate thickness	3.0 in
Material	Alloy X
Ref. temperature for material properties	Figure 3.4.27 (implemented in ANSYS) Table 3.1.13 (implemented in LS-DYNA)

3.2 WEIGHTS AND CENTERS OF GRAVITY

As stated in Chapter 1, while the diameters of the MPC, HI-STORM FW, and HI-TRAC VW are fixed, their height is dependent on the length of the fuel assembly. The MPC cavity height (which determines the external height of the MPC) is set equal to the nominal fuel length (along with control components, if any) plus Δ, where Δ is between 1.5" (minimum), 2.0" (maximum), Δ is increased above 1.5" so that the MPC cavity height is a full inch or half-inch number. Thus, for the PWR reference fuel (Table 1.0.4), whose length including control components is 167.2" (Table 2.1.1), Δ = 1.8" so that the MPC cavity height, c, becomes 169". Δ is provided to account for irradiation and thermal growth of the fuel in the reactor. Table 3.2.1 provides the height of the internal cavities and bottom-to-top external dimension of all system components. Table 3.2.2 provides the parameters that affect the weight of cask components and their range of values assumed in this FSAR.

The cavity heights of the HI-STORM FW overpack and the HI-TRAC VW transfer cask are set greater than the MPC height by fixed amounts to account for differential thermal expansion and manufacturing tolerances. Table 3.2.1 provides the height data on HI-STORM FW, HI-TRAC VW, and the MPC as the adder to the MPC cavity length.

Table 3.2.5 provides the reference weight of the HI-STORM FW overpack for storing MPC-37 and MPC-89 containing reference PWR and BWR fuel, respectively. The weight of the HI-STORM FW overpack body is provided for two discrete concrete densities and for two discrete heights for PWR and BWR fuel. The weight at any other density and any other height can be obtained by linear interpolation. Similarly the weight of the HI-STORM FW lid is provided for two discrete values of concrete density. The weight corresponding to any other density can be computed by linear interpolation.

As discussed in Section 1.2, the weight of the HI-TRAC VW transfer cask is maximized for a particular site to take full advantage of the plant's crane capacity within the architectural limitations of the Fuel Building. Accordingly, the thickness of the lead shield and outer diameter of the water jacket can be increased to maximize shielding. The weight of the empty HI-TRAC VW cask in Table 3.2.4 is provided for three lengths corresponding to PWR fuel. Using the data for three lengths, the transfer cask's weight corresponding to any other length can be obtained by linear interpolation (or extrapolation). For MPC-89, the weight data is provided for the minimum and reference fuel lengths, as well as the reference fuel assembly with a DFC and therefore likewise the transfer cask's weight corresponding to any other length can be obtained by linear interpolation (or extrapolation).

The approximate change in the empty weight of HI-TRAC VW (in kilo pounds) of a certain height, h (inch), by virtue of changing the thickness of the lead by an amount, δ (inch), is given by the formula:

$$\Delta W_{lead} = 0.1128(h - 13.5)\ \delta$$

The approximate change in the empty weight of HI-TRAC VW (in kilo pounds) of a certain length, h

(inch), by virtue of changing the thickness of the water layer by δ (inch) is given by:

$$\Delta W_{water} = 0.01077\,(h - 13.5)\,\delta$$

The above formulas serve as a reasonable approximation for the weight change whether the thickness of lead (or water) is being increased or decreased.

The weights of the loaded MPCs containing "reference SNF" with and without water are provided in Table 3.2.3. All weights in the aforementioned tables are nominal values computed using the SOLIDWORKS™ computer code or using standard material density and geometric shapes for the respective subcomponents of the equipment.

Table 3.2.5 provides the loaded weight of the HI-STORM FW system on the ISFSI pad for two different concrete densities for both PWR and BWR reference fuel. Table 3.2.6 contains the weight data on loaded HI-TRAC VW under the various handling scenarios expected during loading.

The maximum and minimum locations of the centers of gravity (CGs) are presented (in dimensionless form) in Table 3.2.7. The radial eccentricity, ϕ, of a cask system is defined as:

$$\phi = \frac{\Delta_r}{D} \times 100 \text{ (}\phi\text{ is dimensionless)}$$

where Δ_r is the radial offset distance between the CG of the cask system and the geometric centerline of the cask, and D is the outside diameter of the cask. In other words, the value of ϕ defines a circle around the axis of symmetry of the cask within which the CG lies (see Figure 3.2.1). All centers of gravity are located close to the geometric centerline of the cylindrical cask since the non-axisymmetric effects of the cask system and its contents are very small. The vertical eccentricity, Ψ, of a cask system is defined similarly as:

$$\Psi = \frac{\Delta_v}{H} \times 100 \text{ (}\Psi\text{ is dimensionless)}$$

Where Δ_v is the vertical offset distance between the CG of the cask system and the geometric center of the cask (i.e., cask mid-height), and H is the overall height of the cask. A positive value of Ψ indicates that the CG is located above the cask mid-height, and a negative value indicates that the CG is located below the cask mid-height. Figure 3.2.2 illustrates how Ψ is defined.

The values of ϕ and Ψ given in Table 3.2.7are bounding values, which take into consideration material and fabrication tolerances. The tabulated values of ϕ and Ψ can be converted into dimensionless form using the equations above. For example, from Table 3.2.7 the empty HI-STORM FW with lid installed has maximum eccentricities of ϕ = 2.0 and Ψ = ±3.0. Therefore, the maximum radial and vertical offset distances are (D=140", H=207.75" for PWR reference fuel):

$$\Delta_r = \frac{\phi D}{100} = \frac{(2.0)(140in)}{100} = 2.8in$$

$$\Delta_v = \frac{\Psi H}{100} = \frac{(\pm 3.0)(207.75 in)}{100} = \pm 6.23 in \text{ (CG height relative to H/2)}$$

The C.G. information provided above shall be used in designing the lifting and handling ancillary for the HI-STORM FW cask components. In addition, the maximum CG height per Table 3.2.7 shall be used for the stability analysis of the HI-STORM FW under DBE conditions. Using the weight data in the previously mentioned tables, Table 3.2.8 has been constructed to provide the bounding weights for structural analyses so that every load case is analyzed using the most conservative data (to *minimize the computed safety margins*). The weight data in Table 3.2.8 is used in all structural analyses in this chapter.

Table 3.2.1 OPTIMIZED MPC, HI-TRAC, AND HI-STORM HEIGHT DATA FOR A SPECIFIC UNIRRADIATED FUEL LENGTH, ℓ †	
MPC Cavity Height, c	$\ell + \Delta$‡
MPC Height (including top lid), h	c + 12”
HI-TRAC VW Cavity Height	h + 1”
HI-TRAC VW Total Height	h + 6.5”
HI-STORM FW Cavity Height	h + 3.5”
HI-STORM FW Body Height (height from the bottom of the HI-STORM FW to the top surface of the shear ring at the top of the HI-STORM FW body)	h + 4.5”
HI-STORM FW Height (loaded over the pad)	h + 27”

† Fuel Length, ℓ, shall be based on the fuel assembly length with or without a damaged fuel container (DFC). Users planning to store fuel in DFCs shall adjust the length ℓ to include the additional height of the DFC. The maximum additional height for the DFC shall be 5”. Note that users who plan to store any fuel in a DFC will need to utilize a system designed for the additional length and will need to use fuel shims (if required) to reduce the gap between the fuel without a DFC and the enclosure cavity to approximately 1.5-2.5 inches.

‡ Δ shall be selected as 1.5” < Δ < 2.0” so that c is an integral multiple of 1/2 inch (add 1.5” to the fuel length and round up to the nearest 1/2” or full inch).

Table 3.2.2 LIMITING PARAMETERS			
	Item	PWR	BWR
1.	Minimum fuel assembly length, inch	157	171
2.	Maximum fuel assembly length, inch	199.2	181.5[3]
3.	Nominal thickness of the lead cylinder in the lowest weight HI-TRAC VW, inch	2.75	2.50
4.	Maximum nominal thickness of the lead cylinder, inch	4.25	4.25
5.	Nominal (radial) thickness of the water in the external jacket, inch	4.75	4.75

[3] Maximum fuel assembly length for the BWR fuel assembly refers to the maximum fuel assembly length plus an additional 5” to account for a Damage Fuel Container (DFC).

Table 3.2.3

MPC WEIGHT DATA (COMPUTED NOMINAL VALUES)

Item	BWR Fuel Based on length below			PWR Fuel Based on length below		
	Reference	**Shortest from Table 3.2.2**	**Longest from Table 3.2.2**	**Reference**	**Shortest from Table 3.2.2**	**Longest from Table 3.2.2**
Enclosure Vessel	27,500	27,100	27,800	28,600	27,800	31,100
Fuel Basket	8,600	8,300	8,800	7,900	7,400	9,400
Water in the MPC @ SG = 1 (See Note 1)	16,700	16,200	18,900	15,400	14,400	18,700
Water mass displaced by a closed MPC Enclosure Vessel (SG = 1)	30,800	29,900	31,600	29,300	27,600	34,500

SG = Specific Gravity

Note 1: Water weight in the MPC assumes that water volume displaced by the fuel is equal to the fuel weight divided by an average fuel assembly density of 0.396 lb/in3. The fuel weights used for calculating the fuel volumes for Reference/Shortest/Longest PWR and BWR fuel assemblies are 1750/1600/2050 and 750/700/850 pounds respectively.

Table 3.2.4

HI-TRAC VW WEIGHT DATA (COMPUTED NOMINAL VALUES)

Item	**BWR Fuel Based on length below**			**PWR Fuel Based on length below**		
	Reference	**Shortest from Table 3.2.2**	**Longest from Table 3.2.2**	**Reference**	**Shortest from Table 3.2.2**	**Longest from Table 3.2.2**
HI-TRAC VW Body (no Bottom Lid, water jacket empty)	84,000	81,700	86,200	85,200	80,400	99,600
HI-TRAC VW Bottom Lid	11,300	11,300	11,300	11,300	11,300	11,300
MPC with Basket	36,100	35,400	36,600	36,500	35,200	40,500
Fuel Weight (assume 50% with control components or channels, as applicable)	66,800 (750 lb per assembly average)	64,600 (725 lb per assembly average)	71,200 (800 lb per assembly average)	62,000 (1,675 lb per assembly average)	59,200 (1,600 lb per assembly average)	69,400 (1,875 lb per assembly average)
Water in the Annulus	600	600	600	600	600	700
Water in the Water Jacket	8,800	8,500	9,000	8,400	7,900	9,900
Displaced Water Mass by the Cask in the Pool (Excludes MPC)	18,900	18,400	19,400	18,600	17,600	21,600

Table 3.2.5

ON-ISFSI WEIGHT OF LOADED HI-STORM FW

Scenario		**Weight of Cask Body (kilo-pounds)**	**Weight of HI-STORM FW Lid (kilo-pounds)**
Fuel Type	**HI-STORM FW Concrete Density (lb/cubic feet)**		
Ref. PWR	150	198.0	20.1
Ref. PWR	200	246.2	23.3
Maximum length – PWR	150	229.0	20.1
Maximum length – PWR	200	286.1	23.3
Ref. BWR	150	206.7	20.1
Ref. BWR	200	257.4	23.3
Maximum length – BWR	150	211.6	20.1
Maximum length – BWR	200	263.7	23.3

Table 3.2.6 HI-TRAC VW OPERATING WEIGHT DATA FOR REFERENCE FUEL				
Scenario			**HI-TRAC VW[4] Weight in Kilo-Pounds**	
Water in the MPC	**Water in the Water Jacket**	**Cask in (pool) Water/Air**	**Ref. PWR Fuel**	**Ref. BWR Fuel**
Yes	Yes	Water	167.7	173.3
Yes	Yes	Air	215.5	222.9
Yes	No	Water	159.4	164.6
No	No	Water	143.7	147.9
No	Yes	Air	199.9	206.2
No	No	Air	191.5	197.5

Weights above include the weight of the fuel assembly alone and do not include any additional weight for non-fuel hardware or damaged fuel containers.

[4] Add 4,000 lbs for the weight of the lift yoke.

Table 3.2.7

LOCATION OF C.G. WITH RESPECT TO THE CENTERPOINT ON THE EQUIPMENT'S GEOMETRIC CENTERLINE

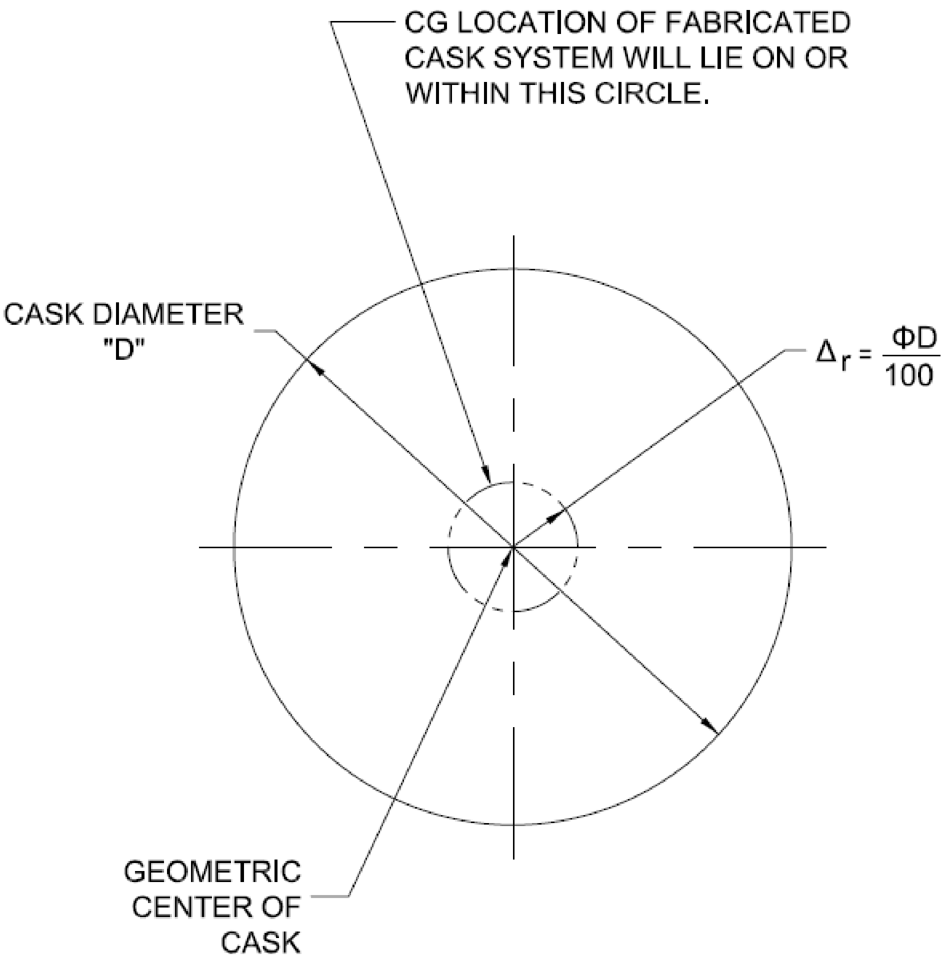
	Item	Radial eccentricity (dimensionless) [5], ϕ	Vertical eccentricity (dimensionless), Above (+)* or Below (-), ψ
1.	Empty HI-STORM FW with lid installed	2.0	±3.0
2.	Empty HI-STORM FW without top lid	2.0	±3.0
3.	HI-STORM FW with fully loaded stored MPC without top lid	2.0	±2.0
4.	HI-STORM FW with lid and a fully loaded MPC	2.0	±3.0
5.	HI-TRAC VW with Bottom lid and loaded MPC	2.0	±2.0
6.	Empty HI-TRAC VW without bottom lid	2.0	±2.0

[5] ϕ and Ψ are dimension values as explained in Section 3.2.

Table 3.2.8

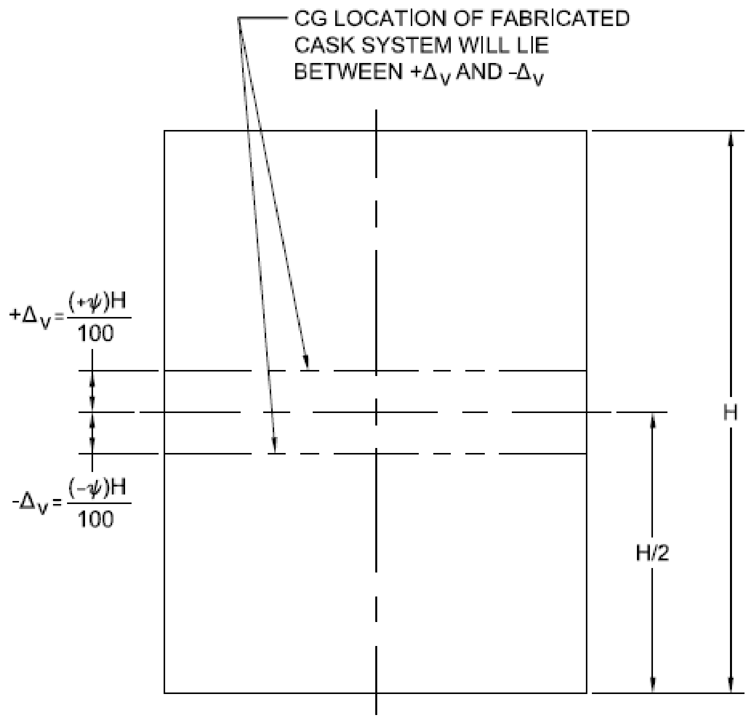
BOUNDING WEIGHTS FOR STRUCTURAL ANALYSES
(Height from Tables 3.2.1 and 3.2.2)

	Case	Purpose	Assumed Weight (Kilo-pounds)
1.	Loaded HI-STORM FW on the pad containing maximum length/weight fuel and 200 lb/cubic feet concrete – maximum possible weight scenario	Sizing and analysis of lifting and handling locations and cask stability analysis under overturning loads such as flood and earthquake	425.7
2.	Loaded HI-STORM FW on the pad with 150 lb concrete, shortest length MPC	Stability analysis under missile strike	302.1
3.	Loaded HI-TRAC VW with maximum length fuel and maximum lead and water shielding	Analysis for NUREG-0612 compliance of lifting and handling locations (TALs)	270.0
4.	Loaded HI-TRAC VW with shortest length MPC and minimum lead and water shielding	Stability analysis under missile strike	186.0
5.	Loaded MPC containing maximum length/weight fuel – maximum possible weight scenario	Analysis for NUREG-0612 compliance of lifting and handling locations (TALs)	116.4



Top View of Cask

Figure 3.2.1: Radial Eccentricity of Cask Center of Gravity



Elevation View of Cask

Figure 3.2.2: Vertical Eccentricity of Cask Center of Gravity

3.3 MECHANICAL PROPERTIES OF MATERIALS

This section provides the mechanical properties used in the structural evaluation. The properties include yield stress, ultimate stress, modulus of elasticity, Poisson's ratio, weight density, and coefficient of thermal expansion. Values are presented for a range of temperatures which envelopes the maximum and minimum temperatures under all service conditions applicable to the HI-STORM FW system components.

The materials selected for use in the MPC, HI-STORM FW overpack, and HI-TRAC VW transfer cask are presented on the drawings in Section 1.5. In this chapter, the materials are divided into two categories, structural and nonstructural. Structural materials are materials that act as load bearing members and are, therefore, significant in the stress evaluations. Materials that do not support mechanical loads are considered nonstructural. For example, the HI-TRAC VW inner shell is a structural material, while the lead between the inner and outer shell is a nonstructural material. For nonstructural materials, the principal property that is used in the structural analysis is weight density. In local deformation analysis, however, such as the study of penetration from a tornado-borne missile, the properties of lead in HI-TRAC VW and plain concrete in HI-STORM FW are included.

3.3.1 Structural Materials

a. Alloy X

A hypothetical material termed Alloy X is defined for the MPC pressure retaining boundary. The material properties of Alloy X are the least favorable values from the set of candidate alloys. The purpose of a least favorable material definition is to ensure that all structural analyses are conservative, regardless of the actual MPC material. For example, when evaluating the stresses in the MPC, it is conservative to work with the minimum values for yield strength and ultimate strength. This guarantees that the material used for fabrication of the MPC will be of equal or greater strength than the hypothetical material used in the analysis.

Table 3.3.1 lists the numerical values for the material properties of Alloy X versus temperature. These values, taken from the ASME Code, Section II, Part D [3.3.1], are used in all structural analyses. As is shown in Chapter 4, the maximum metal temperature for Alloy X used at or within the Confinement Boundary remains below 1000^{o}F under all service modes. As shown in ASME Code Case N-47-33 (Class 1 Components in Elevated Temperature Service, 2007 Code Cases, Nuclear Components), the strength properties of austenitic stainless steels do not change due to exposure to 1000^{o}F temperature for up to 10,000 hours. Therefore, there is no risk of a significant effect on the mechanical properties of the confinement or boundary material during the short time duration loading. A further description of Alloy X, including the materials from which it is derived, is provided in Appendix 1.A.

Two properties of Alloy X that are not included in Table 3.3.1 are weight density and Poisson's ratio. These properties are assumed constant for all structural analyses, regardless of temperature. The values used are shown in the table below.

PROPERTY	VALUE
Weight Density (lb/in^3)	0.290
Poisson's Ratio	0.30

b. Metamic-HT

Metamic-HT is a composite of nano-particles of aluminum oxide (alumina) and finely ground boron carbide particles dispersed in the metal matrix of pure aluminum. Metamic-HT is the principal constituent material of the HI-STORM FW fuel baskets. Metamic-HT neutron absorber is an enhanced version of the Metamic (classic) product widely used in dry storage fuel baskets [3.1.4, 3.3.2] and spent fuel storage racks [1.2.11]. The enhanced properties of Metamic-HT derive from the strengthening of its aluminum matrix with ultra fine-grained (nano-particle size) alumina (Al_2O_3) particles that anchor the grain boundaries. The strength properties of Metamic-HT have been characterized through a comprehensive test program, and Minimum Guaranteed Values suitable for structural design are archived in [Table 1.2.8]. The Metamic-HT metal matrix composite thus exhibits excellent mechanical strength properties (notably creep resistance) in addition to the proven thermal and neutron absorption properties that are intrinsic to borated aluminum materials. The specific Metamic-HT composition utilized in this FSAR has 10% (min.) B_4C by weight.

Section 1.2.1.4.1 provides detailed information on Metamic-HT. Mechanical properties are provided in Table 1.2.8

c. Carbon Steel, Low-Alloy and Nickel Alloy Steel

The carbon steels in the HI-STORM FW system are SA516 Grade 70, SA515 Grade 70, and SA36. The low alloy steel is SA350-LF3. The material properties of SA516 Grade 70 and SA515 Grade 70 are shown in Tables 3.3.2. The material properties of SA350-LF2 and SA350-LF3 are given in Table 3.3.3. The material properties of SA36 are shown in Table 3.3.6.

Two properties of these steels that are not included in Tables 3.3.2, 3.3.3 and 3.3.6 are weight density and Poisson's ratio. These properties are assumed constant for all structural analyses. The values used are shown in the table below.

PROPERTY	VALUE
Weight Density (lb/in^3)	0.283
Poisson's Ratio	0.30

d. Bolting Materials

Material properties of the bolting materials used in the HI-STORM FW system are given in Table 3.3.4.

e. Weld Material

All weld materials utilized in the welding of the Code components comply with the provisions of the appropriate ASME subsection (e.g., Subsection NB for the MPC enclosure vessel) and Section IX. All non-code welds will be made using weld procedures that meet Section IX of the ASME Code. The minimum tensile strength of the weld wire and filler material (where applicable) will be equal to or greater than the tensile strength of the base metal listed in the ASME Code.

3.3.2 Nonstructural Materials

a. Concrete

The primary function of the plain concrete in the HI-STORM FW storage overpack is shielding. Concrete in the HI-STORM FW overpack is not considered as a structural member, except to withstand compressive, bearing, and penetrant loads. Therefore the mechanical behavior of concrete must be quantified to determine the stresses in the structural members (steel shells surrounding it) under accident conditions. Table 3.3.5 provides the concrete mechanical properties. Allowable, bearing strength in concrete for normal loading conditions is calculated in accordance with ACI 318-05 [3.3.5]. The procedure specified in ASTM C-39 is utilized to verify that the assumed compressive strength will be realized in the actual in-situ pours. Appendix 1.D in the HI-STORM 100 FSAR [3.1.4] provides additional information on the requirements on plain concrete for use in HI-STORM FW storage overpack.

To enhance the shielding performance of the HI-STORM FW storage overpack, high density concrete can be used during fabrication. The permissible range of concrete densities is specified in Table 1.2.5. The structural calculations consider the most conservative density value (i.e., maximum or minimum weight), as appropriate.

b. Lead

Lead is not considered as a structural member of the HI-STORM FW system. Its load carrying capacity is neglected in all structural analysis, except in the analysis of a tornado missile strike where it acts as a missile barrier. Applicable mechanical properties of lead are provided in Table 3.3.5.

c. Fuel Basket Shims

The fuel basket shims (basket shims), as presented on the drawings in Section 1.5, are made of an aluminum alloy to ensure a high thermal conductivity and to ensure stable mechanical properties in the temperature range obtained in the peripheral region of the fuel basket. Nominal mechanical properties for the basket shims are tabulated in Table 3.3.7.

Strictly speaking, the shim is not a structural material because it does not withstand any tensile loads and is located in a confined space which would prevent its uncontrolled deformation under load. The simulation of the shim in the basket's structural model, however, utilizes its mechanical properties of which only the Yield Strength has a meaningful (but secondary) role. Accordingly, in this FSAR, the nominal value of the Yield Strength specified in Table 3.3.7 herein, is set down as a "critical characteristic" for the shim material. The minimum value of the Yield Strength reported in the material supplier's CoC must be at least 90% of the nominal value in the above referenced table to ensure that the non-mechanistic tip-over analysis will not have to be revisited.

Table 3.3.1

ALLOY X MATERIAL PROPERTIES

Temp. (Deg. F)	Alloy X			
	S_y	**S_u**†	**α**	**E**
-40	30.0	75.0 (70.0)	--	28.88
100	30.0	75.0 (70.0)	8.6	28.12
150	27.5	73.0 (68.1)	8.8	27.81
200	25.0	71.0 (66.3)	8.9	27.5
250	23.7	68.6 (64.05)	9.1	27.25
300	22.4	66.2 (61.8)	9.2	27.0
350	21.55	65.3 (60.75)	9.4	26.7
400	20.7	64.4 (59.7)	9.5	26.4
450	20.05	63.9 (59.45)	9.6	26.15
500	19.4	63.4 (59.2)	9.7	25.9
550	18.85	63.35 (59.1)	9.8	25.6
600	18.3	63.3 (59.0)	9.8	25.3
650	17.8	62.85 (58.6)	9.9	25.05
700	17.3	62.4 (58.3)	10.0	24.8
750	16.9	62.1 (57.9)	10.0	24.45
800	16.5	61.7 (57.6)	10.1	24.1

Definitions:

S_y = Yield Stress (ksi)
α = Mean Coefficient of thermal expansion (in./in. per degree F x 10^{-6})
S_u = Ultimate Stress (ksi)
E = Young's Modulus (psi x 10^6)

Notes:

1. Source for S_y values is Table Y-1 of [3.3.1].
2. Source for S_u values is Table U of [3.3.1].
3. Source for α values is Table TE-1 of [3.3.1].
4. Source for E values is material group G in Table TM-1 of [3.3.1].

† The ultimate stress of Alloy X is dependent on the product form of the material (i.e., forging vs. plate). Values in parentheses are based on SA-336 forged materials (type F304, F304LN, F316, and F316LN), which are used solely for the one-piece construction MPC lids. All other values correspond to SA-240 plate material.

Table 3.3.2

SA516 AND SA515, GRADE 70 MATERIAL PROPERTIES

Temp. (Deg. F)	SA516 and SA515, Grade 70			
	S_y	S_u	α	E
-40	38.0	70.0	---	29.98
100	38.0	70.0	6.5	29.26
150	35.7	70.0	6.6	29.03
200	34.8	70.0	6.7	28.8
250	34.2	70.0	6.8	28.55
300	33.6	70.0	6.9	28.3
350	33.05	70.0	7.0	28.1
400	32.5	70.0	7.1	27.9
450	31.75	70.0	7.2	27.6
500	31.0	70.0	7.3	27.3
550	30.05	70.0	7.3	26.9
600	29.1	70.0	7.4	26.5
650	28.2	70.0	7.5	26.0
700	27.2	70.0	7.6	25.5
750	26.3	69.1	7.7	24.85

Definitions:

S_y = Yield Stress (ksi)
α = Mean Coefficient of thermal expansion (in./in. per degree F x 10^{-6})
S_u = Ultimate Stress (ksi)
E = Young's Modulus (psi x 10^6)

Notes:
1. Source for S_y values is Table Y-1 of [3.3.1].
2. Source for S_u values is Table U of [3.3.1].
3. Source for α values is material group 1 in Table TE-1 of [3.3.1].
4. Source for E values is “Carbon steels with C less than or equal to 0.30%” in Table TM-1 of [3.3.1]

Table 3.3.3

SA350-LF3 AND SA350-LF2 MATERIAL PROPERTIES

Temp. (Deg. F)	**SA350-LF3 (SA350-LF2)**			**SA350-LF3 (SA350-LF2)**	
	S_m	S_y	S_u	**E**	α
-20	23.3	37.5 (36.0)	70.0	28.22 (29.88)	---
100	23.3	37.5 (36.0)	70.0	27.64 (29.26)	6.5
200	22.9 (22.0)	34.3 (33.0)	70.0 (70.0)	27.1 (28.8)	6.7
300	22.1 (21.2)	33.2 (31.8)	70.0 (70.0)	26.7 (28.3)	6.9
400	21.4 (20.5)	32.0 (30.8)	70.0 (70.0)	26.2 (27.9)	7.1
500	20.3 (19.6)	30.4 (29.3)	70.0 (70.0)	25.7 (27.3)	7.3
600	18.8 (18.4)	28.2 (27.6)	70.0 (70.0)	25.1 (26.5)	7.4
700	16.9 (17.2)	25.3 (25.8)	66.5 (70.0)	24.6 (25.5)	7.6

Definitions:

S_m = Design Stress Intensity (ksi)
S_y = Yield Stress (ksi)
S_u = Ultimate Stress (ksi)
α = Mean Coefficient of Thermal Expansion (in./in. per degree F x 10^{-6})
E = Young's Modulus (psi x 10^6)

Notes:

1. Source for S_m values is Table 2A of [3.3.1].
2. Source for S_y values is Table Y-1 of [3.3.1].
3. Source for S_u values is ratioing S_m values.
4. Source for α values is group 1 alloys in Table TE-1 of [3.3.1].
5. Source for E values is material group B (for SA350-LF3) and "Carbon steels with C less than or equal to 0.30%" (for SA350-LF2) in Table TM-1 of [3.3.1].
6. Values for LF2 are given in parentheses where different from LF3.

Table 3.3.4

BOLTING MATERIAL PROPERTIES

SB637-N07718 (less than or equal to 6 inches diameter)					
Temp. (Deg. F)	S_y	S_u	E	α	S_m
-100	150.0	185.0	29.9	---	50.0
-20	150.0	185.0	29.43	---	50.0
70	150.0	185.0	28.9	7.1	50.0
100	150.0	185.0	28.76	7.1	50.0
200	144.0	177.6	28.3	7.2	48.0
300	140.7	173.5	27.9	7.3	46.9
400	138.3	170.6	27.5	7.5	46.1
500	136.8	168.7	27.2	7.6	45.6
600	135.3	166.9	26.8	7.7	45.1
SA193 Grade B7 (2.5 to 4 inches diameter)					
Temp. (Deg. F)	S_y	S_u	E	α	S_m
100	95.0	115.0	29.46	6.5	31.7
200	88.5	115.0	29.0	6.7	29.5
300	85.1	115.0	28.5	6.9	28.4
400	82.7	115.0	28.0	7.1	27.6
500	80.1	115.0	27.4	7.3	26.7
600	77.1	115.0	26.9	7.4	25.7

Definitions:

S_m = Design stress intensity (ksi)
S_y = Yield Stress (ksi)
α = Mean Coefficient of thermal expansion (in./in. per degree F x 10^{-6})
S_u = Ultimate Stress (ksi)
E = Young's Modulus (psi x 10^6)

Notes:

1. Source for S_m values is Table 4 of [3.3.1].
2. Source for S_y values is ratioing design stress intensity values and Table Y-1 of [3.3.1], as applicable.
3. Source for S_u values is ratioing design stress intensity values and Table U of [3.3.1], as applicable.
4. Source for α values is Tables TE-1 and TE-4 of [3.3.1], as applicable.
5. Source for E values is Tables TM-1 and TM-4 of [3.3.1], as applicable.

Table 3.3.4 (CONTINUED)

BOLTING MATERIAL PROPERTIES

Temp. (Deg. F)	S_y	S_u	E	α	S_m
SA193 Grade B8 Class 2 (less than or equal to 2 inches diameter)					
100	75.0	95.0	28.12	8.6	---
200	62.5	89.93	27.5	8.9	---
300	56.0	83.85	27.0	9.2	---
400	51.75	81.07	26.4	9.5	---
500	48.5	80.31	25.9	9.7	---
600	46.0	80.31	25.3	9.8	---

Definitions:

S_m = Design stress intensity (ksi)
S_y = Yield Stress (ksi)
α = Mean Coefficient of thermal expansion (in./in. per degree F x 10^{-6})
S_u = Ultimate Stress (ksi)
E = Young's Modulus (psi x 10^6)

Notes:

1. Source for S_y values is ratioing S_y values of SA193 B8 Class 1 bolt material obtained from Table Y-1 of [3.3.1].
2. Source for S_u values is ratioing S_u values of SA193 B8 Class 1 bolt material obtained from Table U of [3.3.1].
3. Source for α values is group 3 alloys in Table TE-1 of [3.3.1].
4. Source for E values is material group G in Table TM-1 of [3.3.1].

Table 3.3.5

CONCRETE AND LEAD MECHANICAL PROPERTIES

PROPERTY	VALUE					
CONCRETE:						
Compressive Strength (psi)	3,300 psi					
Nominal Density (lb/ft^3)	150 lb/cubic feet					
Allowable Bearing Stress (psi)	1,543†					
Allowable Axial Compression (psi)	1,042†					
Allowable Flexure, extreme fiber tension (psi)	158†,††					
Allowable Flexure, extreme fiber compression (psi)	1,543†					
Mean Coefficient of Thermal Expansion (in/in/deg. F)	5.5E-06					
Modulus of Elasticity (psi)	57,000 (compressive strength (psi))$^{1/2}$					
LEAD:	-40°F	-20°F	70°F	200°F	300°F	600°F
Yield Strength (psi)	700	680	640	490	380	20
Modulus of Elasticity (ksi)	2.4E+3	2.4E+3	2.3E+3	2.0E+3	1.9E+3	1.5E+3
Coefficient of Thermal Expansion (in/in/deg. F)	15.6E-6	15.7E-6	16.1E-6	16.6E-6	17.2E-6	20.2E-6
Poisson's Ratio	0.40					
Density (lb/cubic ft.)	708					

Notes:
1. Concrete allowable stress values based on ACI 318-05.
2. Lead properties are from [3.3.7].

† Values listed correspond to concrete compressive stress = 3,300 psi.
†† No credit for tensile strength of concrete is taken in the calculations.

Table 3.3.6

SA36 MATERIAL PROPERTIES

Temp. (Deg. F)	SA36			
	S_y	S_u	α	E
-40	36.0	58.0	---	29.98
100	36.0	58.0	6.5	29.26
150	33.8	58.0	6.6	29.03
200	33.0	58.0	6.7	28.8
250	32.4	58.0	6.8	28.55
300	31.8	58.0	6.9	28.3
350	31.3	58.0	7.0	28.1
400	30.8	58.0	7.1	27.9
450	30.05	58.0	7.2	27.6
500	29.3	58.0	7.3	27.3
550	28.45	58.0	7.3	26.9
600	27.6	58.0	7.4	26.5
650	26.7	58.0	7.5	26.0
700	25.8	58.0	7.6	25.5

Definitions:

S_y = Yield Stress (ksi)
α = Mean Coefficient of thermal expansion (in./in./^{0}F x 10^{-6})
S_u = Ultimate Stress (ksi)
E = Young's Modulus (psi x 10^6)

Notes:
1. Source for S_y values is Table Y-1 of [3.3.1].
2. Source for S_u values is Table U of [3.3.1].
3. Source for α values is group 1 alloys in Table TE-1 of [3.3.1].
4. Source for E values is “Carbon steels with C less than or equal to 0.30%” in Table TM-1 of [3.3.1].

Table 3.3.7 FUEL BASKET SHIMS – NOMINAL MECHANICAL PROPERTIES					
Temp. °C (°F)	**Aluminum Alloy (B221 2219-T8511)**				
	S_y	**S_u**	**E**	**α**	**% Elongation**
25 (75)	290 (42)	400 (58)	7.2 (10.5)	–	5
150 (300)	243 (35)	307 (44)	6.8 (9.8)	23.9 (13.3)	6.4
204 (400)	188 (27)	231 (34)	6.3 (9.1)	24.5 (13.6)	8.2
230 (450)	171 (25)	209 (30)	6.1 (8.8)	24.8 (13.8)	8.6
260 (500)	154 (22)	182 (26)	5.9 (8.5)	25.0 (13.9)	8.6
290 (550)	98 (14)	116 (17)	5.5 (8.0)	25.4 (14.1)	10.5

Definitions:

S_y = Yield Stress, MPa (ksi)
α = Mean Coefficient of thermal expansion, cm/cm-ºC x 10^{-6} (in/in-ºF x 10^{-6})
S_u = Ultimate Stress, MPa (ksi)
E = Young's Modulus, MPa x 10^4 (psi x 10^6)

Notes:

1. Source for E values is "Properties of Aluminum Alloys", page 82 [3.3.3] (properties listed in the table above are not affected by time at temperature).
2. Source for Sy, Su, and % Elongation values at room temperature is ASTM Specification B221M [3.3.8]. Values at elevated temperatures are obtained by scaling the room temperature values using the data from [3.3.3].
3. Source for α is Table TE-2 of [3.3.1] (values listed in TE-2 are also considered representative of Aluminum Alloy (2219-T8511) (UNS No. A92219)).

3.4 GENERAL STANDARDS FOR CASKS

3.4.1 Chemical and Galvanic Reactions

Chapter 8 provides discussions on chemical and galvanic reactions, material compatibility and operating environments. Section 8.12 provides a summary of compatibility all HI-STORM FW system materials with the operating environment.

3.4.2 Positive Closure

There are no quick-connect/disconnect ports in the Confinement Boundary of the HI-STORM FW system. The only access to the MPC is through the storage overpack lid, which weighs over 10 tons (see Table 3.2.5). The lid is fastened to the storage overpack with large bolts. Inadvertent opening of the storage overpack is not feasible because opening a storage overpack requires mobilization of special tools and heavy-load lifting equipment.

3.4.3 Lifting Devices

3.4.3.1 Identification of Lifting Devices and Required Safety Factors

The safety of the lifting and handling operations involving HI-STORM FW system components is considered in this section. In particular, the compliance of the appurtenances integral to the cask components used in the lifting operations to NUREG-0612, Reg. Guide 3.61, and the ASME Code is evaluated.

The following design features of Threaded Anchor Locations (TALs) are relevant to their stress analysis:

i. All TALs consist of vertically tapped penetrations in the solid metal blocks. For example, the HI-STORM FW overpack body and overpack lid (like all HI-STORM models) have tapped holes in the "anchor blocks" that are engaged for lifting. The loaded MPC is lifted at eight threaded penetrations in the top lid as depicted on the licensing drawings in Section 1.5. However, the MPC lifting analysis in this section conservatively takes credit for only 4 TALs. Likewise, eight vertically tapped holes in the top flange provide the lift points for HI-TRAC VW transfer cask.

   Specifically, trunnions are not used in the HI-STORM FW system components because of the radiation streaming paths introduced by their presence and high stresses produced at the trunnion's root by the cantilever action during lifting.

ii. Operations involving loaded HI-STORM FW cask components involve handling evolutions in the vertical orientation (with the rare handling exception of the transfer cask as described in Subsection 4.5.1). While the lifting devices used by a specific nuclear site shall be custom engineered to meet the architectural constraints of the site, all lifting devices are required to

engage the tapped connection points using a vertical tension member such as a threaded rod. Thus, the loading on the cask during lifting is purely vertical.

iii. There are no rotation trunnions in the HI-STORM FW components. All components are upended and downended at the nuclear plant site using “cradles” of the same design used at the factory (viz., the Holtec Manufacturing Division) during their manufacturing.

The stress analysis of the HI-STORM FW components, therefore, involves applying a vertical load equal to D*/n at each of the n TAL locations. Thus, for the case of the HI-STORM FW overpack, n = 4 (four “anchor blocks” as shown in the licensing drawings in Section 1.5).

The stress limits for individual components are as follows:

i. Lift points (MPC and HI-TRAC VW): The stress in the threads must be the lesser of 1/3rd of the material’s yield strength and 1/10th of its ultimate strength pursuant to NUREG-0612 and Reg. Guide 3.61.

ii. Lift points (HI-STORM FW): The stress in the threads must be less than 1/3rd of the material’s yield strength pursuant to Reg. Guide 3.61. This acceptance criterion is consistent with the stress limits used for the lifting evaluation of the HI-STORM 100 overpack in [3.1.4].

iii. Balance of the components: The maximum primary stress (membrane plus bending) must be below the Level A service condition limit using ASME Code, Section III, Subsection NF (2007 issue) as the reference code.

To incorporate an additional margin of safety in the reported safety factors, the following assumptions are made:

i. As the system description in Chapter 1 indicates, the heights of the MPCs, HI-STORM FW and HI-TRAC VW are variable. Further, the quantity of lead shielding installed in HI-TRAC VW and the density of concrete can be increased to maximize shielding. All lift point capacity evaluations are performed using the maximum possible weights for each component, henceforth referred to as the “heaviest weight configuration”. Because a great majority of site applications will utilize lower weight components (due to shorter fuel length and other architectural limitations such as restricted crane capacity or DAS slab load bearing capacity, or lack of floor space in the loading pit), there will be an additional margin of safety in the lifting point’s capacity at specific plant sites.

ii. All material yield strength and ultimate strength values used are the minimum from the ASME Code. Actual yield and tensile data for manufactured steel usually have up to 20% higher values.

The stress analysis of the lifting operation is carried out using the load combination D+H, where H is the "handling load". The term D denotes the dead load. Quite obviously, D must be taken as the

bounding value of the dead load of the component being lifted. In all lifting analyses considered in this document, the handling load H is assumed to be 0.15D. In other words, the inertia amplifier during the lifting operation is assumed to be equal to 0.15g. This value is consistent with the guidelines of the Crane Manufacturer's Association of America (CMAA), Specification No. 70, 1988, Section 3.3, which stipulates a dynamic factor equal to 0.15 for slowly executed lifts. Thus, the "apparent dead load" of the component for stress analysis purposes is $D^* = 1.15D$. Unless otherwise stated, all lifting analyses in this FSAR use the "apparent dead load", D^*, as the lifted load.

Unless explicitly stated otherwise, all analyses of lifting operations presented in this FSAR follow the load definition and allowable stress provisions of the foregoing. Consistent with the practice adopted throughout this chapter, results are presented in dimensionless form, as safety factors, defined as

$$\text{Safety Factor, } \beta = \frac{\text{Allowable Stress}}{\text{Computed Stress}}$$

In the following subsections, the lifting device stress analyses performed to demonstrate compliance with regulations are presented. Summary results are presented for each of the analyses.

3.4.3.2 Analysis of Lifting Scenarios

In the following, the safety analyses of the HI-STORM FW components under the following lifting conditions are summarized.

a. MPC Lifts

The governing condition for the MPC lift is when it is being raised or lowered in a radiation shielded space defined by the HI-TRAC VW or HI-STORM FW stack. In this condition, as stated in Section 3.4.3.1, only four tapped holes in the MPC lid (Alloy X material) are credited to carry the weight.

The criteria derived from NUREG-0612, Reg. Guide 3.61, and the ASME Code Level A condition, stated earlier, apply. The stress analysis is carried out in two parts.

i. Strength analysis of the TALs (connection points) using classical strength-of-materials.

ii. A finite element analysis of the MPC as a cylindrical vessel with the weight of the fuel and basket applied on its baseplate which along with the weight of the Confinement Boundary metal is equilibrated by the reaction loads at the our lift points.

    The primary stress intensities must meet the Level A stress limits for "NB" Class 3 plate and shell structures.

<u>Case (i): Stress Analysis of MPC Threaded Anchor Locations (TALs)</u>

Per Table 3.2.8, the maximum weight of a loaded MPC is

D = 116,400 lb

Per the above, the apparent dead load of the MPC during handling operations is

D* = 1.15 x D = 133,860 lb

The MPC lid has 8 TALs as shown on the drawings in Section 1.5, but as stated in Section 3.4.3.1, only four tapped holes in the MPC lid are credited to carry the weight. Therefore, the lifted load per TAL is equal to

$$\frac{D^*}{4} = 33{,}465 lb$$

Per Machinery's Handbook [3.4.12], the shear area of the internal threads (1 3/4" - 5UNC x 3. 0" min length.) at each TAL is computed as

A = 11.8 in^2

Finally, the shear stress on the TALs is computed as follows

$$\tau = \frac{D^*}{4A} = 2{,}836 psi$$

The MPC lid is made from Alloy X material, whose mechanical properties are listed in Table 3.3.1. Based on a design temperature of 600ºF (Table 2.2.3), and assuming the yield and ultimate strengths in shear to be 60% of the corresponding tensile strengths, the allowable stress in the threads is determined as follows

$$Sa = 0.6 \times \min\left(\frac{Sy}{3}, \frac{Su}{10}\right) = 3{,}540 psi$$

Therefore, the safety factor against shear failure of the TALs in the MPC lid is

$$SF = \frac{Sa}{\tau} = 1.248$$

Case (ii): Finite Element Analysis of MPC Enclosure Vessel

The stress analysis of the MPC Enclosure Vessel under normal handling conditions is performed using ANSYS [3.4.1]. The finite element model, which is shown in Figure 3.4.1, is ¼ -symmetric,

and it represents the maximum height MPC as defined by Tables 3.2.1 and 3.2.2. The maximum height MPC is analyzed because it is also the heaviest MPC. The key attributes of the ANSYS finite element model of the MPC Enclosure Vessel are described in Subsection 3.1.3.2.

The loads are statically applied to the finite element model in the following manner. The self weight of the Enclosure Vessel is simulated by applying a constant acceleration of 1.15g in the vertical direction. The apparent dead weight of the stored fuel inside the MPC cavity (which includes a 15% dynamic amplifier) is accounted for by applying a uniformly distributed pressure of 18.8 psi on the top surface of the MPC baseplate. The amplified weight of the fuel basket and the fuel basket shims is applied as a ring load on the MPC baseplate at a radius equal to the half-width of the fuel basket cross section. The magnitude of the ring load is equal to 100.4 lbf/in. All internal surfaces of the MPC storage cavity are also subjected to an internal pressure of 95 psig, which exceeds the normal operating pressure per Table 4.4.5. Finally, the model is constrained by fixing one node on the top surface of the ¼-symmetric MPC lid, which coincides with the TAL. Symmetric boundary conditions are applied to the two vertical symmetry planes. The boundary conditions and the applied loads are graphically depicted in Figure 3.4.28.

The resulting stress intensity distribution in the Enclosure Vessel under the applied handling loads is shown in Figure 3.4.2. Figures 3.4.29 and 3.4.30 plot the thru-thickness variation of the stress intensity at the baseplate center and at the baseplate-to-shell juncture, respectively. The maximum primary and secondary stress intensities in the MPC Enclosure Vessel are compared with the applicable stress intensity limits from Subsection NB of the ASME Code [3.4.4]. The allowable stress intensities are taken at 450°F for the MPC shell and MPC lids, 300°F for the baseplate, and 250°F at the baseplate-to-shell juncture. These temperatures bound the operating temperatures for these parts under normal operating conditions (Table 4.4.3). The maximum calculated stress intensities and the corresponding safety factors are summarized in Table 3.4.1.

The shear stress in the MPC lid-to-shell weld under normal handling conditions is independently calculated, as shown below.

Per Table 3.2.8, the maximum weight of a loaded MPC is

W_{MPC} = 116,400 lb

The diameter and weight of the MPC lid assembly are

D = 74.5 in

W_{lid} = 11,500 lb

From Table 4.4.5, the bounding pressure inside the MPC cavity under normal operating conditions is

P = 95 psig

Thus, the total force acting on the MPC lid-to-shell weld is

$$F = 1.15 \cdot (W_{MPC} - W_{lid}) + P \cdot \left(\frac{\pi \cdot D^2}{4} \right) = 534{,}755 lb$$

which includes a 15% dynamic amplifier. The MPC lid-to-shell weld is a ¾" partial groove weld, which has an effective area equal to

$$A = \pi \cdot D \cdot \left(t_w - \frac{1}{8} in \right) \cdot 0.8 = 117.0 in^2$$

where t_w is the weld size (= 0.75in). The calculated weld area includes a strength reduction factor of 0.8 per ISG-15 [3.4.17]. Thus, the average shear stress in the MPC lid-to-shell weld is

$$\tau = \frac{F}{A} = 4{,}571 psi$$

The MPC Enclosure Vessel is made from Alloy X material, whose mechanical properties are listed in Table 3.3.1. Based on a temperature of 450ºF (Table 4.4.3), and assuming that the weld strength is equal to the base metal ultimate strength, the allowable shear stress in the weld under normal conditions is

$$\tau_a = 0.3 \times S_u = 19{,}170 psi$$

Therefore, the safety factor against shear failure of the MPC lid-to-shell weld is

$$SF = \frac{\tau_a}{\tau} = 4.19$$

b. Heaviest Weight HI-TRAC VW Lift

The HI-TRAC VW transfer cask is at its heaviest weight when it is being lifted out of the loading pit with the MPC full of fuel and water and the MPC lid lying on it for shielding protection (Table 3.2.8). The threaded lift points provide for the anchor locations for lifting.

The stress analysis of the transfer cask consists of two steps:

i. A strength evaluation of the tapped connection points to ensure that it will not undergo yielding at 3 times D* and failure at 10 times D*.

ii. A strength evaluation of the HI-TRAC VW vessel using strength of materials formula to establish the stress field under D*. The primary membrane plus primary bending stresses

throughout the HI-TRAC VW body and the bottom lid shall be below the Level A stress limits for “NF” Class 3 plate and shell structures.

Case (i): Stress Analysis of HI-TRAC VW Threaded Anchor Locations (TALs)

Per Table 3.2.8, the maximum lifted weight of a loaded HI-TRAC VW is

D = 270,000 lb

Per the above, the apparent dead load of the HI-TRAC VW during handling operations is

D* = 1.15 x D = 310,500 lb

The HI-TRAC VW top flange has 8 TALs as shown on the drawing in Section 1.5. Therefore, the lifted load per TAL is equal to

$$\frac{D^*}{8} = 38{,}813 lb$$

Per Machinery’s Handbook [3.4.12], the shear area of the internal threads (2 1/4” - 4.5UNC x 2.25” min length.) at each TAL is

A = 12.228 in^2

Finally, the shear stress on the TALs is computed as follows

$$\tau = \frac{D^*}{8A} = 3{,}174 psi$$

The HI-TRAC VW top flange is made from SA-350 LF3 material, whose mechanical properties are listed in Table 3.3.3. Based on a design temperature of 400ºF (Table 2.2.3), and assuming the yield and ultimate strengths in shear to be 60% of the corresponding tensile strengths, the allowable stress in the threads is determined as follows

$$Sa = 0.6 \times \min\left(\frac{Sy}{3}, \frac{Su}{10}\right) = 4{,}200 psi$$

Therefore, the safety factor against shear failure of the TALs in the HI-TRAC VW top flange is

$$SF = \frac{Sa}{\tau} = 1.323$$

Case (ii): Stress Analysis of HI-TRAC VW Body

The stress analysis of the HI-TRAC VW steel structure during lifting operations is performed using strength of materials. All structural members in the load path are evaluated for the maximum lifted weight (Table 3.2.8). In particular, the following stresses are calculated:

- the shear stress in the welds between the top flange and the inner and outer shells
- the primary membrane stress in the inner and outer shells
- the tensile stress in the bottom lid bolts
- the primary bending stress in the bottom lid

To determine the bending stress in the bottom lid, the weight of the loaded MPC (Table 3.2.8) plus the weight of the water inside the HI-TRAC VW cavity (Table 3.2.4) is applied as a uniformly distributed pressure on the top surface of the lid. The bending stress is calculated at the center of the bottom lid assuming that the lid is simply supported at the bolt circle diameter. The calculated stresses are compared with the Level A stress limits for "NF" Class 3 plate and shell structures. The detailed calculations are documented in [3.4.13]. Table 3.4.2 summarizes the stress analysis results for the HI-TRAC VW steel structure under the maximum lifted load.

c. HI-STORM FW Overpack Related Lifts

Two related lift conditions are:

i. HI-STORM FW loaded with the heaviest MPC and closure lid installed being lifted (heaviest weight configuration).

ii. HI-STORM FW lid being lifted (heaviest weight configuration)

Case (i): HI-STORM FW Lift Using Anchor Block Connections

Calculations to establish the margin of safety in the TALs and the HI-STORM FW overpack's steel structure are summarized below.

Per Table 3.2.8, the maximum weight of a loaded HI-STORM FW is

D = 425,700 lb

Per the above, the apparent dead load of the HI-STORM FW during handling operations is

D* = 1.15 x D = 489,555 lb

The HI-STORM FW overpack has 4 TALs as shown on the drawing in Section 1.5. Therefore, the lifted load per TAL is equal to

$$\frac{D^*}{4} = 122{,}389 lb$$

Per Machinery's Handbook [3.4.12], the shear area of the internal threads (3 1/4" - 4UNC x 3 1/4" min length.) at each TAL is

A = 24.1 in^2

Finally, the shear stress on the TALs is computed as follows

$$\tau = \frac{D^*}{4A} = 5{,}072\, psi$$

The HI-STORM FW anchor blocks are made from SA-350 LF2 material, whose mechanical properties are listed in Table 3.3.3. Based on a design temperature of 350ºF (Table 2.2.3), and assuming the yield strength in shear to be 60% of the corresponding tensile yield strength, the allowable stress in the threads is determined as follows

$$Sa = 0.6 \times \frac{Sy}{3} = 6{,}260\, psi$$

Therefore, the safety factor against shear failure of the TALs in the HI-STORM FW overpack is

$$SF = \frac{Sa}{\tau} = 1.234$$

The stress analysis of the overpack body under normal handling conditions is performed using ANSYS [3.4.1]. The finite element model, which is shown in Figure 3.4.3, is ¼-symmetric, and it represents the maximum height HI-STORM FW as defined by Tables 3.2.1 and 3.2.2. The concrete density is also maximized (Table 3.2.5) in the ANSYS model. The key attributes of the ANSYS finite element model of the HI-STORM FW overpack are described in Subsection 3.1.3.1.

The self weight of the overpack is simulated by applying a constant acceleration of 1.15g in the vertical direction. The apparent dead weight of the fully loaded MPC (which includes a 15% dynamic amplifier) is accounted for by applying a uniformly distributed pressure of 23.8 on the top surface of the HI-STORM FW baseplate. Finally, the model is constrained by fixing four nodes on the top surface of the HI-STORM FW, which coincide with the TALs. Symmetric boundary conditions are applied to the two vertical symmetry planes. The boundary conditions and the applied loads are graphically depicted in Figure 3.4.26.

The resulting stress distribution in the overpack under the applied handling loads is shown in Figure 3.4.4. The maximum primary stresses in the HI-STORM overpack body are compared with the applicable stress limits from Subsection NF of the ASME Code [3.4.2]. The allowable stresses for the load-bearing members are taken at 300°F, which exceeds the maximum operating temperature for the overpack under normal operating conditions (Table 4.4.3). The maximum stresses and the corresponding safety factors are summarized in Table 3.4.3.

Case (ii): Lid Lift Analysis

The weight of the HI-STORM FW lid is dependent on the shielding concrete's density. The maximum possible weight of the lid is provided in Table 3.2.5. The HI-STORM FW lid is lifted using the four equally spaced TALs on the lid top surface, which are shown on the licensing drawing in Section 1.5. Calculations to establish the margin of safety in the TALs and the lid's steel structure are summarized below.

Per Table 3.2.5, the maximum weight of the HI-STORM FW lid is

D = 23,300 lb

Per the above, the apparent dead load of the HI-STORM FW lid during handling operations is

D* = 1.15 x D = 26,795 lb

The HI-STORM FW lid has 4 TALs as shown on the drawing in Section 1.5. Therefore, the lifted load per TAL is equal to

$$\frac{D*}{4} = 6{,}699\text{lb}$$

Per Machinery's Handbook [3.4.12], the shear area of the internal threads (1 1/2" - 6UNC x 1" min length.) at each TAL is

$A = 3.567\ in^2$

Finally, the shear stress on the TALs is computed as follows

$$\tau = \frac{D*}{4A} = 1878\, psi$$

The HI-STORM FW lid anchor blocks are made from carbon steel material, whose yield and ultimate strengths at 450ºF (Table 2.2.3) are conservatively input as 15,000 psi and 40,000 psi, respectively. Assuming the yield and ultimate strengths in shear to be 60% of the corresponding tensile strengths, the allowable stress in the threads is determined as follows

$$\text{Sa} = 0.6 \times \min\left(\frac{\text{Sy}}{3}, \frac{\text{Su}}{10}\right) = 2{,}400\text{psi}$$

Therefore, the safety factor against shear failure of the TALs in the HI-STORM FW lid is

$$SF = \frac{Sa}{\tau} = 1.278$$

The global stress analysis of the overpack lid under normal handling conditions is performed using ANSYS [3.4.1]. Figure 3.4.5 shows the finite element model of the lid, which incorporates the maximum concrete density (Table 3.2.5). The key attributes of the ANSYS finite element model of the HI-STORM FW lid are described in Subsection 3.1.3.1.

The self weight of the overpack lid is simulated by applying a constant acceleration of 1.15g in the vertical direction. The model is constrained by fixing four nodes on the top surface of the HI-STORM FW lid, which coincide with the TALs.

The resulting stress distribution in the steel structure of the overpack lid under the applied handling load is shown in Figure 3.4.6. The maximum stresses and the corresponding safety factors are summarized in Table 3.4.4. For conservatism, the maximum calculated stress at any point on the lid, including secondary stress contributions, is compared against the primary membrane and primary bending stress limits per Subsection NF of the ASME Code for Level A conditions. The allowable stresses are taken at 300°F, which exceeds the maximum operating temperature for the overpack top lid under normal operating conditions.

3.4.3.3 Safety Evaluation of Lifting Scenarios

As can be seen from the above, the computed factors of safety have a large margin over the allowable (of 1.0) in every case. In the actual fabricated hardware, the factors of safety will likely be much greater because of the fact that the actual material strength properties are generally substantially greater than the Code minimums. Minor variations in manufacturing, on the other hand, may result in a small subtraction from the above computed factors of safety. A part 72.48 safety evaluation will be required if the cumulative effect of manufacturing deviation and use of the CMTR (or CoC) material strength in a manufactured hardware renders a factor of safety to fall below the above computed value. Otherwise, a part 72.48 evaluation is not necessary. The above criterion applies to all lift calculations covered in this FSAR.

3.4.4 Heat

The thermal evaluation of the HI-STORM FW system is reported in Chapter 4.

a. Summary of Pressures and Temperatures

Design pressures and design temperatures for all conditions of storage are listed in Tables 2.2.1 and 2.2.3, respectively.

b. Differential Thermal Expansion

The effect of differential thermal expansion among the constituent components in the HI-STORM FW system is considered in Chapter 4 wherein the temperatures necessary to perform the differential thermal expansion analyses for the MPC in the HI-STORM FW and HI-TRAC VW casks are computed. The material presented in Section 4.4 demonstrates that a constraint to free expansion due to differential growth between discrete components of the HI-STORM FW system (e.g., storage overpack and enclosure vessel) will not develop under any operating condition.

i. Normal Hot Environment

Results presented in Section 4.4 demonstrate that initial gaps between the HI-STORM FW storage overpack or the HI-TRAC VW transfer cask and the MPC canister, and between the MPC canister and the fuel basket, will not close due to thermal expansion of the system components normal operating conditions.

The clearances between the MPC basket and canister structure, as well as between the MPC shell and storage overpack or HI-TRAC VW inside surface, are shown in Section 4.4 to be sufficient to preclude a temperature induced interference from differential thermal expansions under normal operating conditions.

ii. Fire Accident

It is shown in Chapter 4 that the fire accident has a small effect on the MPC temperatures because of the short duration of the fire accidents and the large thermal inertia of the storage overpack. Therefore, a structural evaluation of the MPC under the postulated fire event is not required. The conclusions reached in item (i) above are also appropriate for the fire accident with the MPC housed in the storage overpack. Analysis of fire accident temperatures of the MPC housed within the HI-TRAC VW for thermal expansion is unnecessary, as the HI-TRAC VW, directly exposed to the fire, expands to increase the gap between the HI-TRAC VW and MPC.

As expected, the external surfaces of the HI-STORM FW storage overpack that are directly exposed to the fire event experience maximum rise in temperature. The outer shell and top plate in the top lid are the external surfaces that are in direct contact with heated air from fire. Table 4.6.2 provides the maximum temperatures attained at the key locations in HI-STORM FW storage overpack under the

postulated fire event.

The following conclusions are evident from the above table.

- The maximum metal temperature of the carbon steel shell most directly exposed to the combustion air is well below 700°F (Table 2.2.3 applicable short-term temperature limit). 700°F is the permissible temperature limit in the ASME Code for the outer shell material.

- The bulk temperature of concrete is well below the normal condition temperature limit of 300°F specified in Table 2.2.3. ACI-349-85 [3.3.6] permits 350°F as the short-term temperature limit; the shielding concrete in the HI-STORM FW overpack. As the detailed information in Section 4.6 shows, the radial extent in the concrete where the local temperature exceeds 350°F begins at the outer shell/concrete interface and ends in less than one-inch. Therefore, the potential loss in the shielding material's effectiveness is less than 4% of the concrete shielding mass in the overpack annulus.

- The metal temperature of the inner shell does not exceed 300°F at any location, which is well below the accident condition temperature specified in Table 2.2.3 for the inner shell.

- The presence of a vented space at the top of the overpack body ensures that there will be no pressure buildup in the concrete annulus due to the evaporation of vapor and gaseous matter from the shielding concrete.

Thus, it is concluded that the postulated fire event will not jeopardize the structural integrity of the HI-STORM FW overpack or significantly diminish its shielding effectiveness.

The above conclusions, as relevant, also apply to the HI-TRAC VW fire considered in Chapter 4. Water jacket over-pressurization is prevented by the pressure relief devices. The non-structural effects of loss of water have been evaluated in Chapter 5 and shown to meet regulatory limits. Therefore, it is concluded that the postulated fire event will not cause a state of non-compliance with the regulations to materialize.

3.4.4.1 Safety Analysis

Calculations of the stresses and displacements in the different components of the HI-STORM FW system from the effects of mechanical load case assembled in Table 3.1.1 for the MPC, the HI-STORM FW storage overpack and the HI-TRAC VW transfer cask are presented in the following. The purpose of the analyses summarized herein is to provide the necessary assurance that there will be no unacceptable risk of criticality, unacceptable release of radioactive material, unacceptable radiation levels, or impairment of ready retrievability of fuel from the MPC (for normal and off-normal conditions of storage) and the MPC from the HI-STORM FW storage overpack or from the HI-TRAC VW transfer cask.

Because many of the analyses must be performed for a particular ISFSI to demonstrate the acceptability of site-specific loads under the provisions of 10CFR72.212, the analyses presented here also set down the acceptable methodologies. Accordingly, the analysis methodologies are configured to exaggerate the severity of response. Also, because the weight and height of all three components (overpack, MPC, and HI-TRAC VW) can vary between specified ranges (see tables in Section 3.2), each analysis is carried out for the dimensional and weight condition of the component that maximizes response. Thus, for example, the seismic stability analysis of the loaded HI-STORM FW (Load Case 2 in Table 3.1.1) is performed for the case of maximum height, but the stability under the impact of a large tornado missile (Load Case 3) is analyzed assuming maximum height and minimum weight (MPC is assumed to contain only one fuel assembly).

Each load case in Table 3.1.1 is considered sequentially and all affected components are analyzed to determine the factors of safety.

All factors of safety reported in this FSAR utilize nominal dimensions and minimum material strengths. Actual factors of safety in the manufactured hardware are apt to be considerably larger than those reported herein chiefly because of the actual material strengths being much greater than the values used in the safety analyses. A part 72.48 safety assessment will be required if the combined effect of the actual material strength and manufacturing deviation produces a lower safety factor for a design basis loading than that referenced in the safety evaluation in this FSAR.

3.4.4.1.1 Load Case 1: Moving Floodwater

The object of the analysis is to determine the maximum floodwater velocity that a loaded HI-STORM FW on the ISFSI pad can withstand before tipping over or sliding. The flood data for the ISFSI shall be based on a 40-year (minimum) return flood. The kinematic stability analysis consists of writing static equilibrium equations for tipping and sliding.

The flood condition subjects the HI-STORM FW system to external pressure, together with a horizontal load due to water velocity. Because the HI-STORM FW storage overpack is equipped with ventilation openings, the hydrostatic pressure from flood submergence acts only on the MPC. As stated in Subsection 2.2.3, the design external pressure for the MPC bounds the hydrostatic pressure from flood submergence.

The water velocity associated with flood produces a horizontal drag force, which may act to cause sliding or tip-over. In accordance with the provisions of ANSI/ANS 57.9, the acceptable upper bound flood velocity, V, must provide a minimum factor of safety of 1.1 against overturning and sliding.

The overturning horizontal force, F, due to hydraulic drag, is given by the classical formula:

$$F = Cd\ A\ V^{*} \qquad \text{[Equation 1]}$$

where:

V^{*} = velocity head = $\frac{\rho V^2}{2g}$ (ρ is water weight density, and g is acceleration due to gravity).

A = projected area of the HI-STORM FW cylinder perpendicular to the fluid velocity vector, equal to D times h, where h is the height of the floodwater.

Cd = drag coefficient

The value of Cd for flow past a cylinder at Reynolds number above 5E+05 is given as 0.5 in the literature (viz. Hoerner, Fluid Dynamics, 1965).

The drag force tending to cause HI-STORM FW's sliding is opposed by the friction force, which is given by

$$F_f = \mu\ W^{*} \qquad \text{[Equation 2]}$$

where:

μ = limiting value of the friction coefficient at the HI-STORM FW/ISFSI pad interface is assumed to be equal to 0.53 (the NRC-approved value in Docket No. 72-1014).

W* = apparent (buoyant) weight of HI-STORM FW with an empty MPC.

i. <u>Sliding Factor of Safety</u>

The factor of safety against sliding, β_1, is given by

$$\beta_1 = \frac{F_f}{F} = \frac{\mu W^{*}}{Cd\ A\ V^{*}} = \frac{2g\mu W^{*}}{Cd(Dh)\rho V^2} \qquad \text{[Equation 3]}$$

The factor of safety, β_1, must be greater than 1.1. For g = 32.2 ft/sec^2, Cd = 0.5, and ρ = 62.4 lbf/ft^3, the maximum value of V as a function of the floodwater height h is given by

$$V = \sqrt{\frac{1.876\mu W^{*}}{Dh}} \qquad \text{[Equation 4]}$$

ii. Overturning Factor of Safety

For determining the margin of safety against overturning, β_2, the cask is assumed to pivot about a fixed point located at the outer edge of the contact circle at the interface between HI-STORM FW and the ISFSI. The overturning moment due to the hydraulic force F_T is balanced by a restoring moment from the buoyant weight acting at radius D/2.

Overturning moment, $M_o = Fh/2$ where F is given by Equation 1 above.

Restoring moment, M_r, = W* D/2 [Equation 5]

For stability against tipping $M_o \leq M_r$

or $Fh \leq W^*D$

Hence the factor of safety against overturning is

$$\beta_2 = \frac{W^* D}{F h} = \frac{W^* D}{Cd\, A\, V^* h} = \frac{2gW^*}{Cdh^2 \rho V^2} \qquad \text{[Equation 6]}$$

β_2 must be greater than 1.1. For g = 32.2 ft/sec^2, Cd = 0.5, and ρ = 62.4 lbf/ft^3, the maximum value of V as a function of the floodwater height h is given by

$$V = \frac{\sqrt{1.876 W^*}}{h} \qquad \text{[Equation 7]}$$

The smaller of the value of V from Equations 4 and 7 defines the maximum permissible flood velocity for the site. For the HI-STORM FW system, Equation 4 governs since the coefficient of friction (μ) is less than the smallest value of D/h for the limiting overpack geometry (maximum height). The numerical value of V is computed as follows:

From Tables 3.2.1 and 3.2.2 and the drawings in Section 1.5, the diameter and maximum height of the overpack are

D = 139 in = 11.6 ft

h = 240 in = 20.0 ft

From Tables 3.2.3 and 3.2.5, the minimum weight of the HI-STORM FW overpack with an empty MPC (based on Ref. PWR fuel length and 150 pcf concrete density) is

W = 254,600 lbf

Finally, assuming that W* = 0.87W, the acceptable upper bound flood velocity is determined from Equation 4 as

$$V = \sqrt{\frac{1.876(0.53)(0.87 \times 254{,}600)}{(11.6)(20.0)}} = 30.8\text{ft/sec}$$

3.4.4.1.2 Load Case 2: Design Basis Earthquake

In Subsection 2.2.3 (g), the combination of vertical and horizontal ZPA of the earthquake that would cause incipient loss of kinematic stability is derived using static equilibrium. The resulting inequality defines the threshold of the so-called low intensity earthquake for which the HI-STORM FW system is qualified without a dynamic analysis. However, an earthquake is a cyclic loading event which would produce rattling of the MPC inside the overpack and possibly large strains in the Confinement Boundary at the location of rattling impact between the MPC and the overpack guide tubes.

For earthquakes stronger than that defined by the inequalities in Subsection 2.2.3(g), it is necessary to perform a dynamic analysis. The dynamic stability analysis may be performed using either one of the following two approaches:

i. Using the nomographs developed in NUREG/CR-6865 [3.4.7] to predict the cask rotation and sliding.

ii. Performing a time history analysis for the cask modeled with 6 degrees-of-freedom and subjected to 3-dimensional seismic accelerations.

The first approach, although limited in its applications, is simple and conservative for the seismic stability evaluation of the HI-STORM FW storage cask as explained below. The nomograph developed in NUREG/CR-6865 [3.4.7] for cylindrical casks are based on extensive parametric study of the seismic response of HI-STORM 100 with a series of seismic inputs fitting three different spectral shapes. The seismic response is predicted through transient finite element analyses where the cask is supported on a flexible concrete pad founded on three substrates ranging from soft soil to rock. The NUREG study offers two sets of nomographs depending on the match of the site-specific free field horizontal spectrum with the three spectral shapes utilized in the study (after normalization to the Peak (Zero Period) Ground Acceleration (PGA)). The power law for the HI-STORM 100 response "y" (either peak cask top displacement or peak cask rotation) in terms of the ground motion parameter "x" at confidence band "m" standard deviations above the median response is:

$$y = A x^{B} \exp\left(m\, S_{Y|x}\right)$$

In the above equation, "A" and "B" are the nomograph curve fitting parameters, and "S" is the

conditional standard deviation of the result data after undergoing a logarithmic transformation. The value for "m" is 0 (for the median curve), +1 (for the 84% confidence level) and –1 (for the 16% confidence level). The units of "A" are meters (for displacement) and degrees (for rotation). The values for the coefficients are given below, as reproduced from [3.4.7]. The nomograph parameters are affected by the cask/pad coefficient of friction, but are independent of substrate stiffness.

Curve Fitting Parameters for Cylindrical Cask, NUREG/CR-0098 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.216	2.60	0.409	0.0217	0.689	0.718
μ=0.55	0.911	4.06	0.814	6.70	3.94	0.794
μ=0.8	1.150	4.16	0.796	9.01	4.09	0.765

Curve Fitting Parameters for Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.837	2.52	0.465	0.0733	1.71	0.785
μ=0.55	8.96	4.80	1.03	62.5	4.71	0.956
μ=0.8	15.4	5.04	1.13	114	4.94	1.12

Curve Fitting Parameters for Cylindrical Cask, NUREG/CR-6728 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.0897	1.88	0.377	0.0456	1.17	0.777
μ=0.55	0.219	2.63	0.543	1.64	2.53	0.583
μ=0.8	0.253	2.71	0.631	2.11	2.68	0.606

Curve Fitting Parameters for Cylindrical Cask, All Spectral Shapes, 1 Hz PSA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.271	2.15	0.532	0.0335	0.769	0.91
μ=0.55	0.979	3.20	1.07	7.07	3.10	1.04
μ=0.8	1.29	3.31	1.11	10.1	3.25	1.09

The use of the above nomographs for HI-STORM FW seismic stability analysis is conservative, as long as the h/r ratio (h = height to cask centroid, r = radius of the cask at interface with the pad) of HI-STORM FW is smaller than that of HI-STORM 100 cask, which is true in most cases. The nomographs should not be used when the substrate characteristics indicate that liquefaction will occur under a seismic event [3.4.7]. The basic analysis procedure is as follows:

i. Demonstrate that the cask h/r ratio is less than that of HI-STORM 100 cask. If this condition is not satisfied, this approach cannot be used for the seismic stability analysis.

ii. Evaluate the site-specific substrate data to ensure that the site-specific substrate is within the range considered in the NUREG and that there is no potential for soil liquefaction under a seismic event.

iii. Compare the site-specific horizontal free-field response spectrum for 5% damping with those employed in the NUREG (after normalizing the site-specific data to 1g).

   a. If the site-specific spectrum is a good match with one of the spectrums employed, then use the nomograph appropriate to the matched spectrum and site-specific input at the ZPA to predict cask displacement and rotation.

   b. If the site-specific spectrum is not a good match with any of the spectra, then use the nomograph developed for all spectra with site-specific input at 1 Hz and 5% damping to predict cask displacement and rotation.

If the previously described NUREG/CR-6865 approach is not appropriate to use for a specific ISFSI site, the second approach should be used to perform the seismic stability evaluation for HI-STORM FW casks. The time history analysis approach, which is free of the limitations associated with NUREG/CR-6865, was used and approved by the USNRC to demonstrate the seismic stability of HI-STORM 100 casks at the Private Fuel Storage ISFSI. The input seismic acceleration time histories shall meet the relevant requirements specified in the SRP 3.7.1 [3.4.8] and shall be baseline corrected.

Finally, a small clearance between the MPC and the MPC guide tubes may lead to a high localized strain in the region of the shell where impacts from rattling of the canister under a seismic event occur. The extent of local strain from impact is minimized by locating the guide tube in the vertical direction such that its impact footprint is aligned with the surface of the closure lid which has been shimmed to close the crevice between the lid and the shell. Thus the impact between the guide tubes and the MPC lid will occur at a location where the maximum damage to the MPC shell will be local denting in the region where it is buttressed by the edge of a (thick) MPC lid. Therefore, a through-wall damage of the MPC shell is not credible. Furthermore, the force of impact will evidently be greater in the non-mechanistic tip-over case. Therefore, the seismic impact case is designated as non-governing for the guide tube/MPC impact scenario.

3.4.4.1.3 Load Case 3: Tornado-Borne Projectiles

During a tornado event, the HI-STORM FW overpack and the HI-TRAC VW are assumed to be subjected to a constant wind force. They are also subject to impacts by postulated missiles. The maximum wind speed is specified in Table 2.2.4, and the three missiles, designated as large, intermediate, and small, are described in Table 2.2.5.

a. Large Missile

Overturning Analysis

The large tornado missile acting at the top region of the cask (HI-STORM FW or HI-TRAC VW) to produce maximum overturning effect (Table 3.1.1) is analyzed to determine whether the cask will remain stable. Because the site-specific large missile is apt to be different from the one analyzed

herein, the method of analysis presented here will provide the means for the site-specific safety evaluation pursuant to 10CFR72.212.

The overturning analysis of the cask under the tornado wind load and large missile impact is performed by solving the 1-DOF equation of motion for the cask angular rotation, which is same methodology used in the HI-STORM 100 FSAR (Docket No. 72-1014). Specifically, the solution of the post-impact dynamics problem is obtained by solving the following equation of motion:

$$I_r \alpha = \left(- W_c \frac{a}{2} \right) + F_{max} \left(\frac{L}{2} \right)$$

where:

I_r = cask moment of inertia about the pivot point
α = angular acceleration of the cask
W_c = lower bound weight of the cask
a = diameter of cask at its base (see Figure 3.4.7)
F_{max} = force on the cask due to tornado wind/instantaneous pressure drop
L = height of the cask (see Figure 3.4.7)

The impacting missile enters into the above through the post-strike angular velocity of the cask, which is the relevant initial condition for the cask equation of motion. The solution gives the post-impact position of the cask centroid as a function of time, which indicates whether the cask remains stable.

The following assumptions are made in the analysis:

i. The cask is assumed to be a rigid solid cylinder, with uniform mass distribution. This assumption implies that the cask sustains no plastic deformation (i.e. no absorption of energy through plastic deformation of the cask occurs).

ii. The angle of incidence of the missile is assumed to be such that its overturning effect on the cask is maximized (see Figure 3.4.7).

iii. The analysis considers the maximum height cask per Tables 3.2.1 and 3.2.2. The missile is assumed to strike at the highest point of the cask (see Figure 3.4.7), again maximizing the overturning effect.

iv. The cask is assumed to pivot about a point at the bottom of the base plate opposite the location of missile impact and the application of wind force in order to conservatively maximize the propensity for overturning (see Figure 3.4.7).

v. Inelastic impact is assumed, with the missile velocity reduced to zero after impact. This

assumption conservatively lets the missile impart the maximum amount of angular momentum to the cask, and it is in agreement with missile impact tests conducted by EPRI [3.4.14].

vi. The analysis is performed for a cask without fuel in order to provide a conservative solution. A lighter cask will tend to rotate further after the missile strike. The weight of the missile is not included in the total post-impact weight.

vii. Planar motion of the cask is assumed; any loads from out-of-plane wind forces are neglected.

viii. The drag coefficient for a cylinder in turbulent cross flow is used.

ix. The missile and wind loads are assumed to be perfectly aligned in direction.

The results for the post-impact response of the HI-STORM FW overpack and the HI-TRAC VW transfer cask are summarized in Table 3.4.5. The table shows that both casks remain in a vertical upright position (i.e., no overturning) in the aftermath of a large missile impact. The complete details of the tornado wind and large missile impact analyses for the HI-STORM FW overpack and the HI-TRAC VW transfer cask are provided in Appendix 3.A.

<u>Sliding Analysis</u>

A conservative calculation of the extent of sliding of the HI-STORM FW overpack and the HI-TRAC VW cask due to the impact of a large missile (Table 2.2.5) and tornado wind (Table 2.2.4) is obtained using a common formulation as explained below. A more realistic impact simulation using LS-DYNA, with less bounding assumptions, has been used in Subsection 3.4.4.1.4 to qualify the HI-STORM overpack for a non-mechanistic tip over event. While it is not necessary for demonstrating adequate safety margins for this problem, an LS-DYNA analysis could also be used to calculate the sliding potential of the HI-STORM FW and HI-TRAC VW for a large missile impact. In what follows, both HI-STORM FW and HI-TRAC VW are identified by the generic term "cask".

The principal assumptions that render these calculations for sliding conservative are:

i. The weight of the cask used in the analysis is assumed to be the lowest per Table 3.2.8.

ii. The cask is assumed to absorb the energy of impact purely by sliding. In other words, none of the impact energy is dissipated by the noise from the impact, from local plastic deformation in the cask at the location of impact, or from the potential tipping action of the cask.

iii. The missile impact and high wind, which applies a steady drag force on the cask, are assumed to act synergistically to maximize the movement of the cask.

iv. The cask is assumed to be freestanding on a concrete surface. The interface friction coefficient is assumed to be equal to that endorsed in the HI-STORM 100 FSAR (USNRC Docket No. 72-1014) and adopted here in the HI-STORM FW FSAR.

v. The dynamic effect of the impact is represented by the force-time curve developed in the Bechtel topical report "Design of Structures for Missile Impact" [3.4.9], previously used to qualify the HI-STORM 100 System (USNCR Docket No. 72-1014).

The analysis for sliding under the above assumptions reduces to solving Newton's equation of motion of the form:

$$m\frac{d^2x}{dt^2} = F(t) + F_{dp} - \mu mg$$

where

m: mass of the cask,

t: time coordinate with its origin set at the instant when the sum of the missile impact force and wind drag force overcomes the static friction force,

x: displacement as a function of time coordinate t,

$F(t)$: missile impact force as a function of time (from [3.4.9]),

F_{dp} : drag force from high wind,

μ: interface friction set as 0.53 for freestanding cask on a reinforced concrete pad in Docket No. 72-1014,

g: acceleration due to gravity.

The above second-order differential equation is solved numerically in [3.4.15] for the HI-STORM FW overpack and the HI-TRAC VW transfer cask, and the calculated sliding displacements are summarized in Table 3.4.16.

Referring to the spacing dimensions for HI-STORM FW arrays in Table 1.4.1, the minimum space between HI-STORM FW overpacks and the minimum distance of the overpack to the edge of the pad are calculated. The above table demonstrates the HI-STORM FW overpack will not collide with another overpack, and the overpack will not slide off the pad due to the combined effects of a large tornado missile impact and high wind.

No generic limits for sliding are established for the HI-TRAC VW. Therefore, the sliding result for the HI-TRAC VW transfer cask in Table 3.4.16 is strictly informational.

b. Small and Intermediate Missiles

The small and intermediate missiles (Table 2.2.5) are analyzed to determine the extent to which they will penetrate the HI-STORM FW overpack or the HI-TRAC VW and cause potential damage to the MPC Enclosure Vessel. Classical energy balance methods are used to compute the depth of penetration at the following impact locations:

- on the HI-STORM FW outer shell (with concrete backing)
- on the HI-STORM FW lid top plate (with concrete backing)
- on the HI-TRAC VW outer shell (with lead backing)
- on the top surface of the MPC upper lid

The MPC upper lid is analyzed for a direct missile impact because, when the MPC is placed inside the HI-TRAC VW, the MPC lid is theoretically accessible to a vertically downward directed small or intermediate missile.

The following assumptions are made in the analysis:

i. The intermediate missile and the small missile are assumed to be unyielding, and hence the entire initial kinetic energy is assumed to be absorbed by local yielding and denting of the cask surface.

ii. No credit is taken for the missile resistance offered by the HI-TRAC VW water jacket shell. It is assumed a priori that the small and intermediate missiles will penetrate the water jacket shell (with no energy loss). Therefore, in the analysis 100% of the missile impact energy is applied directly to the HI-TRAC VW outer shell.

iii. 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.

iv. 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 Appendix 3.B show 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 FW or the HI-TRAC VW. Therefore, the small missile will dent, but not penetrate, the cask. The 1-inch missile can enter the air inlet/outlet vents in the HI-STORM FW overpack, but geometry prevents a direct impact with the MPC.

For the intermediate missile, the analyses documented in Appendix 3.B 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 VW inner shell. Therefore, there will be no impairment to the Confinement Boundary due to

tornado-borne missile strikes. Furthermore, since the HI-STORM FW and HI-TRAC VW 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.

The penetration results for the small and intermediate missile are summarized in Table 3.4.6.

3.4.4.1.4 Load Case 4: Non-Mechanistic Tipover

The non-mechanistic tipover event, as described in Subsection 2.2.3(b), is site-dependent only to the extent that the stiffness of the target (ISFSI pad) affects the severity of the impact impulse. To bound the majority of ISFSI pad sites, the tipover analyses are performed using a stiff target foundation, which is defined in Table 2.2.9. The objectives of the analyses are to demonstrate that the plastic deformation in the fuel basket is sufficiently limited to permit the stored SNF to be retrieved by normal means and that there is no significant loss of radiation shielding in the storage system. Furthermore, the maximum lateral deflection of the lateral surface of the fuel basket is within the limit assumed in the criticality analyses (Chapter 6), and therefore, the lateral deflection does not have an adverse effect on criticality safety.

The tipover event is an artificial construct wherein the HI-STORM FW overpack is assumed to be perched on its edge with its C.G. directly over the pivot point A (Figure 3.4.8). 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.

In the following, an explicit expression for calculating the angular velocity of the cask at the instant when it impacts on the ISFSI pad is derived. Referring to Figure 3.4.8, let r be the length AC where C is the cask centroid. Therefore,

$$r = \left(\frac{d^2}{4} + h^2 \right)^{1/2}$$

The mass moment of inertia of the HI-STORM FW system, considered as a rigid body, can be written about an axis through point A, as

$$I_A = I_c + \frac{W}{g} r^2$$

where I_c is the mass moment of inertia about a parallel axis through the cask centroid C, and W is the weight of the cask (W = Mg).

Let $\theta_1(t)$ be the rotation angle between a vertical line and the line AC. The equation of motion for rotation of the cask around point A, during the time interval prior to contact with the ISFSI pad, is

$$I_A \frac{d^2 \theta_1}{dt^2} = Mgr \sin \theta_1$$

This equation can be rewritten in the form

$$\frac{I_A}{2} \frac{d(\dot{\theta}_1)^2}{d\theta_1} = Mgr \sin \theta_1$$

which can be integrated over the limits $\theta_1 = 0$ to $\theta_1 = \theta_{2f}$ (Figure 3.4.8). The final angular velocity θ_1 at the time instant just prior to contact with the ISFSI pad is given by the expression

$$\dot{\theta}_1(t_B) = \sqrt{\frac{2\,Mgr}{I_A}(1 - \cos \theta_{2f})}$$

where, from Figure 3.4.8,

$$\theta_{2f} = \cos^{-1}\left(\frac{d}{2r}\right)$$

This equation establishes the initial conditions for the final phase of the tip-over analysis; namely, the portion of the motion when the cask is decelerated by the resistive force at the ISFSI pad interface. Using the data germane to HI-STORM FW (Table 3.4.11) and the above equations, the angular velocity of impact is calculated as

$$\dot{\theta}_1(t_B) = 1.45 \text{ rad/sec}$$

The LS-DYNA analysis to characterize the response of the HI-STORM FW system under the non-mechanistic tipover event is focused on two principal demonstrations, namely:

(i) The lateral deformation of the basket panels in the active fuel region is less than the limiting value in Table 2.2.11.

(ii) The impact between the MPC guide tubes and the MPC does not cause a thru-wall penetration of the MPC shell.

Two LS-DYNA finite element models are developed to simulate the postulated tipover event of HI-STORM FW storage cask with loaded MPC-37 and MPC-89, respectively. The two LS-DYNA models are constructed according to the dimensions specified in the licensing drawings included in Section 1.5; the tallest configuration for each MPC type is considered to ensure a bounding tipover analysis. 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 LS-DYNA models of the HI-STORM FW overpack and the MPC are described in Subsections 3.1.3.1 and 3.1.3.2, respectively.

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 tipover analysis documented in the HI-STORM 100 FSAR [3.1.4]. 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 tipover event, is modeled as an elastic rectangular body). This is an improvement compared with the approach taken in the HI-STORM 100 tipover 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 modeled with solid elements. Each of the two LS-DYNA models consists of forty-two 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 tipover model consists of over 470,000 nodes and 255,000 elements for HI-STORM FW with loaded MPC-37, and the model for the cask with loaded MPC-89 consists of over 689,000 nodes and 350,000 elements.

The same ISFSI concrete pad material model used for the HI-STORM 100 tipover analysis reported in [3.1.4] is repeated for the HI-STORM FW tipover analysis. Specifically, the concrete pad behavior is characterized using the same LS-DYNA material model (i.e., MAT_PSEUDO_TENSOR or MAT_016) as for the end drop and tipover analyses of the HI-STORM 100 storage cask (the only difference between the HI-STORM FW reference ISFSI concrete pad model and the model of the HI-STORM 100 Set B ISFSI concrete pad is thickness). Moreover, the subgrade is also conservatively modeled as an elastic material as before. Note that this ISFSI pad material modeling approach was originally taken in the USNRC approved storage cask tipover and end drop LS-DYNA analyses [3.4.5] where a good correlation was obtained between the analysis results and the test results.

To assess the potential damage of the cask caused by the tipover accident, an LS-DYNA nonlinear material model with strain rate effect is used to model the responses of all HI-STORM FW 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 3.4.9 to 3.4.14 depict the two finite-element tipover analysis models developed for the bounding HI-STORM FW cask configurations with loaded MPC-37 and MPC-89, respectively.

As shown in Figure 3.4.15, the fuel basket does not experience any plastic deformation in the active fuel region; plastic deformation is limited locally in one periphery cell near the top of the basket beyond the active fuel region for both MPC-37 and MPC-89 baskets. The fuel basket is considered to be structurally safe since it can continue maintaining appropriate spacing between fuel assemblies after the tipover event. The MPC enclosure vessel experiences minor plastic deformation at the impact locations with the overpack guide tubes; the maximum local plastic strain (9.9%, see Figure 3.4.16) is well below the failure strain of the material and smaller than the plastic strain limit (i.e., at least 0.2 for stainless steel) recommended by [3.4.6] for ASME NB components. Similarly, local plastic deformation occurs in the overpack shear ring near the cask-to-pad impact location as shown in Figure 3.4.17. However, the shielding capacity of overpack will not be compromised by the tipover 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 tipover event, only a negligibly small plastic strain is observed in the bolt near the impact location (see Figure 3.4.18). Therefore, the cask lid will not dislodge after the tipover event. Finally, Figures 3.4.19 and 3.4.20 present the deceleration time history results of the cask lid predicted by LS-DYNA. The peak rigid body decelerations, measured for the HI-STORM FW lid concrete, are shown to be 61.75 g's in the vertical direction and 16.71 g's in the horizontal direction, respectively. 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 tipover analysis [3.1.4].

The structural integrity of the HI-STORM FW lid cannot be ascertained from the LS-DYNA tipover analyses since some components of the lid, namely the lid outer shell and the lid gussets, are defined as rigid members in order to simplify the modeling effort and maintain proper connectivity. Therefore, a separate tipover analysis has been performed for the HI-STORM FW lid using ANSYS, wherein a bounding peak rigid body deceleration established based on LS-DYNA tipover analysis results is statically applied to the lid. The finite element model is identical to the one used in Subsection 3.4.3 to simulate a vertical lift of the HI-STORM FW lid (Figure 3.4.5), except that the eight circumferential gussets are conservatively neglected (i.e., deleted from the finite element model).

The resulting stress distribution in the HI-STORM FW lid is shown in Figure 3.4.21. Per Subsection 2.2.3, the HI-STORM FW lid should not suffer any gross loss of shielding as a result of the non-mechanistic tipover event. To satisfy this criterion, the primary membrane stresses in the lid components are compared against the material yield strength. The most heavily loaded component is the upper shim plate closest to the point of impact (Figure 3.4.21). In order to determine the primary membrane stress in the upper shim plate, the stresses are linearized along a path that follows the outside vertical edge of the upper shim plate (see Figure 3.4.21 for path definition). Figure 3.4.22 shows the linearized stress results. Since the membrane stress is less than the yield strength of the material at 300ºF (Table 3.3.6), it is concluded that the lid will not suffer any gross loss of shielding

as a result of the non-mechanistic tipover event. The complete details of the lid tipover analysis are provided in [3.4.13].

Finally, to evaluate the potential for crack propagation and growth for the MPC fuel baskets under the non-mechanistic tipover event, a crack propagation analysis is carried out for the MPC-37 fuel basket using the same methodology utilized in Attachment D of [1.2.6] to evaluate the HI-STAR 180 F-37 fuel basket in support of the HI-STAR 180 SAR [3.1.10]. The crack propagation analysis for the MPC-37 is bounding for the MPC-89 fuel basket due to its smaller storage cell width, lower reference metal temperature, and lower fuel assembly weight (see Table 3.4.13).

To begin the analysis, the stress distribution in the MPC-37 fuel basket is determined by implementing the fuel basket finite element model (see Subsection 3.1.3) in ANSYS and performing a static stress analysis of the fuel basket structure for a bounding load of 65-g. The resulting stress distribution in the horizontally oriented Metamic-HT basket panels is shown in Figure 3.4.36. The maximum stress occurs at one of the basket notches, which are conservatively modeled as sharp (90 degree) corners in the finite element model. This peak stress is used as input to the following crack propagation analysis.

Per [1.2.6] the critical stress intensity factor of Metamic-HT panels is estimated to be

$$K_{IC} = 30 ksi\sqrt{in}$$

based on Charpy V-notch absorbed energy (CVE) correlations for steels. The estimated value is consistent with the range for aluminum alloys, which is 20 to 50 $MPa\sqrt{m}$ or 18.2 to 45 $ksi\sqrt{in}$ per Table 3 of [3.4.19]. Next the minimum crack size, a_{min}, for crack propagation to occur is calculated below using the formula for a through-thickness edge crack given in [3.1.5]. Although the formula is derived for a straight-edge specimen, the use of the peak stress, σ_{max}, at a notch in the fuel basket panel (instead of the average stress in the panel as required by the formula) essentially compensates for the geometric difference between the basket panel and the specimen. Moreover, the maximum size of a pre-existing crack (1/16”) in the fuel basket panel is less than 1/9th of the basket panel thickness (0.59”). Thus, the assumption of a through-thickness edge crack is very conservative. The result is

$$a_{\min} = \frac{\left(\dfrac{K_{IC}}{1.12\sigma_{\max}}\right)^2}{\pi} = \frac{\left[\dfrac{30ksi\sqrt{in}}{1.12(17.98ksi)}\right]^2}{\pi} = 0.706in$$

And the safety factor against crack propagation (based on a 1/16” minimum detectable flaw size) is

$$SF = \frac{a_{\min}}{a_{\det}} = \frac{0.706in}{0.0625in} = 11.3$$

The calculated minimum crack size is more than 11 times greater than the maximum possible pre-existing crack size in the fuel basket (based on 100% surface inspection of each panel). The large safety factor ensures that crack propagation in the HI-STORM FW fuel baskets will not occur due to the non-mechanistic tipover event.

3.4.4.1.5 Load Case 5: Design Internal Pressure

The MPC Enclosure Vessel, which is designed to meet the stress intensity limits of ASME Subsection NB [3.4.4], is analyzed for design internal pressure (Table 2.2.1) using the ANSYS finite element code [3.4.1]. Except for the applied loads and the boundary conditions, the finite element model of the MPC Enclosure Vessel used for this load case is identical to the model described in Subsections 3.1.3.2 and 3.4.3.2 for the MPC lifting analysis.

The only load applied to the finite element model for this load case is the MPC design internal pressure for normal conditions (Table 2.2.1). All internal surfaces of the MPC storage cavity are subjected to the design pressure. The center node on the top surface of the MPC upper lid is fixed against translation in all directions. Symmetric boundary conditions are applied to the two vertical symmetry planes. This set of boundary conditions allows the MPC Enclosure Vessel to deform freely under the applied pressure load. Figure 3.4.31 graphically depicts the applied pressure load and the boundary conditions for Load Case 5.

The stress intensity distribution in the MPC Enclosure Vessel under design internal pressure is shown in Figure 3.4.23. Figures 3.4.32 and 3.4.33 plot the thru-thickness variation of the stress intensity at the baseplate center and at the baseplate-to-shell juncture, respectively. The maximum primary and secondary stress intensities in the MPC Enclosure Vessel are compared with the applicable stress intensity limits from Subsection NB of the ASME Code. The allowable stress intensities are taken at 450°F for the MPC shell and MPC lids, 300°F for the baseplate, and 250°F at the baseplate-to-shell juncture. The maximum calculated stress intensities in the MPC Enclosure Vessel, and their corresponding allowable limits, are summarized in Table 3.4.7 for Load Case 5.

Since the stress intensity distribution in the MPC Enclosure Vessel is a linear function of the internal pressure, and the stress intensity limits for normal and off-normal conditions are the same (Table 3.1.7), the minimum calculated safety factor from Table 3.4.7 is used to establish the internal pressure limit for off-normal conditions (Table 2.2.1).

3.4.4.1.6 Load Case 6: Maximum Internal Pressure Under Accident Conditions

The maximum pressure in the MPC Enclosure Vessel under accident conditions is specified in Table 2.2.1. The stress analysis under this pressure condition uses the same model as the one described in the preceding subsection. The only change is the magnitude of the applied pressure. Figure 3.4.34 graphically depicts the applied pressure load and the boundary conditions for Load Case 6.

The stress intensity distribution in the MPC Enclosure Vessel under accident internal pressure is

shown in Figure 3.4.24. The maximum primary stress intensities in the MPC Enclosure Vessel are compared with the applicable stress intensity limits from Subsection NB of the ASME Code [3.4.4]. The allowable stress intensities are taken at 450°F for the MPC shell and MPC lids, 300°F for the baseplate, and 250°F at the baseplate-to-shell juncture. These temperatures bound the calculated temperatures under normal operating conditions for the respective MPC components based on the thermal evaluations in Chapter 4. The allowable stress intensities are determined based on normal operating temperatures since the MPC accident internal pressure is dictated by the 100% fuel rod rupture accident, which does not cause any significant rise in MPC temperatures. In fact, the temperatures inside the MPC tend to decrease as a result of the 100% fuel rod rupture accident due to the increase in the density and internal pressure of the circulating gas. The maximum calculated stress intensities in the MPC Enclosure Vessel, and their corresponding allowable limits, are summarized in Table 3.4.8 for Load Case 6.

3.4.4.1.7 Load Case 7: Accident External Pressure

The only affected component for this load case is the MPC Enclosure Vessel. The accident external pressure (Table 2.2.1) is selected sufficiently high to envelop hydraulic-pressure in the case of flood or explosion-induced pressure at all ISFSI Sites.

The main effect of an external pressure on the MPC is to cause compressive stress in the MPC shell. Therefore, the potential of buckling must be investigated. The methodology used for this investigation is from ASME Code Case N-284-2 (Metal Containment Shell Buckling Design Methods, Section III, Division 1, Class MC (1/07)). This Code Case has been previously used by Holtec in [3.1.4] and accepted by the NRC as a valid method for evaluation of stability in vessels.

The detailed evaluation of the MPC shell under accident external pressure is provided in Appendix 3.C. It is concluded that positive safety margins exist so that elastic or plastic instability of the maximum height MPC shell does not occur under the applied pressure.

3.4.4.1.8 Load Case 8: Non-Mechanistic Heat-Up of the HI-TRAC VW Water Jacket

Even though the analyses presented in Chapter 4 indicate that the temperature of water in the water jacket shall not reach boiling and the rupture disks will not open, it is (non-mechanistically) assumed that the hydraulic pressure in the water jacket reaches the relief devices' set point. The object of this analysis is to demonstrate that the stresses in the water jacket and its welds shall be below the limits set down in an appropriate reference ASME Boiler and Pressure Vessel Code (Section II Class 3) for the Level D service condition. The accident pressure inside the water jacket is given in Table 2.2.1.

The HI-TRAC VW water jacket is analyzed using classical strength-of-materials. Specifically, the unsupported span of the water jacket shell between radial ribs is treated as a curved beam, with clamped ends, under a uniformly distributed radial pressure. The force and moment reactions at the ends of the curved beam for this type of loading are calculated using the formula for Case 5j of Table 18 in [3.4.16]. The primary membrane plus bending stress is then calculated using the formula for Case 1 of Table 16 in [3.4.16]. Figure 3.4.35 depicts the curved beam model that is used to analyze

the water jacket shell and defines the key input variables. The input values that are used in the calculations are provided in Table 3.4.12.

The bottom flange, which serves as the base of the water jacket, is conservatively analyzed as an annular plate clamped at the water jacket inside diameter and simply supported at the water jacket outside diameter. The maximum bending stress in the bottom flange is calculated using the following formula from [3.4.18, Art. 23]:

$$\sigma_{max} = k \frac{q \cdot a^2}{h^2}$$

where q is the internal pressure inside the water jacket (= 73.65 psi), a is the outside radius of the water jacket (= 47.5 in), and h is the thickness of the bottom flange (= 2.0 in). The analyzed pressure accounts for the accident internal pressure inside the water jacket (Table 2.2.1) plus the hydrostatic pressure at the base of the water jacket. The value of k is dependent on the diameter ratio of the annular plate and the boundary conditions. Per Table 5 of [3.4.18], k is equal to 0.122 for a bounding diameter ratio of 1.25 and simply supported-clamped boundary conditions (Case 4). Therefore, the maximum bending stress in the bottom flange is:

$$\sigma_{max} = 5{,}068 \text{ psi}$$

Per Table 3.1.6, the allowable primary membrane plus bending stress intensity for SA-516 Gr. 70 material (at 400ºF) is 58,500 psi, which means the factor of safety is greater than 10.

The maximum stresses in the various water jacket components, including the connecting welds, are summarized in Table 3.4.9.

3.4.4.1.9 Load Case 9: Handling of Components

The stress analyses of the MPC, the HI-STORM FW overpack, and the HI-TRAC VW transfer cask under normal handling conditions are presented in Subsection 3.4.3.

3.4.4.1.10 Load Case 10: Snow Load

In accordance with Table 3.1.1, the HI-STORM FW lid is analyzed using ANSYS to demonstrate that the design basis snow load (Table 2.2.8) does not cause stress levels in the overpack lid to exceed ASME Subsection NF stress limits for Level A. The finite element model is identical to the one used in Subsection 3.4.3 to simulate a vertical lift of the HI-STORM FW lid (see Figure 3.4.5). For conservatism, a pressure load of 10 psig is used in the finite element analysis. The stress distribution in the lid under the bounding snow load is shown in Figure 3.4.25. The maximum stress results are summarized in Table 3.4.10. For conservatism, the maximum calculated stress at any point on the lid, including secondary stress contributions, is compared against the primary membrane and primary bending stress limits per ASME Subsection NF.

3.4.4.1.11 Load Case 11: MPC Reflood Event

During a MPC reflood event, water is introduced to the MPC cavity through the lid drain line to cooldown the MPC internals and support fuel unloading. This quenching operation induces thermal stresses and strains in the fuel rod cladding, which are maximum at the boundary interface between the rising water and the dry (gaseous) cavity. The following analysis demonstrates that the maximum total strain in the fuel cladding due to the reflood event is well below the failure strain limit of the material. Thus, the fuel rod cladding will not be breached due to the MPC reflood event.

The analysis is carried out using the finite element code ANSYS [3.4.1]. The model, which is shown in Figure 3.4.37, is constructed using 4-node plastic large strain elements (SHELL43) based on the cladding dimensions of the PWR reference fuel type. The overall length of the model is equal to 30 times the outside diameter of the fuel cladding. As seen in Figure 3.4.37, the mesh size is reduced at the boundary between the wetted fuel rod and the dry fuel rod, where the highest stresses and strains occur. To account for the gas pressure inside the fuel rod, the top end of the fuel rod is fixed in the vertical direction, and an equivalent axial force is applied at the bottom end. A radial pressure is also applied to the inside surface of the fuel cladding (see Figure 3.4.38). The fuel cladding material is modeled as a bi-linear isotropic hardening material with temperature dependent properties. The key input data used to develop the finite element model are summarized in Table 3.4.14.

The MPC reflood pressure, which is restricted to below the normal condition pressure limit, is too low to have and adverse effect on the fuel cladding, the reflood water pressure acts to produce compressive hoop stresses which help reduce the tensile hoop stress (albeit by a small amount) from the internal gas pressure in the rods. Therefore, the MPC flooding pressure has no harmful consequence to the fuel cladding and is neglected in the analysis.

At t = 0 sec, the uniform temperature throughout the entire fuel rod is set at 752ºF (400ºC), which equals the fuel cladding temperature limit under normal operating conditions. At t = 0.1 sec, the temperature assigned to the lower half of the fuel rod model is suddenly reduced to 80ºF to simulate the water quenching (see Figure 3.4.39). The resulting stress and strain distributions in the fuel rod are shown in Figures 3.4.40 and 3.4.41, respectively. The maximum stress and strain values are summarized in Table 3.4.15. The maximum total strain in the fuel rod is well below the failure strain limit of 1.7% for the cladding material per [3.4.20]. In fact, the maximum stress and strain in the fuel rod remain in the elastic range.

The analysis described above makes a number of assumptions that significantly overstate the computed thru-wall strain in the fuel cladding. The major assumptions are:

1. Even though the peak cladding temperature occurs at a localized location, the fuel rod is modeled as a pressurized tube with closed ends at a uniform temperature that is greater than the maximum peak cladding temperature value reported in Chapter 4 when the MPC is in the HI-TRAC under the Design Basis heat load condition.
2. The rapid thermal straining of the pressurized tube (fuel rod) due to the quenching effect of water is simulated as a step transient wherein the temperature of the quenched portion of the

tube is assumed to drop down to the injected water temperature (assumed to be 80ºF) causing a step change in the cladding wall temperature in the longitudinal direction at its interface with the "dry" portion of the tube. This assumption is extremely conservative because in actuality the immersed portion of the fuel rod is blanketed by vapor which acts to retard the severity of the thermal transient.

3. Even though, as the rod is gradually immersed in water, the axial heat conduction will tend to cool the un-immersed portion of the tube thus reducing the ΔT at the quenched/dry interface, no credit for axial conduction is taken.
4. The cooling of the fuel rod by gradual immersion in the water has the beneficial effect of reducing the internal pressure (per the ideal gas law) and thus the magnitude of pressure induced stress in the fuel cladding. As the peak cladding temperature in the MPC is reached in the upper half of the fuel rods (see Chapter 4), a substantial amount of rod is cooled by water (as its level gradually rises inside the MPC) before the vulnerable zone (where the peak cladding temperature exists) is subjected to the thermal transient from quenching. No credit for this amelioration of the pressure stresses due to the gradual cooling of the rod is taken in the analysis.

In summary, even though the analysis presented above is highly conservative, the maximum stress and strain in the fuel rod remain elastic. Moreover, the maximum strain is less than the failure strain limit by a factor of 6. Thus, the MPC reflood event will not cause a breach of the fuel rod cladding.

3.4.5 Cold

A discussion of the resistance to failure due to brittle fracture is provided in Subsection 3.1.2.

The value of the ambient temperature has two principal effects on the HI-STORM FW system, namely:

i. The steady-state temperature of all material points in the cask system will go up or down by the amount of change in the ambient temperature.

ii. As the ambient temperature drops, the absolute temperature of the contained helium will drop accordingly, producing a proportional reduction in the internal pressure in accordance with the Ideal Gas Law.

In other words, the temperature gradients in the system under steady-state conditions will remain the same regardless of the value of the ambient temperature. The internal pressure, on the other hand, will decline with the lowering of the ambient temperature. Since the stresses under normal storage condition arise principally from pressure and thermal gradients, it follows that the stress field in the MPC under –40 degree F ambient would be smaller than the "heat" condition of storage, treated in the preceding subsection. Additionally, the allowable stress limits tend to increase as the component temperatures decrease.

Therefore, the stress margins computed in Subsection 3.4.4 can be conservatively assumed to apply to the "cold" condition as well.

Finally, it can be readily shown that the HI-STORM FW system is engineered to withstand “cold” temperatures (-40 degrees F) without impairment of its storage function.

Unlike the MPC, the HI-STORM FW storage overpack is an open structure; it contains no pressure. Its stress field is unaffected by the ambient temperature, unless low temperatures produce brittle fracture due to the small stresses which develop from self-weight of the structure and from the minute difference in the thermal expansion coefficients in the constituent parts of the equipment (steel and concrete). To prevent brittle fracture, all steel material in HI-STORM FW is qualified by impact testing pursuant to the ASME Code (Table 3.1.9).

The structural material used in the MPC (Alloy X) is recognized to be completely immune from brittle fracture in the ASME Codes.

As no liquids are included in the HI-STORM FW storage overpack design, loads due to expansion of freezing liquids are not considered. The HI-TRAC VW transfer cask utilizes demineralized water in the water jacket. However, the specified lowest service temperature for the HI-TRAC VW is 0 degrees F and a 25% ethylene glycol solution is required for the temperatures from 0 degrees F to 32 degrees F. Therefore, loads due to expansion of freezing liquids are not considered.

There is one condition, however, that does require examination to ensure ready retrievability of the fuel. Under a postulated loading of an MPC from a HI-TRAC VW transfer cask into a cold HI-STORM FW storage overpack, it must be demonstrated that sufficient clearances are available to preclude interference when the “hot” MPC is inserted into a “cold” storage overpack. To this end, a bounding analysis for free thermal expansions has been performed in Subsection 4.4.6, wherein the MPC shell is postulated at its maximum design basis temperature and the thermal expansion of the overpack is ignored. The results from the evaluation of free thermal expansion are summarized in Table 4.4.6. The final radial clearance is sufficient to preclude jamming of the MPC upon insertion into a cold HI-STORM FW storage overpack.

3.4.6 Miscellaneous Evaluations

3.4.6.1 Structural Integrity of Damaged Fuel Containers (DFCs)

The Damaged Fuel Container (DFC) is used to store fuel that is physically impaired such that it cannot be handled by normal means. The DFC, as shown in the licensing drawings, is equipped with a handle welded to a square cellular box with a perforated baseplate structurally capable of supporting the weight of the fuel while permitting water (but not particulates) to pass through. All load bearing members of the DFC are designed to meet Level A service limit when holding a spent fuel assembly.

Because the DFC is always handled under water, there are no radiation release-related issues

associated with it.

3.4.7 Service Life of HI-STORM FW and HI-TRAC VW

The term of the 10CFR72, Subpart L C of C, granted by the NRC is 20 years; therefore, the License Life (see Glossary) of all components is 20 years. Nonetheless, the HI-STORM FW storage overpack and the HI-TRAC VW transfer cask are engineered for 60 years of design life, while satisfying the conservative design requirements defined in Chapter 2, including the regulatory requirements of 10CFR72. In addition, the storage overpack and HI-TRAC VW are designed, fabricated, and inspected under the comprehensive Quality Assurance Program approved by the USNRC and in accordance with the applicable requirements of the ACI and ASME Codes. This assures high design margins, high quality fabrication, and verification of compliance through rigorous inspection and testing, as described in Chapter 10 and the licensing drawings in Section 1.5. Technical Specifications defined in Chapter 13 assure that the integrity of the cask and the contained MPC are maintained throughout the components' design life. The design life of a component, as defined in the Glossary, is the minimum duration for which the equipment or system is engineered to perform its intended function if operated and maintained in accordance with the FSAR. The design life is essentially the lower bound value of the service life, which is the expected functioning life of the component or system. Therefore, component longevity should be: licensed life < design life < service life. (The licensed life, enunciated by the USNRC, is the most pessimistic estimate of a component’s life span). For purposes of further discussion, we principally focus on the service life of the HI-STORM FW system components that, as stated earlier, is the reasonable expectation of equipment’s functioning life span.

The service life of the storage overpack and HI-TRAC VW transfer cask is further discussed in the following.

3.4.7.1 Storage Overpack

The principal design considerations that bear on the adequacy of the storage overpack for the service life are addressed as follows:

<u>Exposure to Environmental Effects</u>

All exposed surfaces of the HI-STORM FW overpack are made from ferritic steels that are readily painted. Concrete, which serves strictly as a shielding material, is completely encased in steel. Therefore, the potential of environmental vagaries such as spalling of concrete, are ruled out for HI-STORM FW. Under normal storage conditions, the bulk temperature of the HI-STORM FW storage overpack will, because of its large thermal inertia, change very gradually with time. Therefore, material degradation from rapid thermal ramping conditions is not credible for the HI-STORM FW storage overpack. Similarly, corrosion of structural steel embedded in the concrete structures due to salinity in the environment at coastal sites is not a concern for HI-STORM FW because HI-STORM FW does not rely on rebars (indeed, it contains no rebars). As discussed in Appendix 1.D of HI-STORM 100 FSAR, the aggregates, cement and water used in the storage cask concrete are carefully

controlled to provide high durability and resistance to temperature effects. The configuration of the storage overpack assures resistance to freeze-thaw degradation. In addition, the storage overpack is specifically designed for a full range of enveloping design basis natural phenomena that could occur over the 60-year design life of the storage overpack as defined in Subsection 2.2.3 and evaluated in Chapter 12. Chapter 8 provides further discussions on chemical and galvanic reactions, material compatibility and operating environments.

Material Degradation

As discussed in Chapter 8, the relatively low neutron flux to which the storage overpack is subjected cannot produce measurable degradation of the cask's material properties and impair its intended safety function. Exposed carbon steel components are coated to prevent corrosion. The controlled environment of the ISFSI storage pad mitigates damage due to direct exposure to corrosive chemicals that may be present in other industrial applications.

Maintenance and Inspection Provisions

The requirements for periodic inspection and maintenance of the storage overpack throughout the 60-year design life are defined in Chapter 10. These requirements include provisions for routine inspection of the storage overpack exterior and periodic visual verification that the ventilation flow paths of the storage overpack are free and clear of debris. ISFSIs located in areas subject to atmospheric conditions that may degrade the storage cask or canister should be evaluated by the licensee on a site-specific basis to determine the frequency for such inspections to assure long-term performance. In addition, the HI-STORM FW system is designed for easy retrieval of the MPC from the storage overpack should it become necessary to perform more detailed inspections and repairs on the storage overpack.

The above findings are consistent with those of the NRC's Waste Confidence Decision Review [3.4.10], which concluded that dry storage systems designed, fabricated, inspected, and operated in accordance with such requirements are adequate for a 100-year service life while satisfying the requirements of 10CFR72.

3.4.7.2 Transfer Cask

The principal design considerations that bear on the adequacy of the HI-TRAC VW transfer cask for the service life are addressed as follows:

Exposure to Environmental Effects

All transfer cask materials that come in contact with the spent fuel pool are coated to facilitate decontamination. The HI-TRAC VW is designed for repeated normal condition handling operations with high factor of safety to assure structural integrity. The resulting cyclic loading produces stresses that are well below the endurance limit of the cask's materials, and therefore, will not lead to a fatigue failure in the transfer cask. All other off-normal or postulated accident conditions are

infrequent or one-time occurrences that do not contribute significantly to fatigue. In addition, the transfer cask utilizes materials that are not susceptible to brittle fracture during the lowest temperature permitted for loading, as discussed in Subsection 8.4.3.

Chapter 8 provides further discussions on chemical and galvanic reactions, material compatibility and operating environments.

Material Degradation

As discussed in Chapter 8, all transfer cask materials that are susceptible to corrosion are coated. The controlled environment in which the HI-TRAC VW is used mitigates damage due to direct exposure to corrosive chemicals that may be present in other industrial applications. The infrequent use and relatively low neutron flux to which the HI-TRAC VW materials are subjected do not result in radiation embrittlement or degradation of the HI-TRAC's shielding materials that could impair the HI-TRAC's intended safety function. The HI-TRAC VW transfer cask materials are selected for durability and wear resistance for their deployment.

Maintenance and Inspection Provisions

The requirements for periodic inspection and maintenance of the HI-TRAC VW transfer cask throughout the 60-year design life are defined in Chapter 10. These requirements include provisions for routine inspection of the HI-TRAC VW transfer cask for damage prior to each use, including an annual inspection of the lifting attachments. Precautions are taken during lid handling operations to protect the sealing surfaces of the bottom lid. The leak tightness of the liquid neutron shield is verified periodically. The water jacket pressure rupture discs and other fittings used can be easily removed.

3.4.8 MPC Service Life

The term of the 10CFR72, Subpart L C of C, granted by the NRC (i.e., licensed life) is 20 years. Nonetheless, the HI-STORM FW MPCs are designed for 60 years of design life, while satisfying the conservative design requirements defined in Chapter 2, including the regulatory requirements of 10CFR72. Additional assurance of the integrity of the MPC and the contained SNF assemblies throughout the 60-year life of the MPC is provided through the following:

- Design, fabrication, and inspection invoke the pertinent requirements of the ASME Code, as applicable, assures high inherent design margins in operating modes.

- Fabrication and inspection performed in accordance with the comprehensive Quality Assurance program assures competent compliance with the fabrication requirements.

- Use of materials with known characteristics, verified through rigorous inspection and testing, as described in Chapter 10, assures component compliance with design requirements.

- Use of welding procedures in full compliance with Section III of the ASME Code ensures high-quality weld joints.

Technical Specifications, as defined in Chapter 13, have been developed and imposed on the MPC that assure that the integrity of the MPC and the contained SNF assemblies are maintained throughout the 60-year design life of the MPC.

The principal design considerations bearing on the adequacy of the MPC for the service life are summarized below.

Corrosion

All MPC materials are fabricated from corrosion-resistant austenitic stainless steel and passivated aluminum. The corrosion-resistant characteristics of such materials for dry SNF storage canister applications, as well as the protection offered by these materials against other material degradation effects, are well established in the nuclear industry. The moisture in the MPC is removed to eliminate all oxidizing liquids and gases and the MPC cavity is backfilled with dry inert helium at the time of closure to maintain an atmosphere in the MPC that provides corrosion protection for the SNF cladding throughout the dry storage period. The preservation of this non-corrosive atmosphere is assured by the inherent sealworthiness of the MPC Confinement Boundary integrity (there are no gasketed joints in the MPC).

Structural Fatigue

The passive non-cyclic nature of dry storage conditions does not subject the MPC to conditions that might lead to structural fatigue failure. Ambient temperature and insolation cycling during normal dry storage conditions and the resulting fluctuations in MPC thermal gradients and internal pressure is the only mechanism for fatigue. These low-stress, high-cycle conditions cannot lead to a fatigue failure of the MPC that is made from stainless alloy stock (endurance limit well in excess of 20,000 psi). All other off-normal or postulated accident conditions are infrequent or one-time occurrences, which cannot produce fatigue failures. Finally, the MPC uses materials that are not susceptible to brittle fracture.

Maintenance of Helium Atmosphere

The inert helium atmosphere in the MPC provides a non-oxidizing environment for the SNF cladding to assure its integrity during long-term storage. The preservation of the helium atmosphere in the MPC is assured by the robust design of the MPC Confinement Boundary described in Section 7.1. Maintaining an inert environment in the MPC mitigates conditions that might otherwise lead to SNF cladding failures. The required mass quantity of helium backfilled into the canister at the time of closure and the associated fabrication and closure requirements for the canister are specifically set down to assure that an inert helium atmosphere is maintained in the canister throughout the 60-year design life.

Allowable Fuel Cladding Temperatures

The helium atmosphere in the MPC promotes heat removal and thus reduces SNF cladding temperatures during dry storage. In addition, the SNF decay heat will substantially attenuate over a 60-year dry storage period. Maintaining the fuel cladding temperatures below allowable levels during long-term dry storage mitigates the damage mechanism that might otherwise lead to SNF cladding failures. The allowable long-term SNF cladding temperatures used for thermal acceptance of the MPC design are conservatively determined, as discussed in Section 4.3.

Neutron Absorber Boron Depletion

The effectiveness of the fixed borated neutron absorbing material used in the MPC fuel basket design requires that sufficient concentrations of boron be present to assure criticality safety during worst case design basis conditions over the 60-year design life of the MPC. Information on the characteristics of the borated neutron absorbing material used in the MPC fuel basket is provided in Subsection 1.2.1 and Chapter 8. The relatively low neutron flux, to which this borated material is subjected and will continue to decay over time, does not result in significant depletion of the material's available boron to perform its intended safety function. In addition, the boron content of the material used in the criticality safety analysis is conservatively based on the minimum specified boron areal density (rather than the nominal), which is further reduced by 25% for analysis purposes, as described in Section 6.1. Analysis discussed in Section 6.3 demonstrates that the boron depletion in the neutron absorber material is negligible over a 60-year duration. Thus, sufficient levels of boron are present in the fuel basket neutron absorbing material to maintain criticality safety functions over the 60-year design life of the MPC.

The above findings are consistent with those of the NRC's Waste Confidence Decision Review, which concluded that dry storage systems designed, fabricated, inspected, and operated in the manner of the requirements set down in this document are adequate for a 100-year service life, while satisfying the requirements of 10CFR72.

3.4.9 Design and Service Life

The discussion in the preceding sections seeks to provide the logical underpinnings for setting the design life of the storage overpacks, the HI-TRAC VW transfer cask, and the MPCs as sixty years. Design life, as stated earlier, is a lower bound value for the expected performance life of a component (service life). If operated and maintained in accordance with this Safety Analysis Report, Holtec International expects the service life of HI-STORM FW casks to substantially exceed their design life values.

Table 3.4.1

STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL – NORMAL HANDLING

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Lid – Primary Membrane Stress Intensity	6.94	18.05	2.60
Lid – Local Membrane Plus Primary Bending Stress Intensity	6.94	27.1	3.90
Baseplate – Primary Membrane Stress Intensity	8.32	20.0	2.40
Baseplate – Local Membrane Plus Primary Bending Stress Intensity	21.8	30.0	1.38
Shell – Primary Membrane Stress Intensity	13.14	18.05	1.37
Shell – Local Membrane Plus Primary Bending Plus Secondary Stress Intensity	56.50	60.0	1.06

Table 3.4.2 STRESS RESULTS FOR HI-TRAC VW – NORMAL HANDLING			
Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Top Flange-to-Inner/Outer Shell Weld – Primary Shear Stress	5.79	17.4	3.01
Inner/Outer Shell – Primary Membrane Stress	1.72	19.6	11.4
Bottom Lid Bolts – Tensile Stress	9.27	41.2	4.44
Bottom Lid – Primary Bending Stress	3.80	30.0	7.90

Table 3.4.3

STRESS RESULTS FOR HI-STORM FW – NORMAL HANDLING

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Inner/Outer Shell – Primary Membrane Stress	1.92	20.0	10.4
Inner/Outer Shell – Primary Membrane Plus Bending Stress	3.42	30.0	8.77
Baseplate – Primary Membrane Stress	1.97	20.0	10.2
Baseplate – Primary Membrane Plus Bending Stress	3.42	30.0	8.77
Lifting Rib – Primary Membrane Stress	4.79	20.0	4.18
Lifting Rib – Primary Membrane Plus Bending Stress	6.22	30.0	4.82
Shell-to-Baseplate Weld – Primary Shear Stress	4.56	21.0	4.60

Table 3.4.4

STRESS RESULTS FOR HI-STORM FW LID –
NORMAL HANDLING

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Maximum Primary Membrane Stress	1.57	16.6	10.6
Maximum Primary Membrane Plus Bending Stress	1.57	24.9	15.9

Table 3.4.5

CASK ROTATIONS DUE TO LARGE MISSILE IMPACT

Event	Calculated Value (deg)	Allowable Limit (deg)	Safety Factor
Missile Impact plus Tornado Wind on HI-STORM FW	3.37	30.3	8.99
Missile Impact plus Pressure Drop on HI-STORM FW	3.91	30.3	7.75
Missile Impact plus Tornado Wind on HI-TRAC VW	14.40	23.6	1.64
Missile Impact plus Pressure Drop on HI-TRAC VW	12.32	23.6	1.92

Table 3.4.6

MISSILE PENETRATION RESULTS – SMALL AND INTERMEDIATE MISSILE

Missile Type – Impact Location	Calculated Value (in)	Allowable Limit (in)	Safety Factor
Small Missile – All Impact Locations	< 0.4 in	> 0.5 in (MPC shell thickness)†	> 1.25
Intermediate Missile – Side Strike on HI-STORM FW Outer Shell (away from Inlet)	8.39	29.00	3.46
Intermediate Missile – Side Strike on HI-STORM FW Outer Shell (at Inlet)	11.69	24.00	2.05
Intermediate Missile – End Strike on HI-STORM FW Lid	10.46	19.25	1.84
Intermediate Missile – Side Strike on HI-TRAC VW Outer Shell	0.50	1.50	3.00
Intermediate Missile – End Strike on MPC Closure Lid	0.23	9.00	39.13

† In reality, a maximum velocity impact between the small projectile missile and the MPC shell is not credible due to the geometry of the HI-STORM FW inlet and outlet vents (i.e., no direct line of sight).

Table 3.4.7

STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL –
DESIGN INTERNAL PRESSURE

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Lid – Primary Membrane Stress Intensity	5.98	18.05	3.02
Lid – Local Membrane Plus Primary Bending Stress Intensity	5.98	27.1	4.53
Baseplate – Primary Membrane Stress Intensity	7.12	20.0	2.81
Baseplate – Local Membrane Plus Primary Bending Stress Intensity	18.65	30.0	1.61
Shell – Primary Membrane Stress Intensity	11.50	18.05	1.57
Shell – Local Membrane Plus Primary Bending Plus Secondary Stress Intensity	50.10	60.0	1.20

Table 3.4.8

STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL – ACCIDENT INTERNAL PRESSURE

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Lid – Primary Membrane Stress Intensity	11.97	43.3	3.62
Lid – Local Membrane Plus Primary Bending Stress Intensity	11.97	64.95	5.43
Baseplate – Primary Membrane Stress Intensity	14.25	46.3	3.25
Baseplate – Local Membrane Plus Primary Bending Stress Intensity	37.29	69.45	1.86
Shell – Primary Membrane Stress Intensity	22.99	43.3	1.88

Table 3.4.9

STRESS RESULTS FOR HI-TRAC VW WATER JACKET –
ACCIDENT INTERNAL PRESSURE

Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Bottom Flange – Primary Membrane Plus Bending Stress	5.07	58.5	11.54
Water Jacket Shell – Primary Membrane Plus Bending Stress	7.97	58.5	7.34
Water Jacket Rib – Primary Membrane Stress	4.72	39.0	8.26
Water Jacket Shell-to-Bottom Flange Weld – Primary Shear Stress	3.70	29.4	7.94

Table 3.4.10 STRESS RESULTS FOR HI-STORM FW LID – SNOW LOAD			
Item	Calculated Value (ksi)	Allowable Limit (ksi)	Safety Factor
Maximum Primary Membrane Stress	1.81	16.6	9.16
Maximum Primary Membrane Plus Bending Stress	1.81	24.9	13.7

Table 3.4.11 INPUT DATA USED FOR CALCULATING ANGULAR VELOCITY OF OVERPACK DURING NON-MECHANISTIC TIPOVER (LOAD CASE 4)	
Item	Value
Maximum weight of loaded HI-STORM FW (W)	426,300 lbf†
Mid-height of maximum length HI-STORM FW (h)	119.75 in
Outer diameter of HI-STORM FW (d)	140 in
Distance between cask pivot point and cask center (r)	138.709 in
Mass moment of inertia of loaded HI-STORM FW about cask pivot point (I_A)	1.076×10^{10} lb-in^2

† Bounds value in Table 3.2.8.

Table 3.4.12 INPUT VALUES USED FOR CALCULATING STRESS IN WATER JACKET SHELL (LOAD CASE 8)	
Item	Value
Mean radius of water jacket shell (R)	47.25 in
Thickness of water jacket shell (d)	0.5 in
Width of beam strip (b)	1 in
Extreme fiber distance of beam cross-section (c)	0.25 in
Unsupported span of water jacket shell (θ)	45 deg
Distributed load on water jacket shell (w)	-75 lbf/in[†]
Span of distributed load on water jacket shell (ϕ)	45 deg

Note: Variables are defined in Figure 3.4.35.

[†] Bounds accident internal pressure in Table 2.2.1 for HI-TRAC water jacket.

Table 3.4.13

PARAMETERS SIGNIFICANT TO CRACK PROPAGATION OF METAMIC-HT FUEL BASKETS

	HI-STAR 180 F-37 (Attachment D of [1.2.6])	HI-STORM FW MPC-37	HI-STORM FW MPC-89
Storage cell width, w (in)	8.11	8.94	6.01
Panel thickness, t (in)	0.59	0.59	0.40
Reference metal temperature (°C)	275	365	325
Design basis g-load under lateral loading event*, acc (g)	95	61.75	54.14
Fuel dead load per unit length, f (lbf/in)	8.04	9.79	4.25
Panel stress**, σ(ksi)	13.35	11.64	6.48

* For HI-STORM FW MPCs, the limiting lateral loading is from the non-mechanistic tip-over scenario.
** To facilitate comparison, panel stress is computed according to the following formula (parameters are defined in first column of table):

$$\sigma = \frac{3 \cdot acc \cdot f \cdot w}{4 \cdot t^2}$$

which assumes that the storage cell wall acts as a simply supported beam strip under a uniformly distributed load equal to the amplified fuel weight.

Table 3.4.14

KEY INPUT DATA FOR FUEL ROD INTEGRITY ANALYSIS DURING MPC REFLOOD EVENT (LOAD CASE 11)

Item	Input Value	Source
Cladding Thickness (for reference PWR fuel), in	0.022	SAR Tables 1.0.4 and 2.1.2
Cladding OD (for reference PWR fuel), in	0.377	SAR Tables 1.0.4 and 2.1.2
Fuel Rod Pressure, psi	2,000	Ref. [3.4.24] (upper bound value)
Yield Strength of Zircaloy, psi	100,000 (at 80°F) 50,500 (at 750°F)	Ref. [3.4.21]
Tensile Strength of Zircaloy, psi	112,100 (at 80°F) 68,200 (at 750°F)	Ref. [3.4.21]
Elastic Modulus of Zircaloy, $\times 10^6$ psi	13.42 (at 80°F) 10.4 (at 750°F)	Ref. [3.4.21]
Coefficient of Thermal Expansion of Zircaloy, $\times 10^{-6}$ in/in/ºF	3.3 (at 80°F) 4.5 (at 750°F)	Ref. [3.4.22]
Poisson's Ratio of Zircaloy	0.4	Appendix C of Ref. [3.4.23]

Table 3.4.15 MAXIMUM RESULTS FOR FUEL ROD INTEGRITY ANALYSIS DURING MPC REFLOOD EVENT (LOAD CASE 11)	
Result	Value
Maximum Stress in Fuel Rod Cladding	29,995 psi
Maximum Strain in Fuel Rod Cladding	2.66×10^{-3}

Table 3.4.16

CASK SLIDING DISPLACEMENTS DUE LARGE MISSILE IMPACT (LOAD CASE 3)

Cask	Calculated Sliding Displacement (ft)	Allowable Sliding Displacement (ft)	Safety Factor
HI-STORM FW	0.352	3.33 (cask to cask) 6.2 (cask to edge of ISFSI pad)	9.46 17.6
HI-TRAC VW	1.07	None Established	-

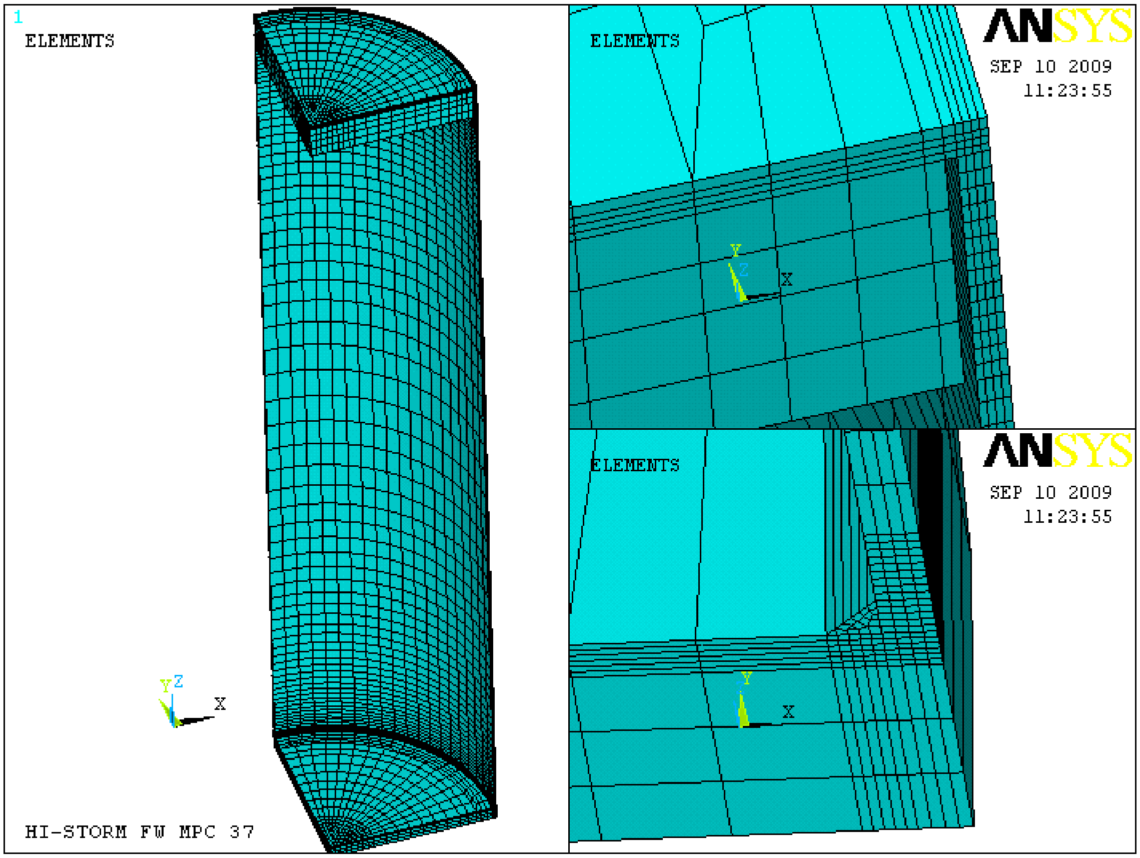


Figure 3.4.1: ANSYS Model of MPC Enclosure Vessel – Normal Handling

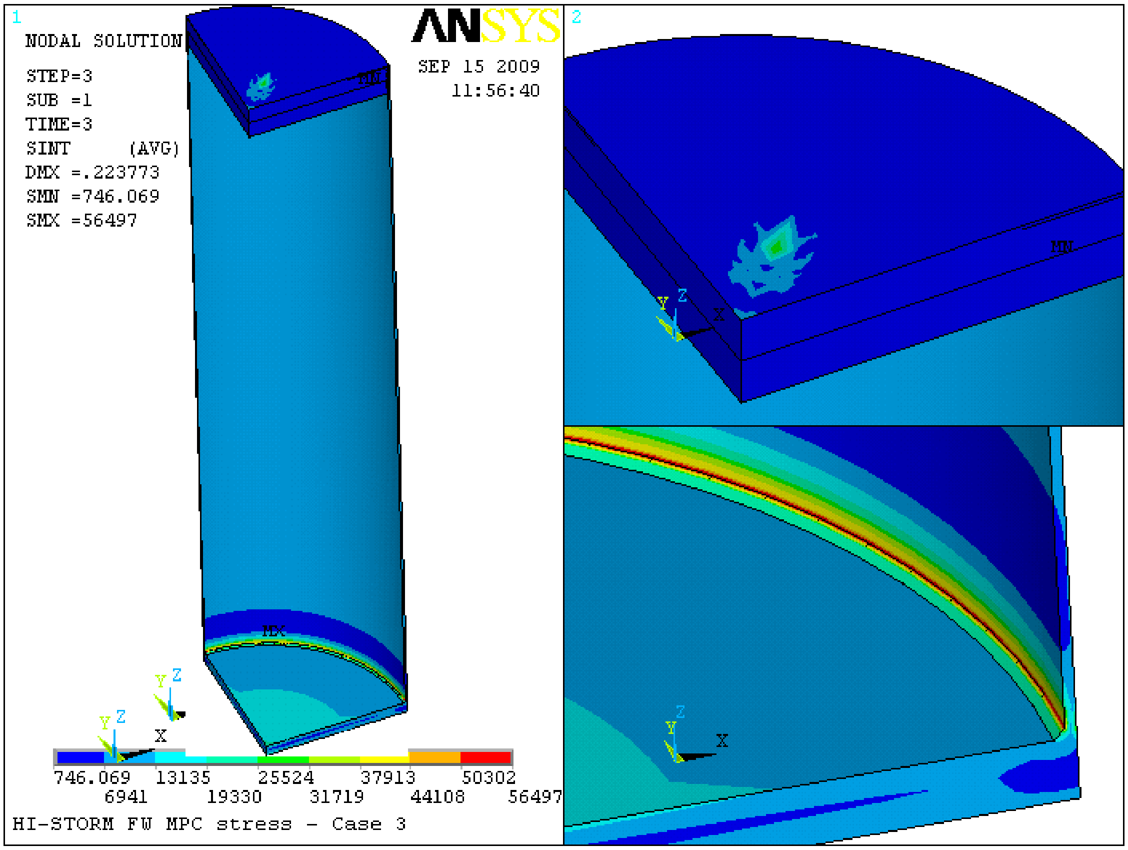


Figure 3.4.2: Stress Intensity Distribution in MPC Enclosure Vessel – Normal Handling

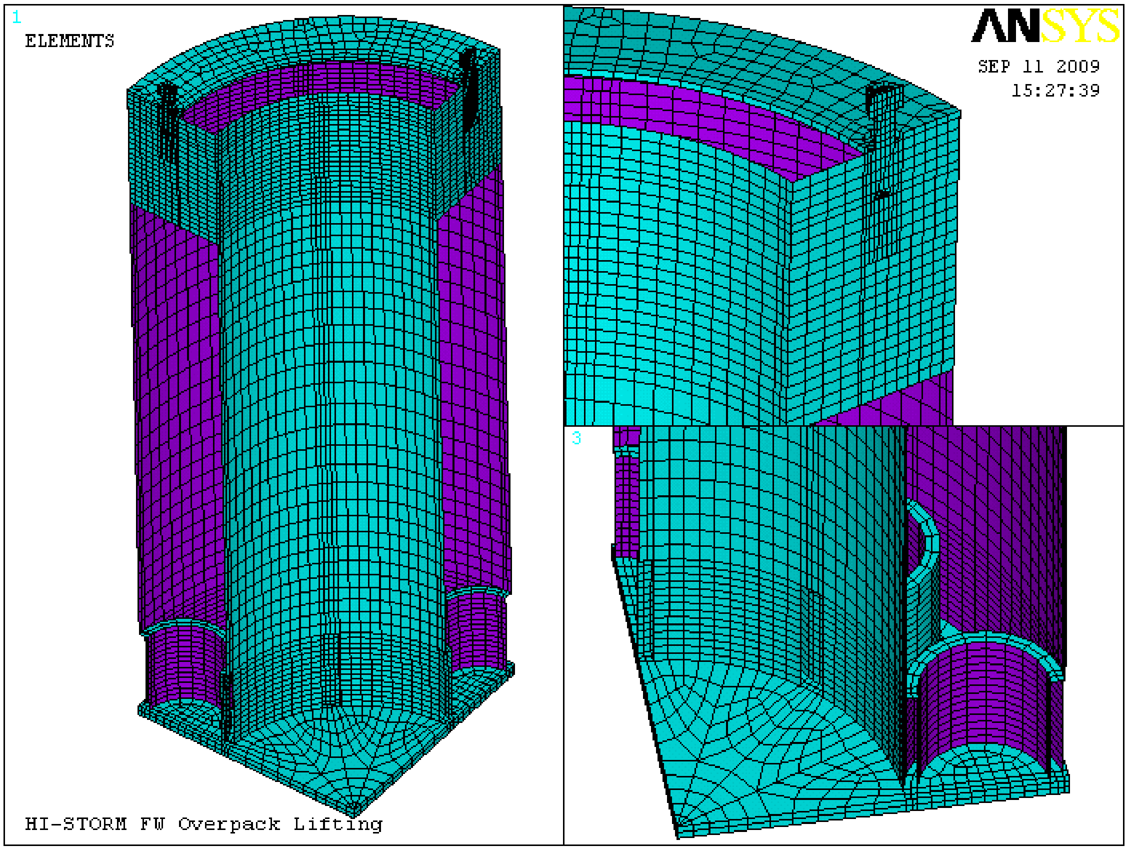


Figure 3.4.3: ANSYS Model of HI-STORM FW Overpack – Normal Handling

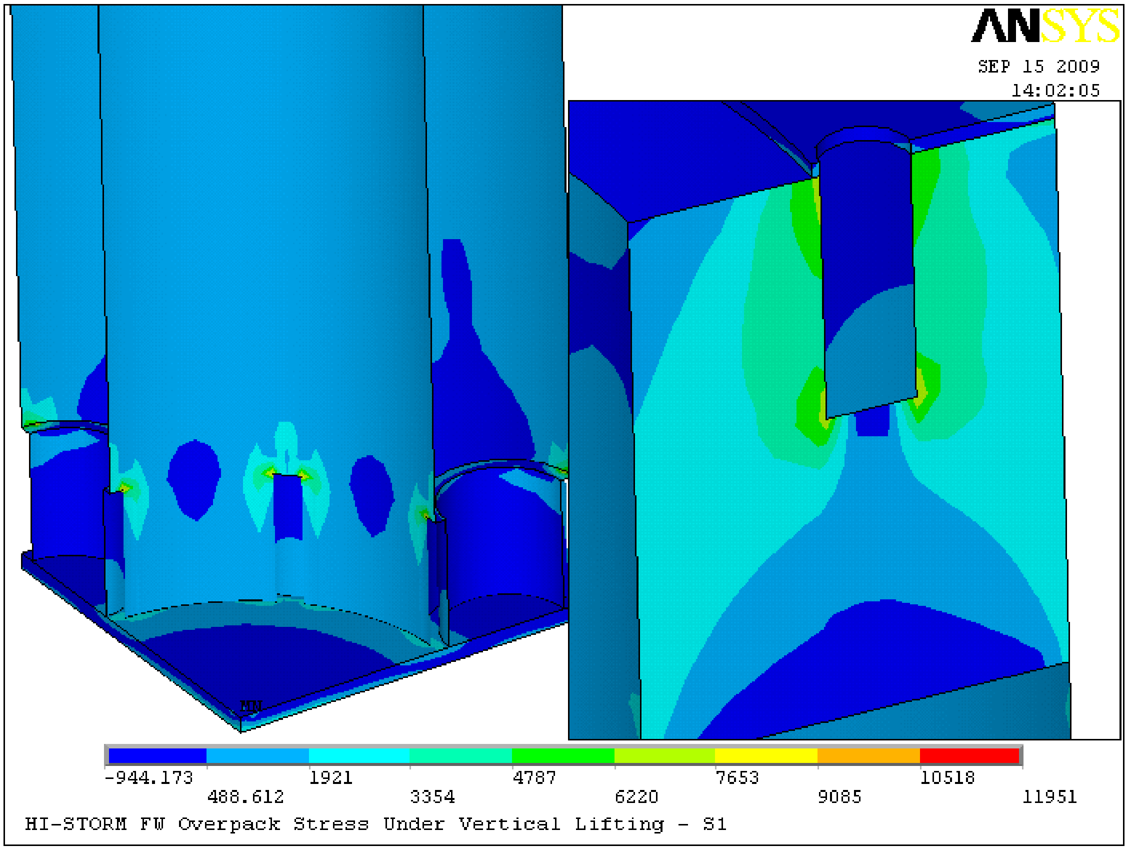


Figure 3.4.4: Stress Distribution in HI-STORM FW Overpack – Normal Handling

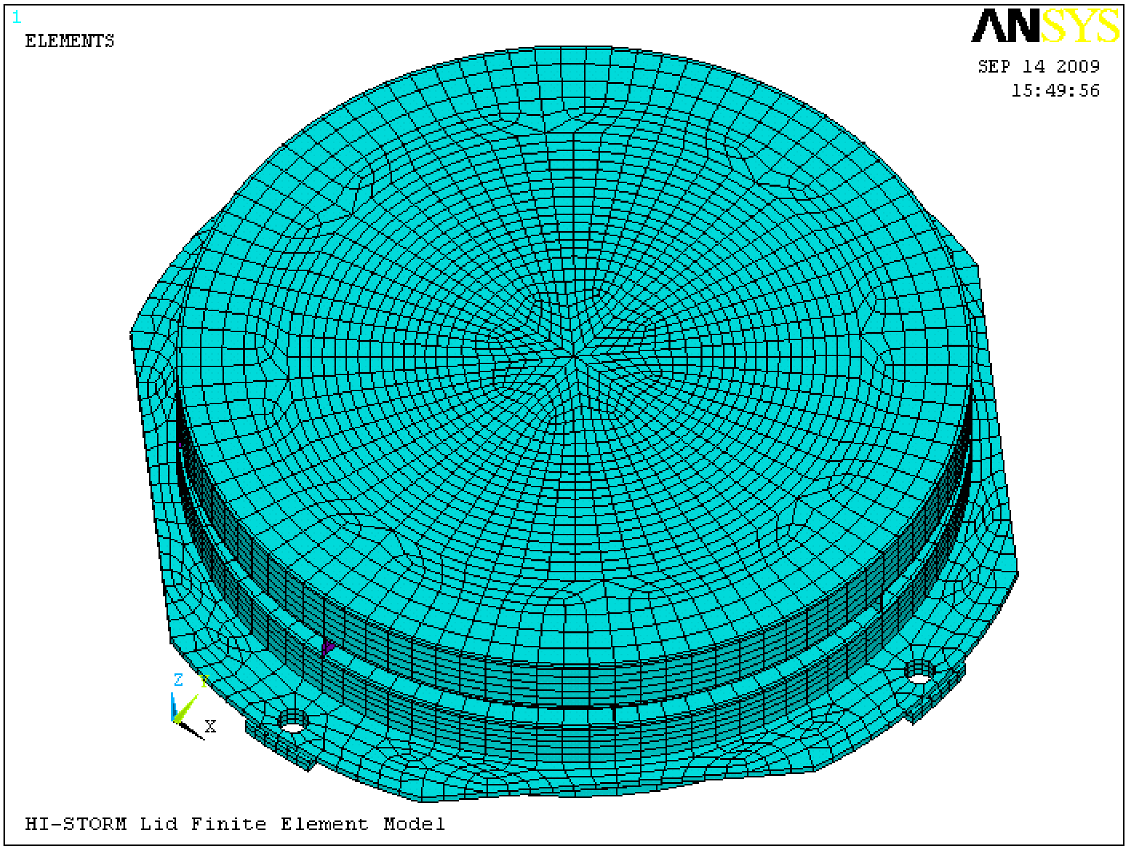


Figure 3.4.5: ANSYS Model of HI-STORM FW Lid – Normal Handling

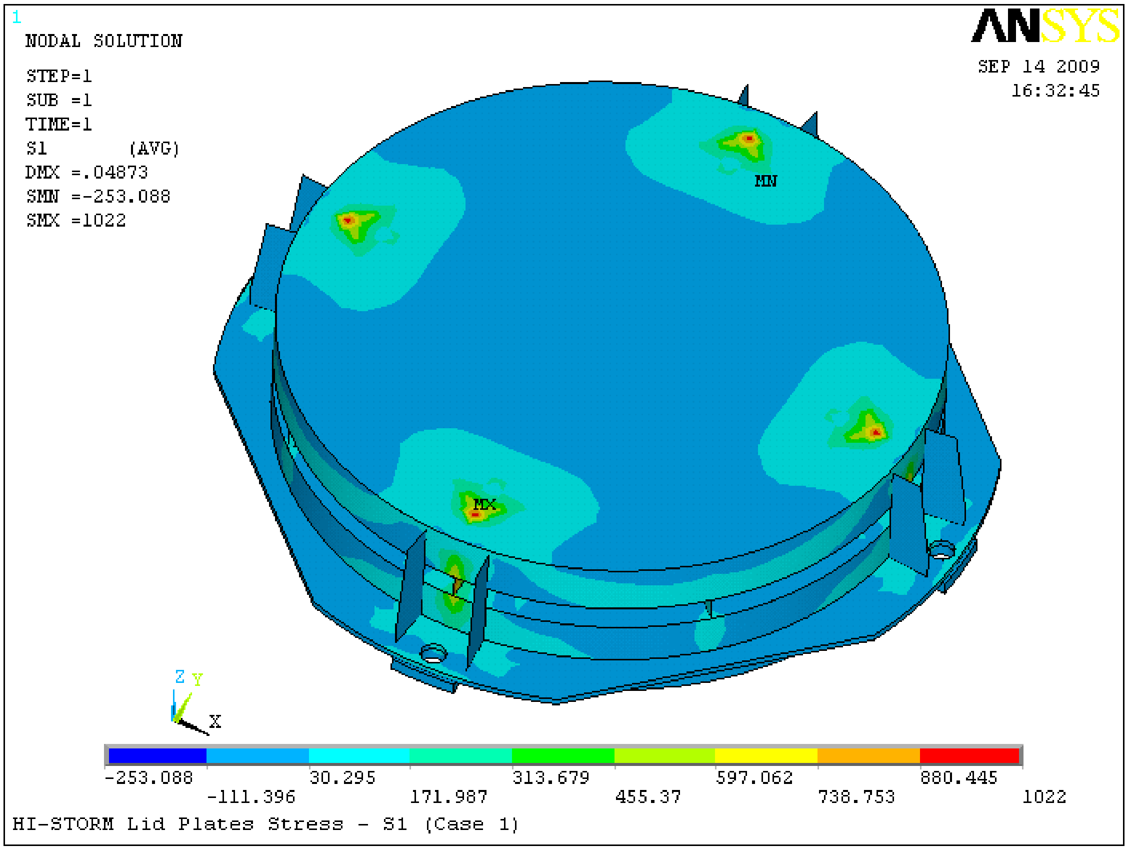


Figure 3.4.6: Stress Distribution in HI-STORM FW Lid – Normal Handling

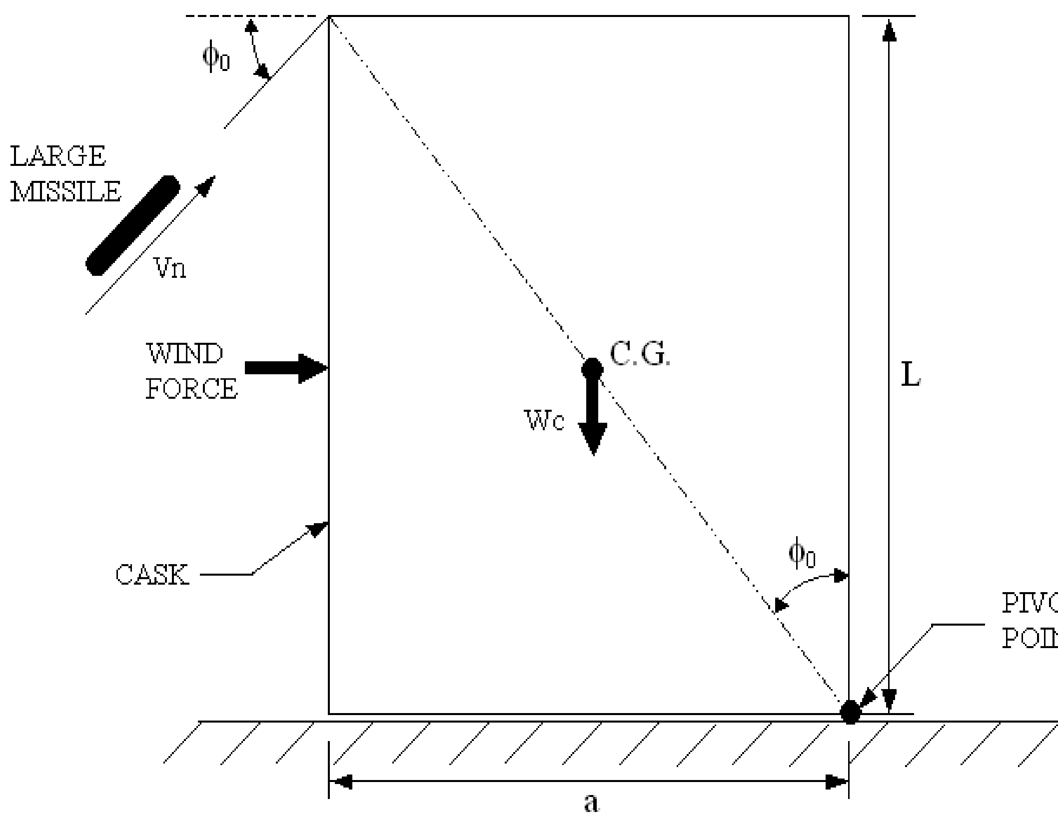


Figure 3.4.7: Free Body Diagram of Cask for Large Missile Strike/Tornado Event

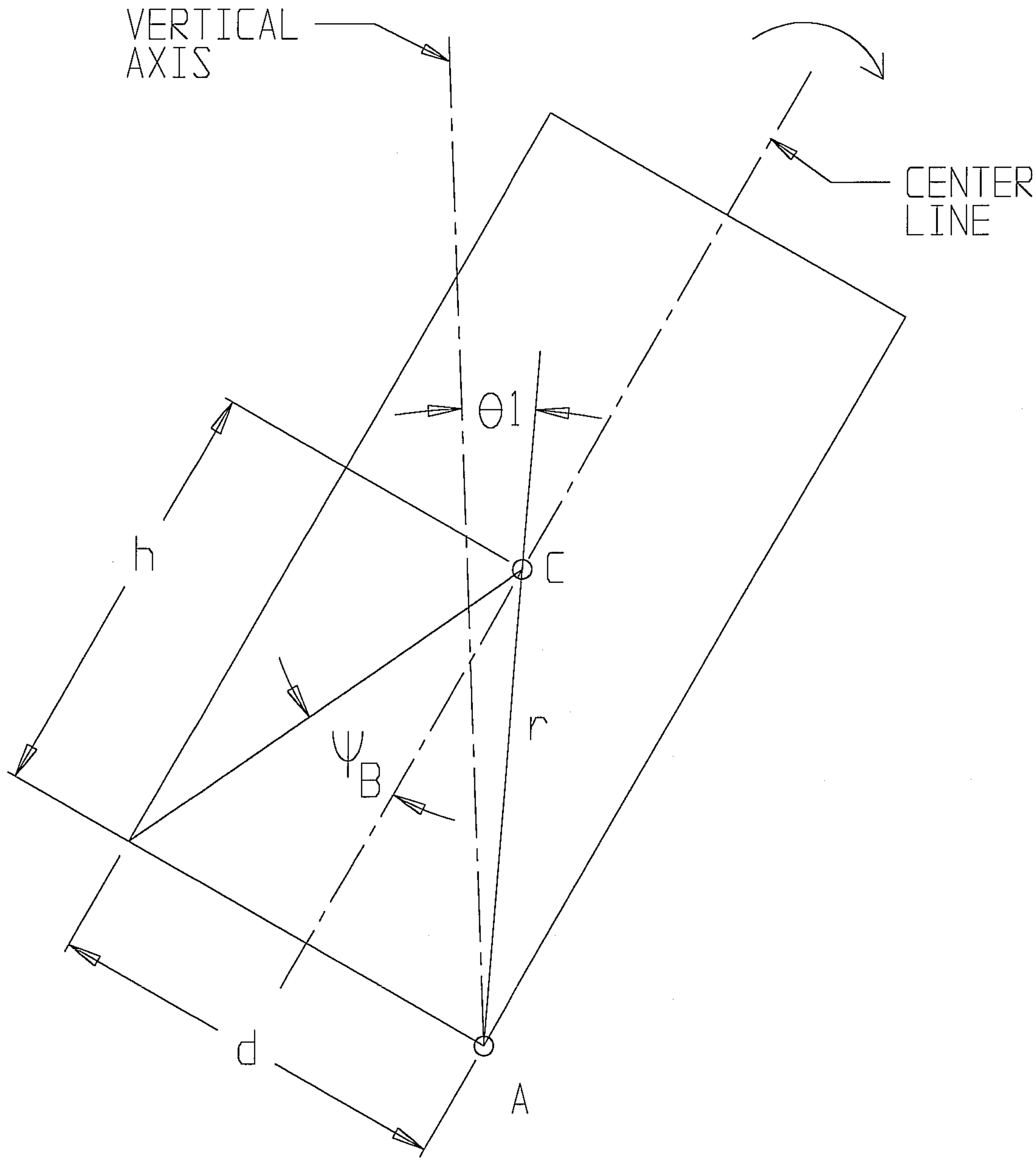


Figure 3.4.8: Cask Configuration at Incipient Tipping

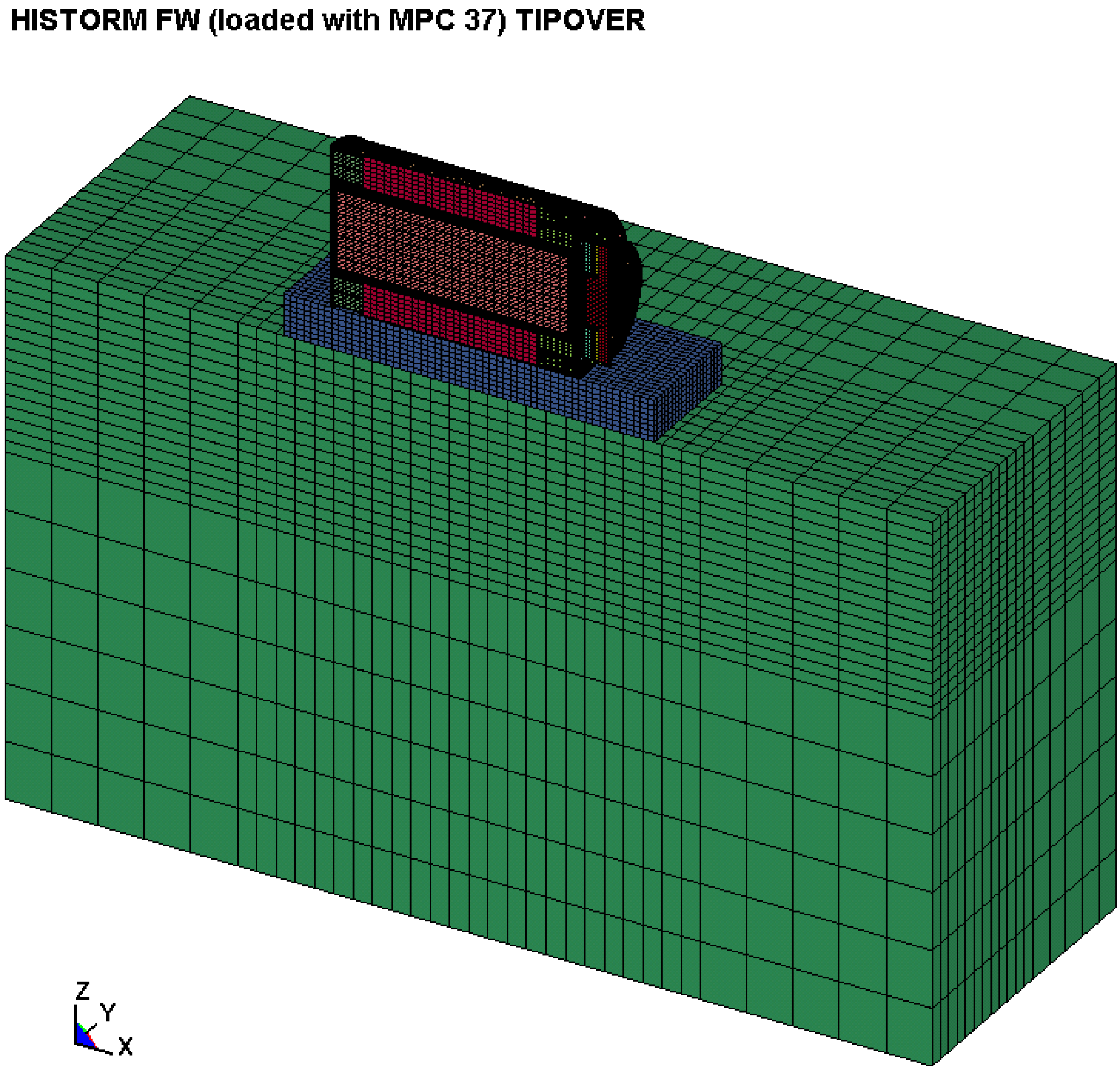


Figure 3.4.9A: LS-DYNA Tipover Model – HI-STORM FW Loaded with MPC-37

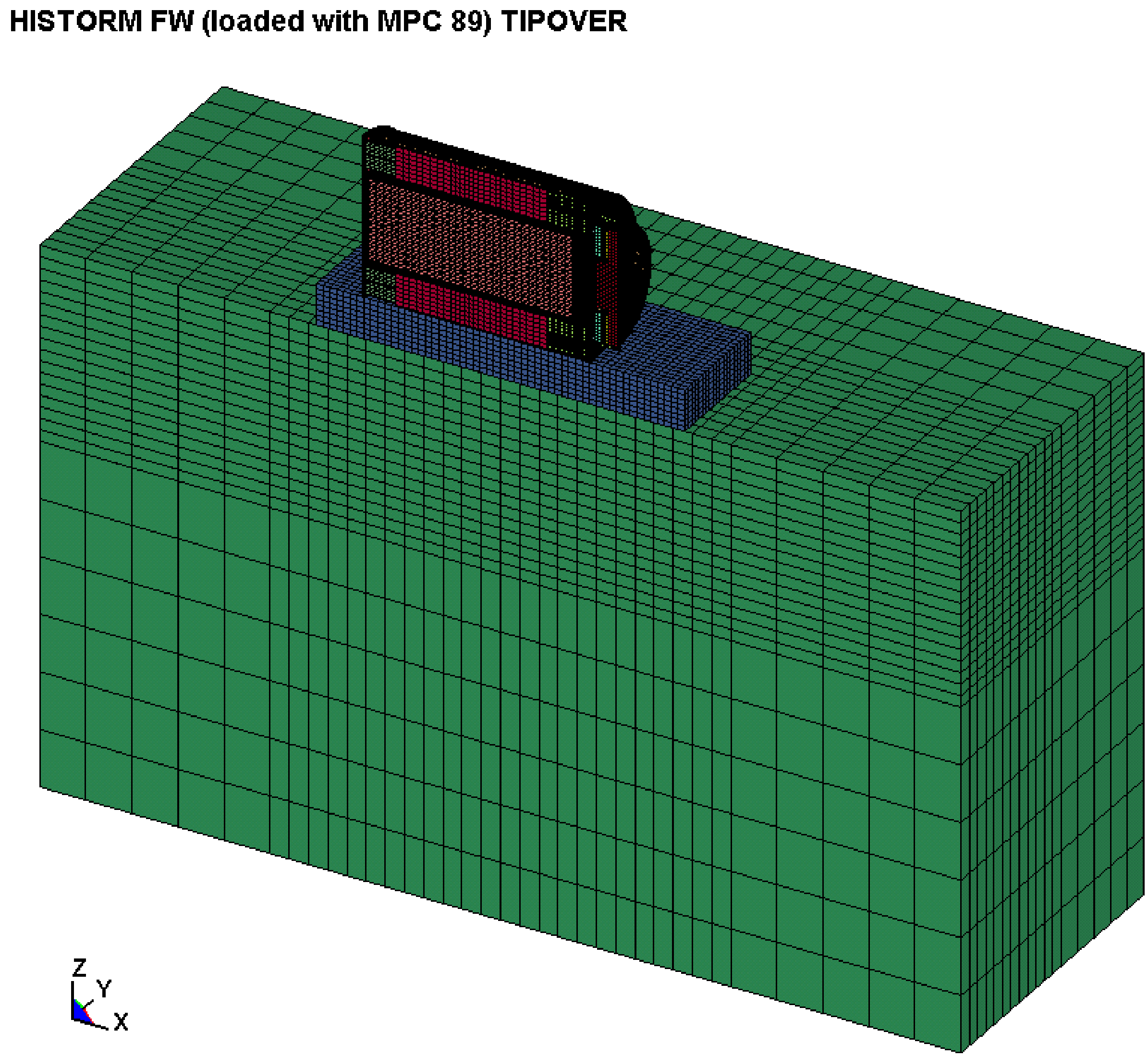


Figure 3.4.9B: LS-DYNA Tipover Model – HI-STORM FW Loaded with MPC-89

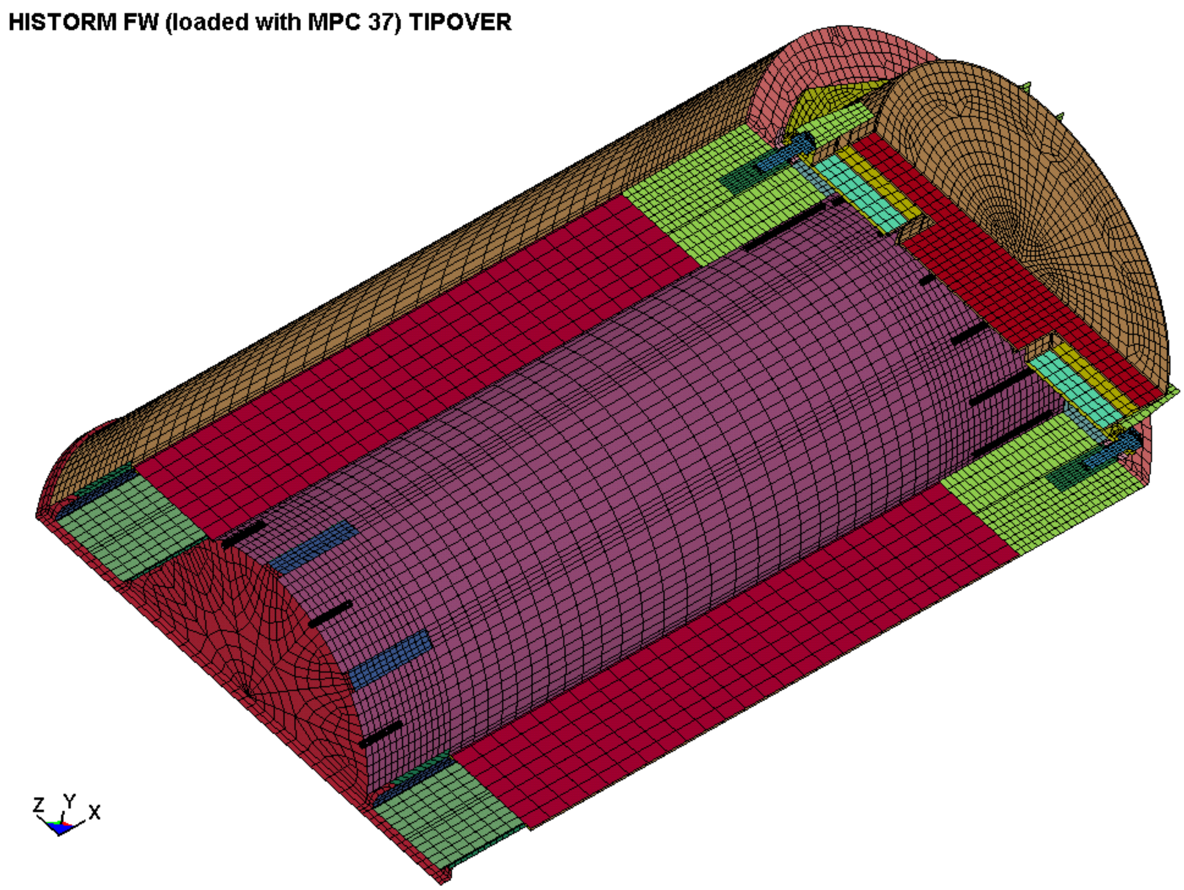


Figure 3.4.10A: LS-DYNA Model – HI-STORM FW for MPC-37

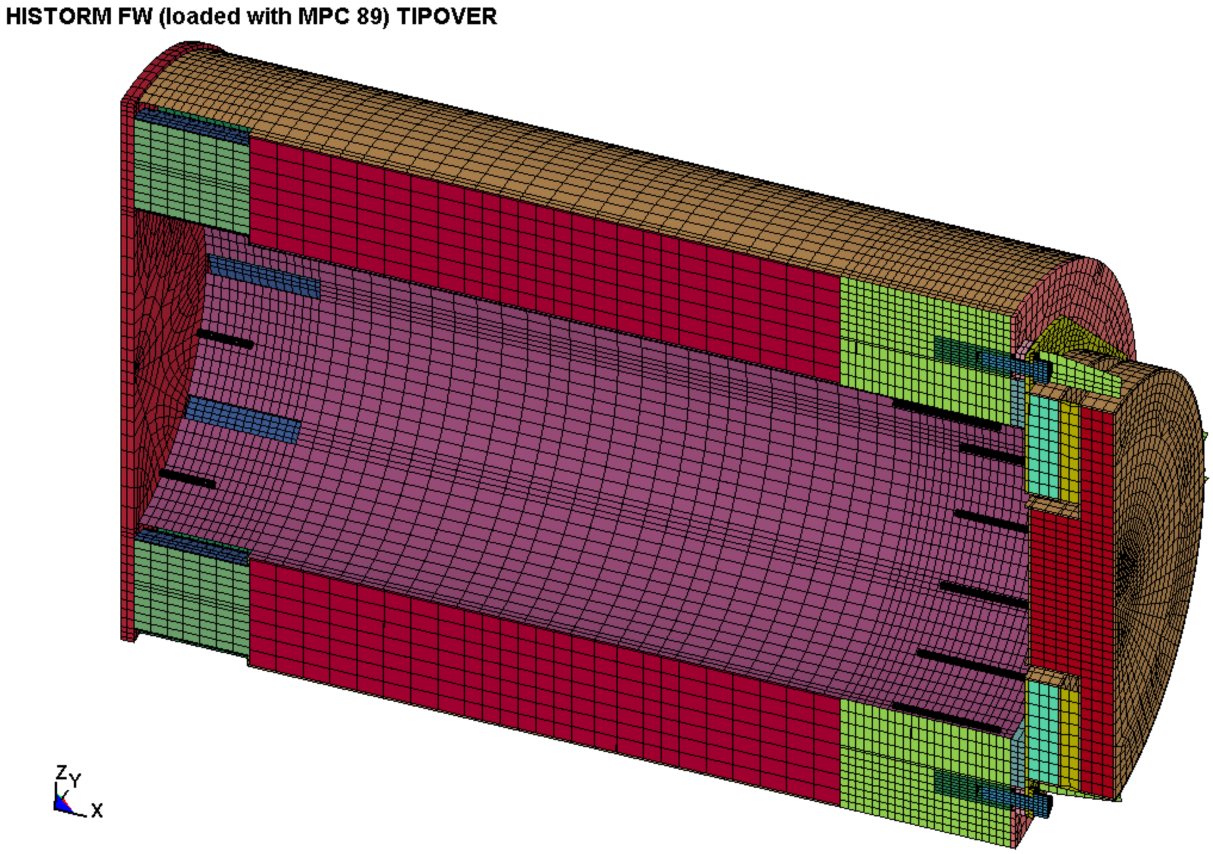


Figure 3.4.10B: LS-DYNA Model – HI-STORM FW for MPC-89

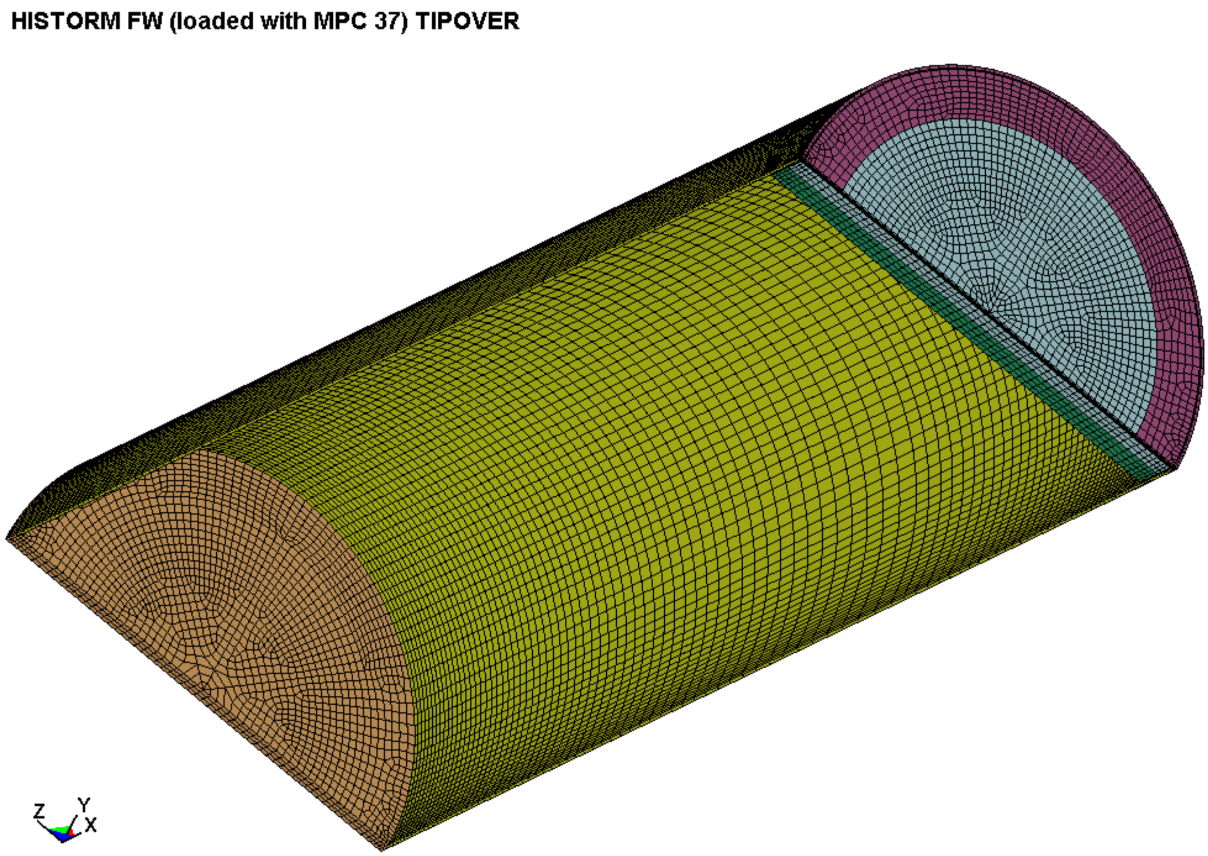


Figure 3.4.11A: LS-DYNA Model – MPC-37 Enclosure Vessel

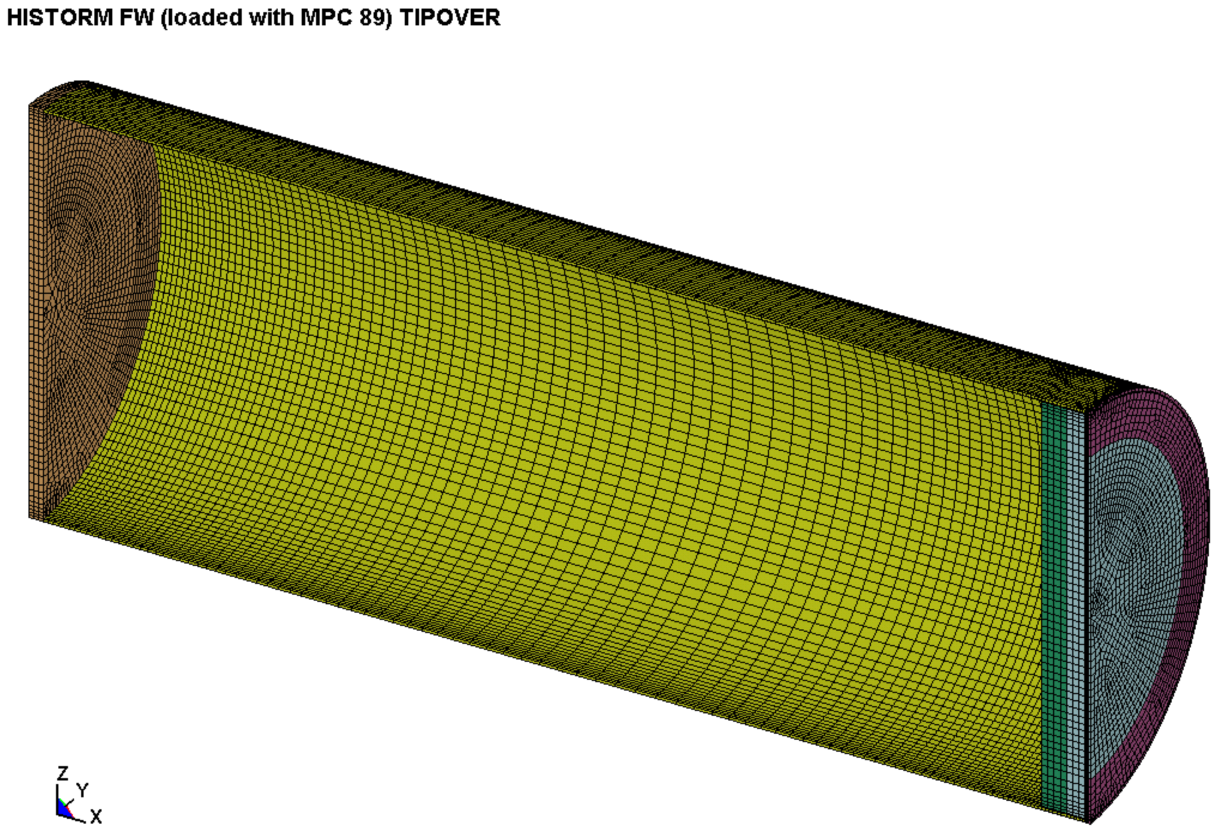


Figure 3.4.11B: LS-DYNA Model – MPC-89 Enclosure Vessel

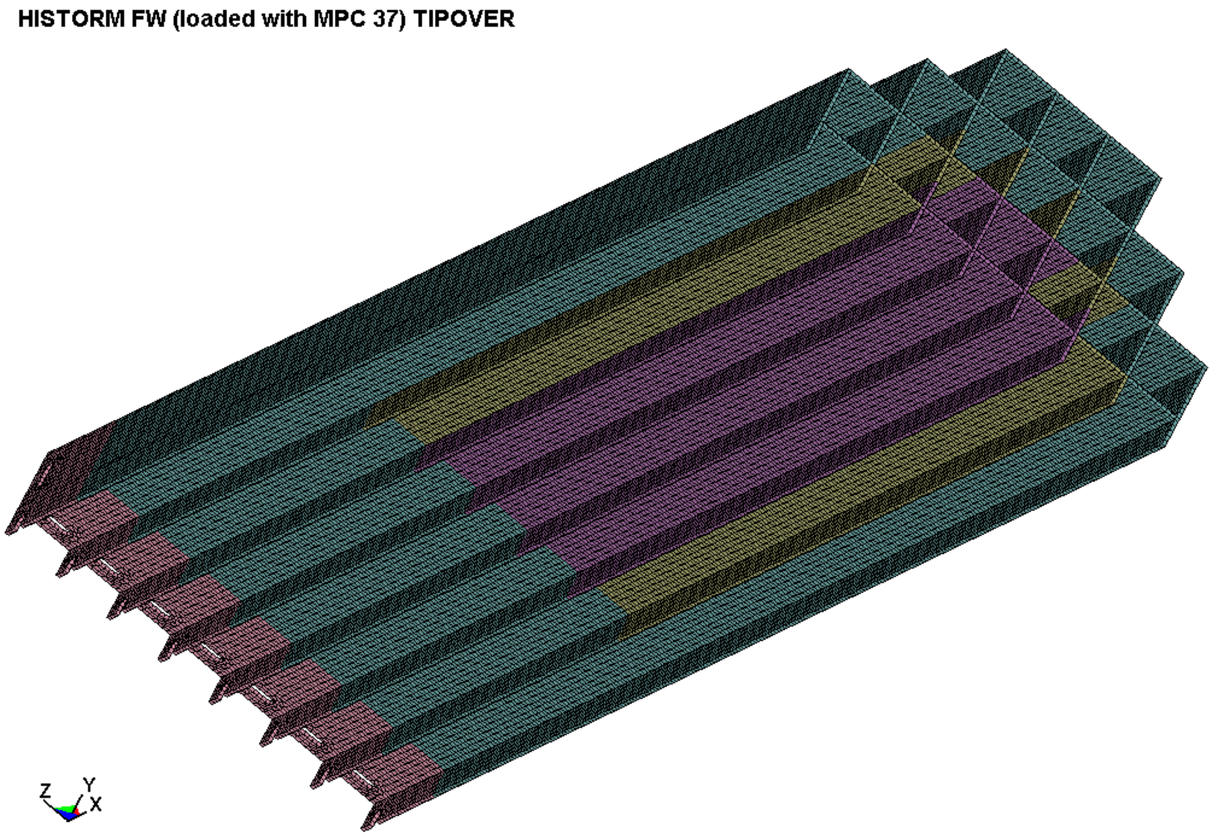


Figure 3.4.12A: LS-DYNA Model – MPC-37 Fuel Basket
(note: the different colors represent regions with bounding temperatures of 340°C, 325°C, 300°C and 250°C, respectively)

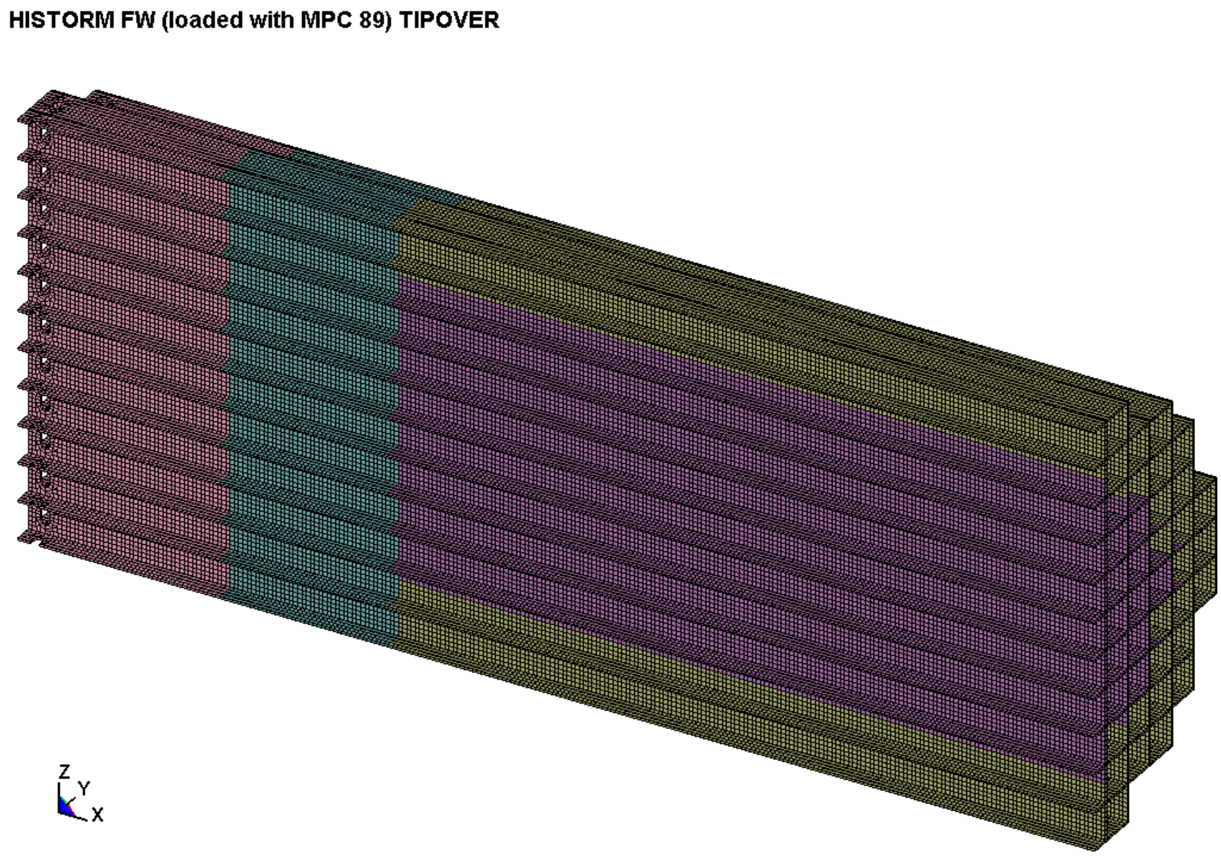


Figure 3.4.12B: LS-DYNA Model – MPC-89 Fuel Basket
(note: the different colors represent regions with bounding temperatures of
325°C, 300°C, 250°C and 200°C, respectively)

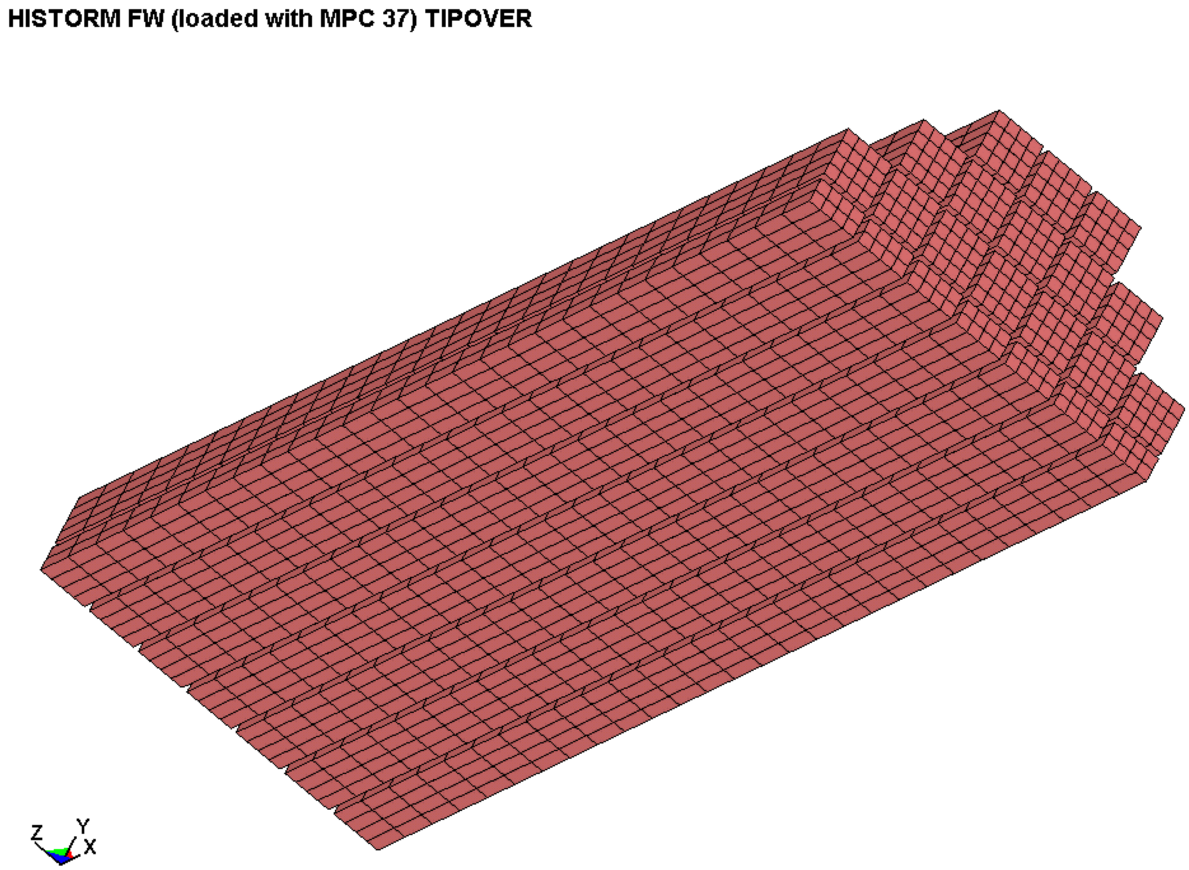


Figure 3.4.13A: LS-DYNA Model – PWR Fuel Assemblies

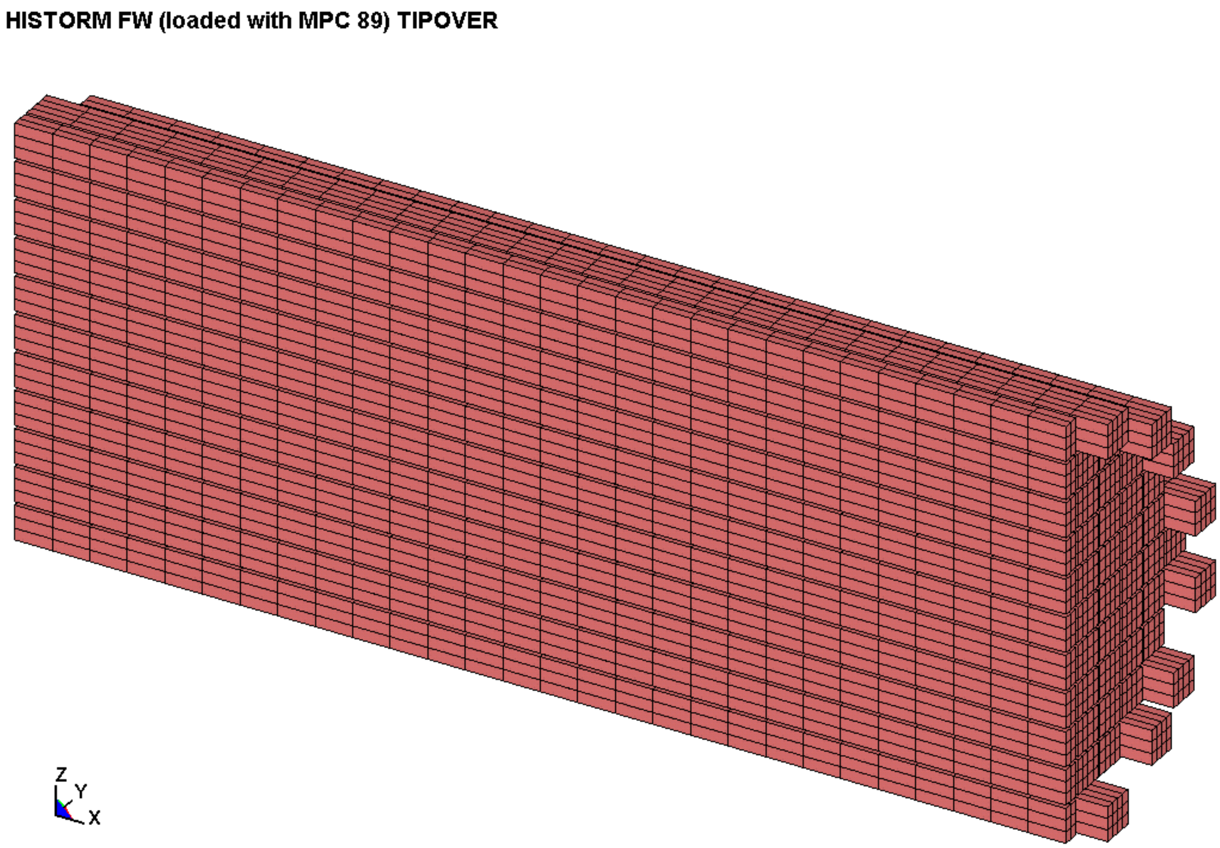


Figure 3.4.13B: LS-DYNA Model – BWR Fuel Assemblies & Damaged Fuel Containers

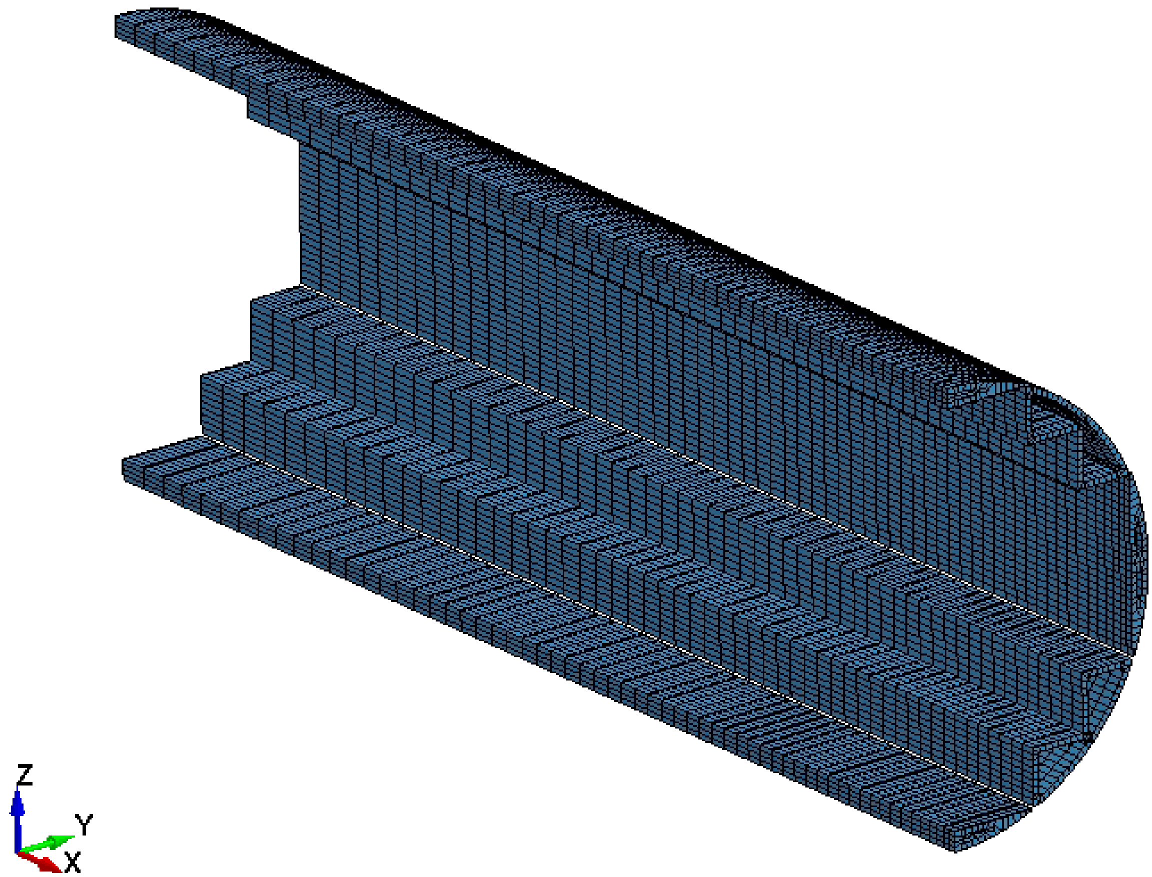


Figure 3.4.14A: LS-DYNA Model – MPC-37 Fuel Basket Shims

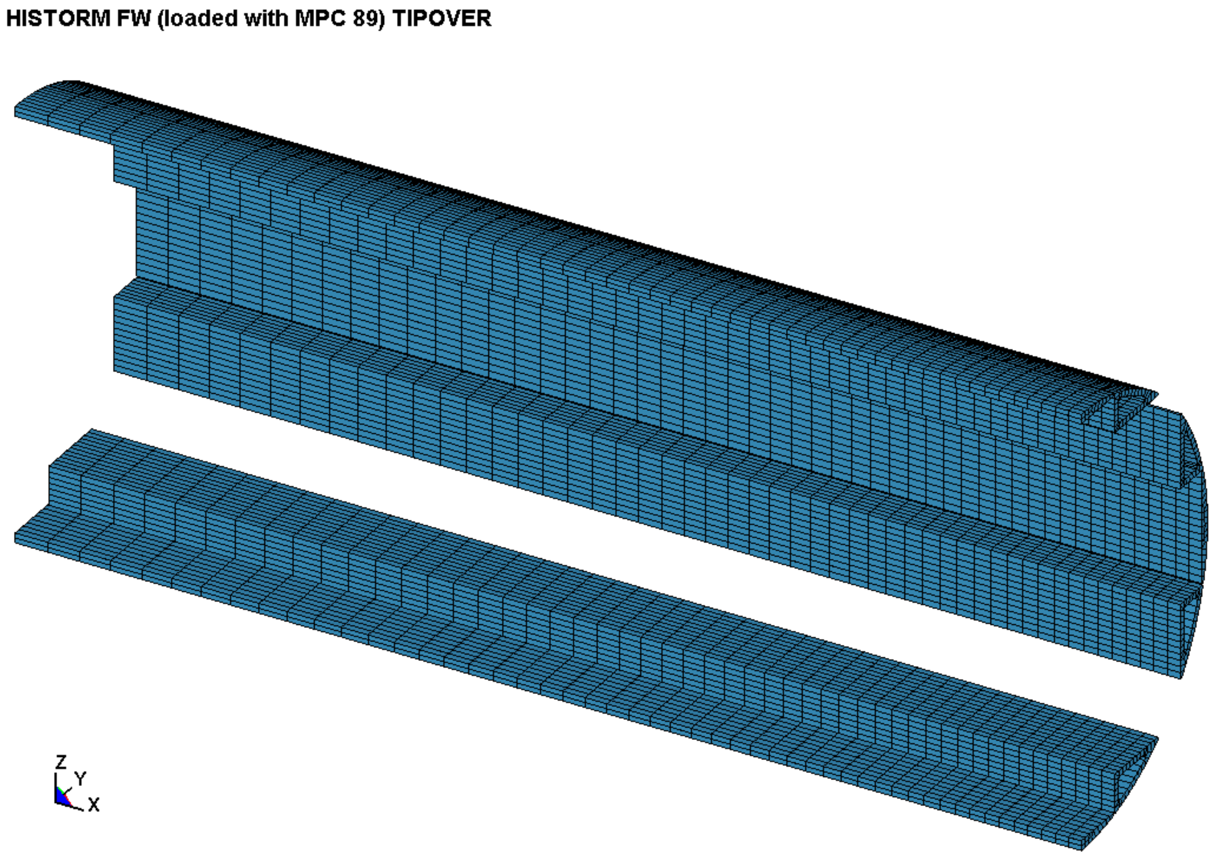


Figure 3.4.14B: LS-DYNA Model – MPC-89 Fuel Basket Shims

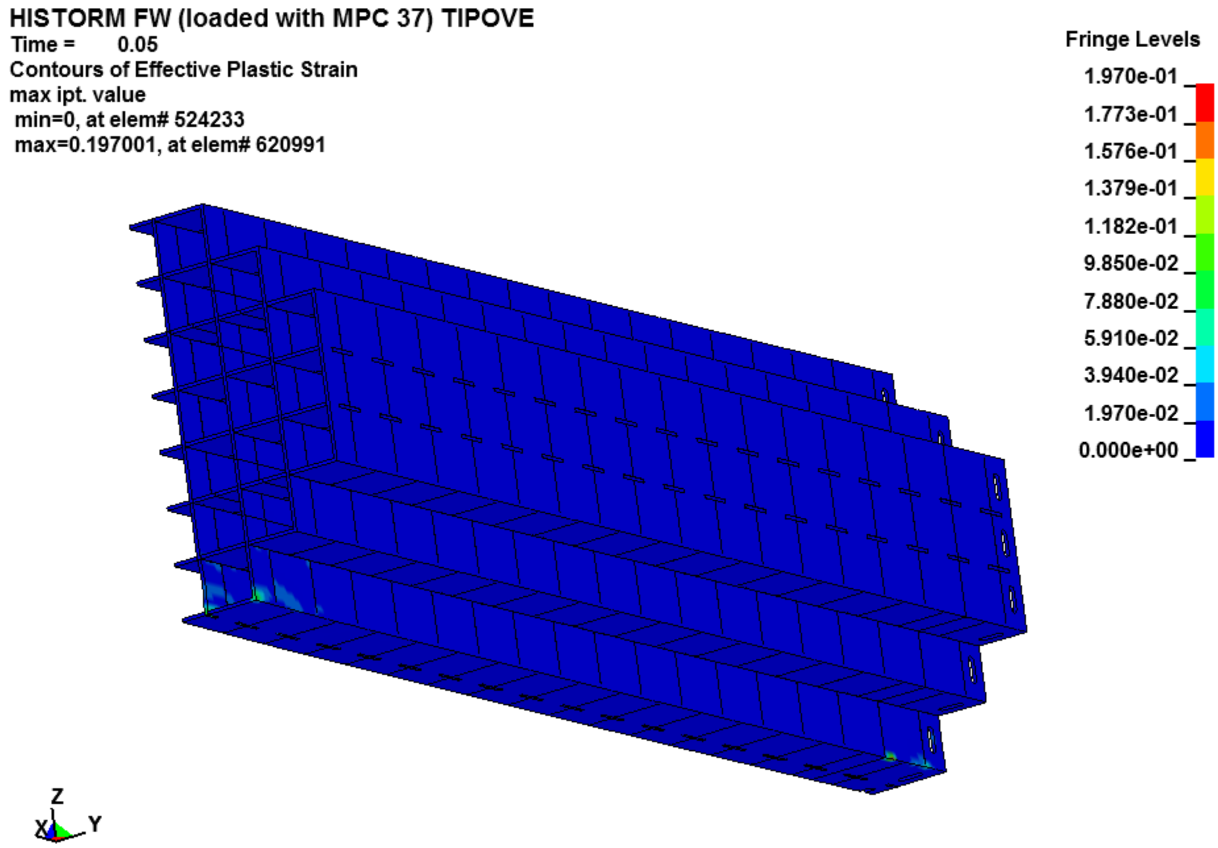


Figure 3.4.15A: Maximum Plastic Strain – MPC-37 Fuel Basket

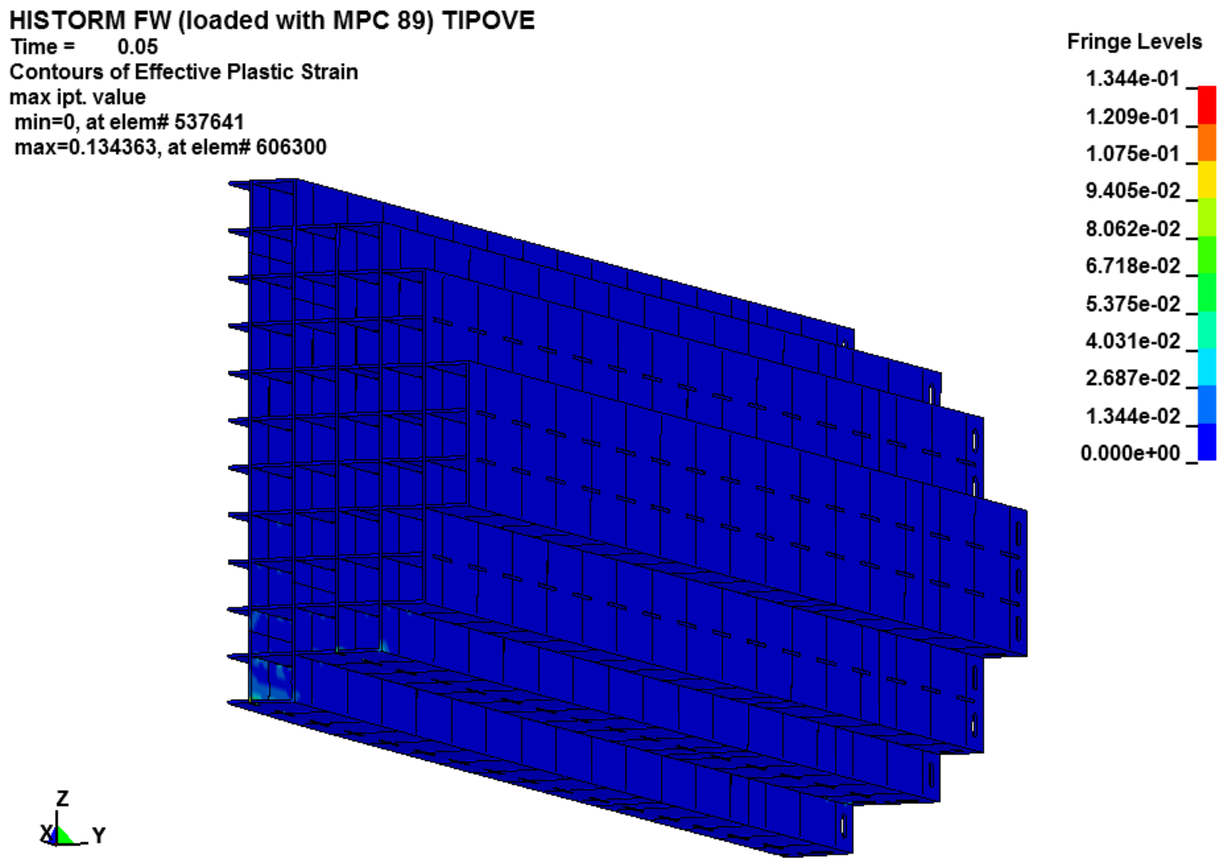


Figure 3.4.15B: Maximum Plastic Strain – MPC-89 Fuel Basket

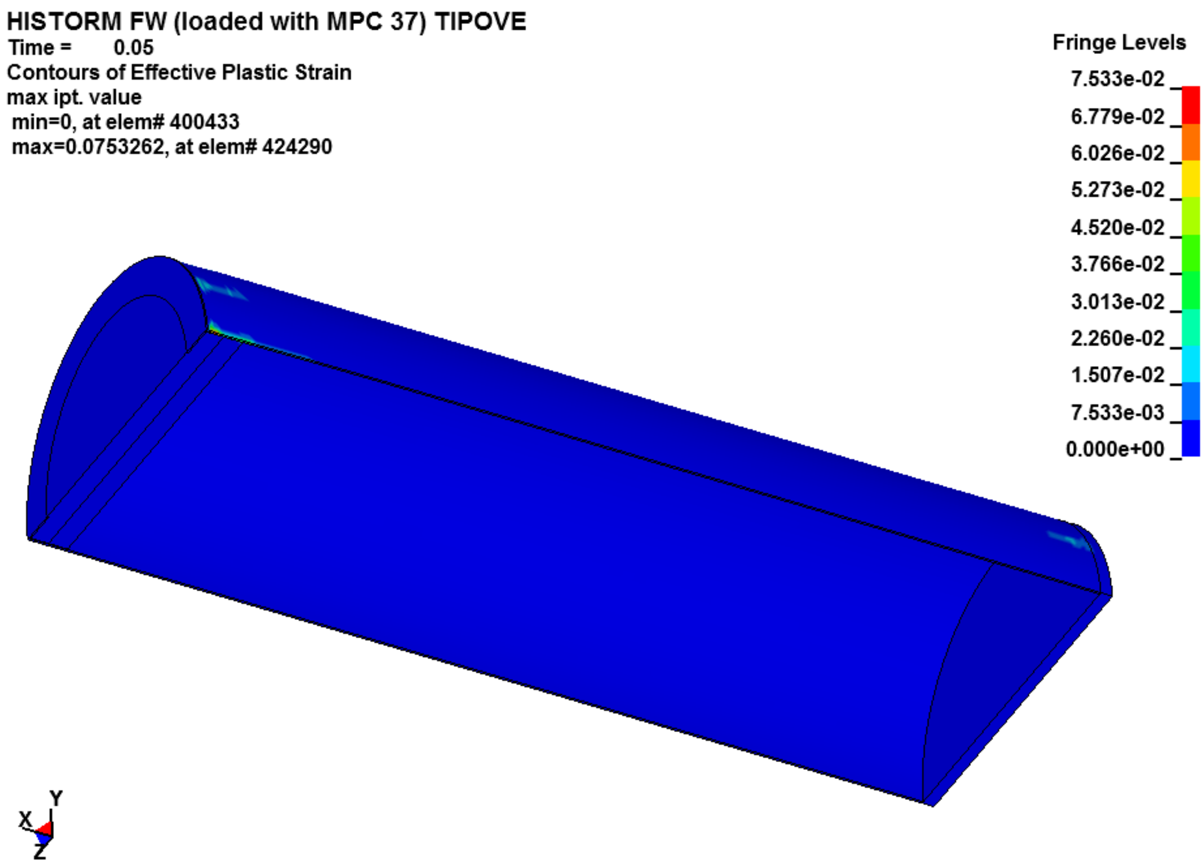


Figure 3.4.16A: Maximum Plastic Strain – MPC-37 Enclosure Vessel

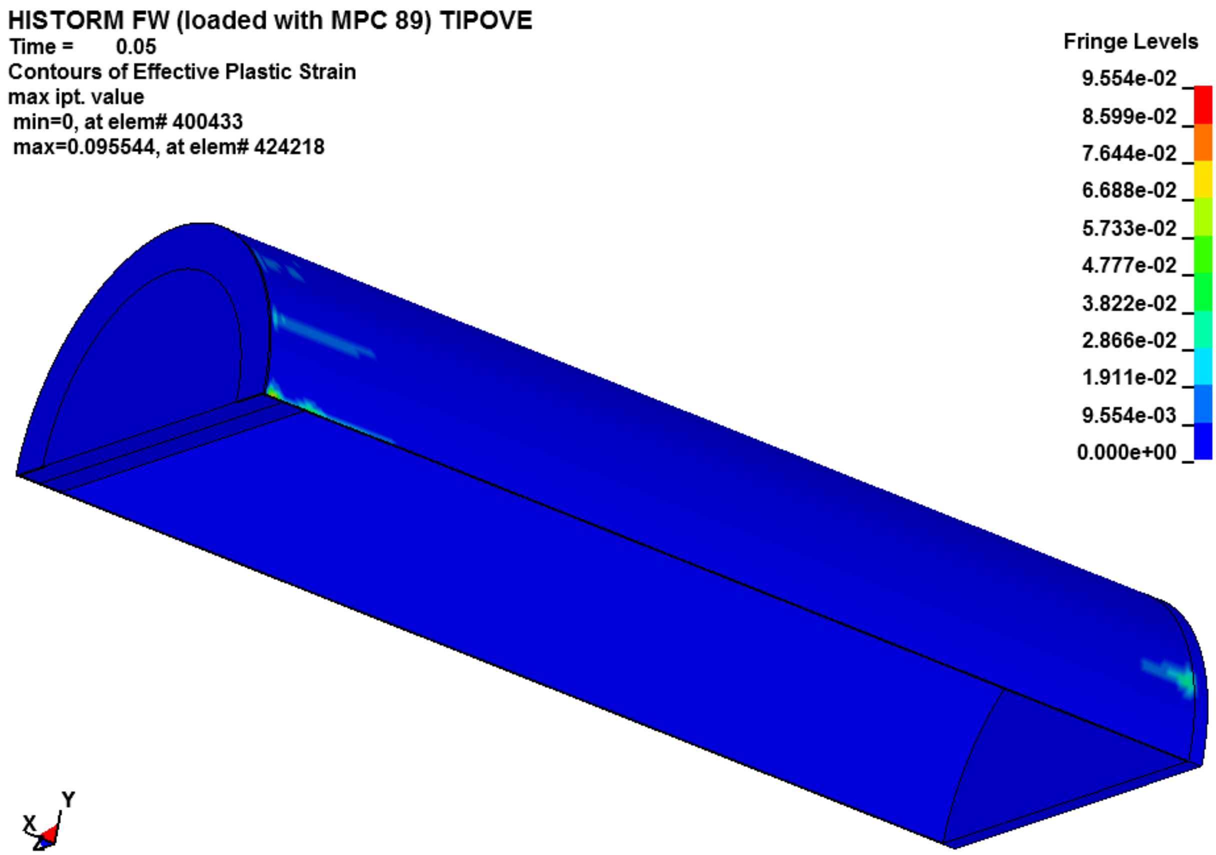


Figure 3.4.16B: Maximum Plastic Strain – MPC-89 Enclosure Vessel

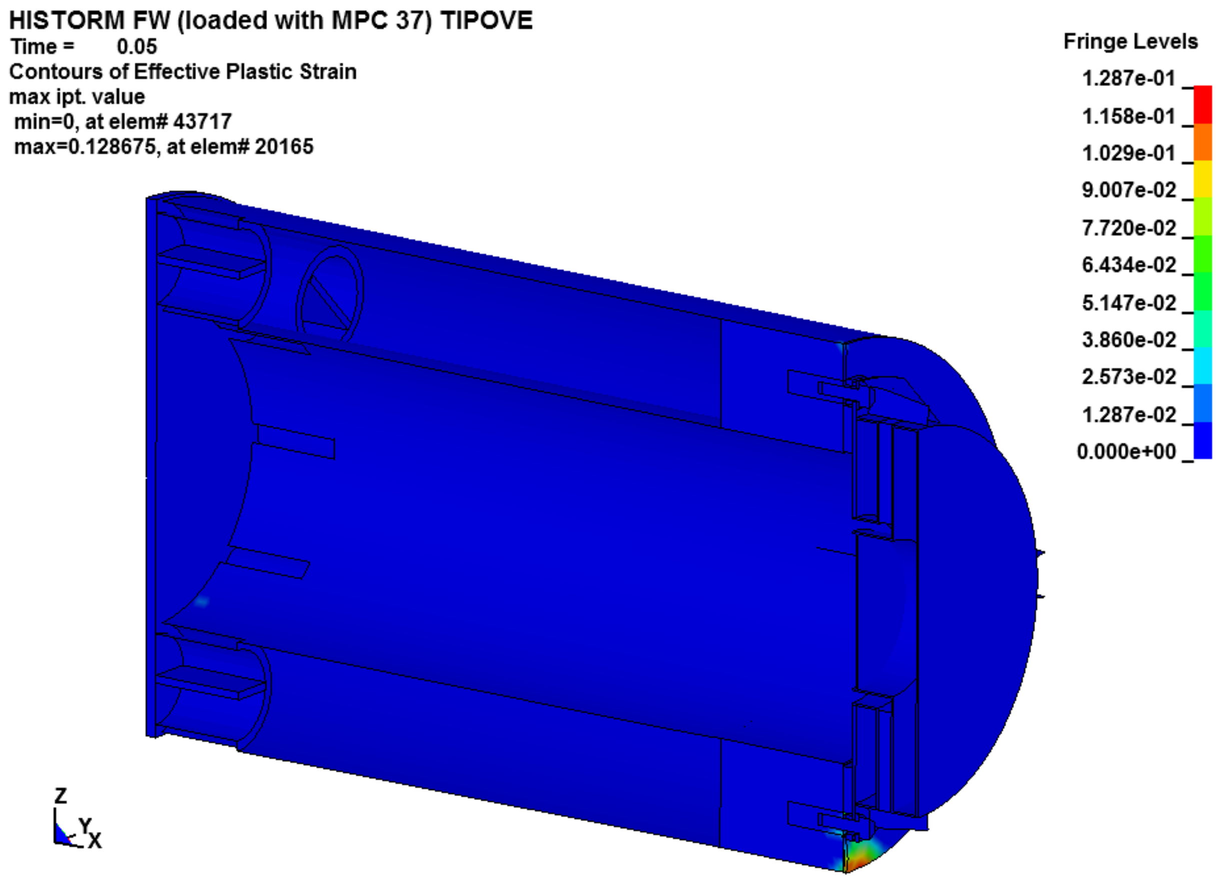


Figure 3.4.17A: Maximum Plastic Strain – HI-STORM FW Overpack
(for MPC-37, Excluding MPC Guide Tubes)

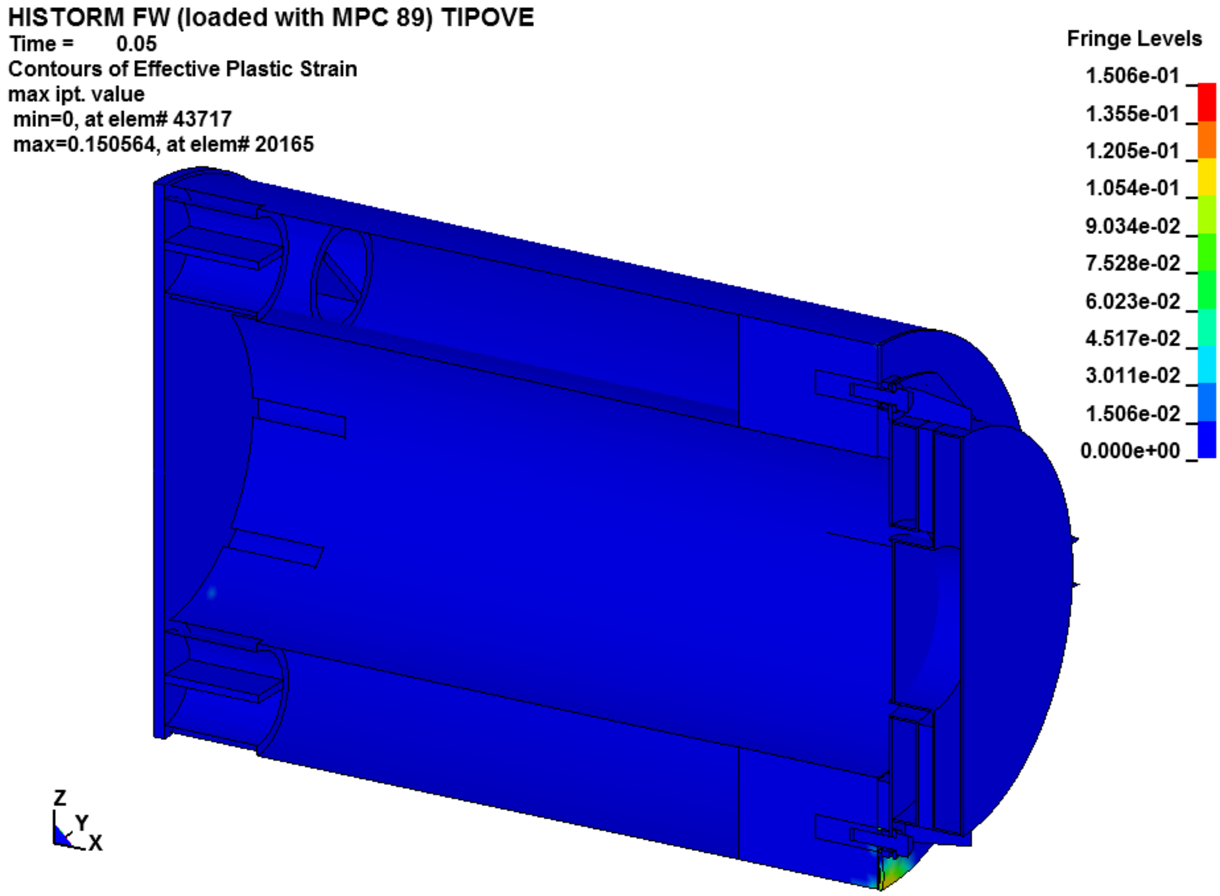


Figure 3.4.17B: Maximum Plastic Strain – HI-STORM FW Overpack
(for MPC-89, Excluding MPC Guide Tubes)

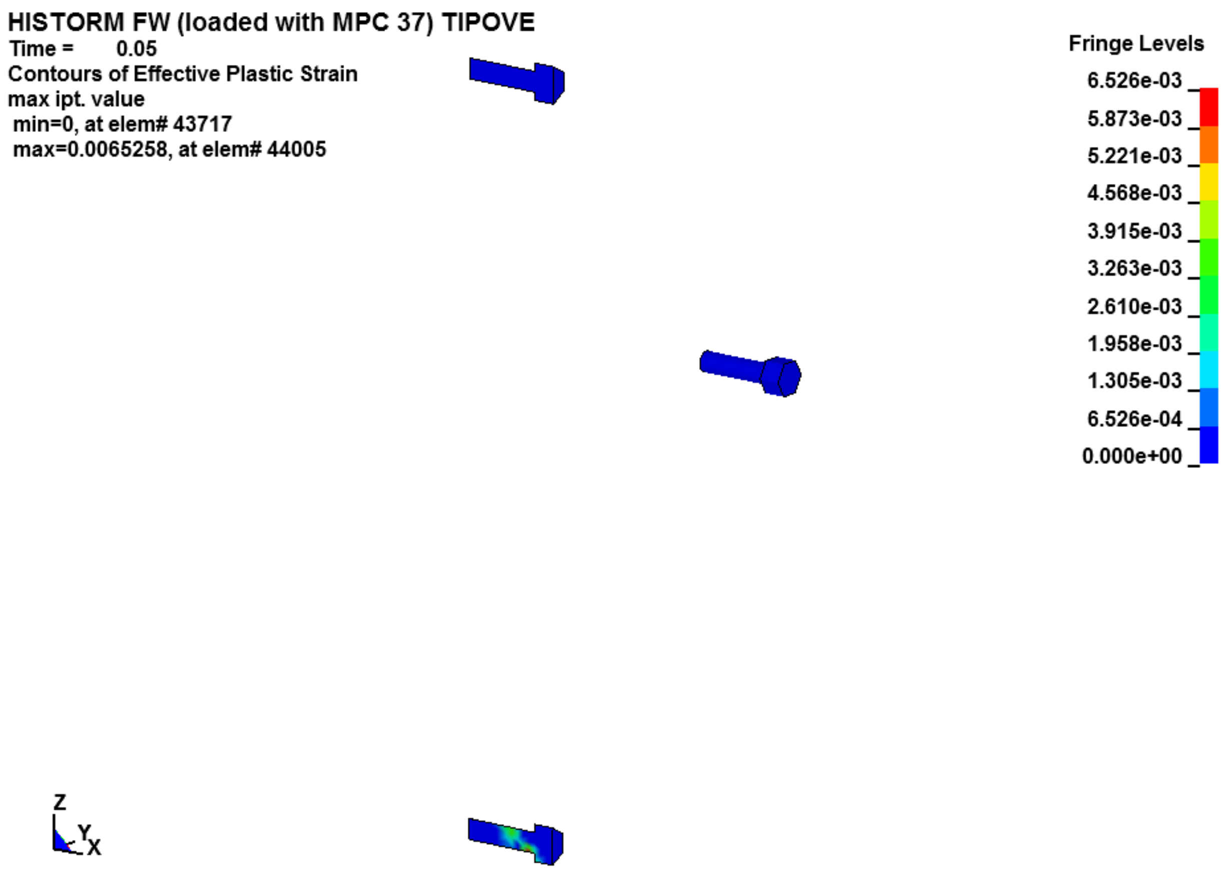


Figure 3.4.18A: Maximum Plastic Strain –
HI-STORM FW Overpack (for MPC-37) Closure Lid Bolts

Figure 3.4.18B: Maximum Plastic Strain –
HI-STORM FW Overpack (for MPC-37) Closure Lid Bolts

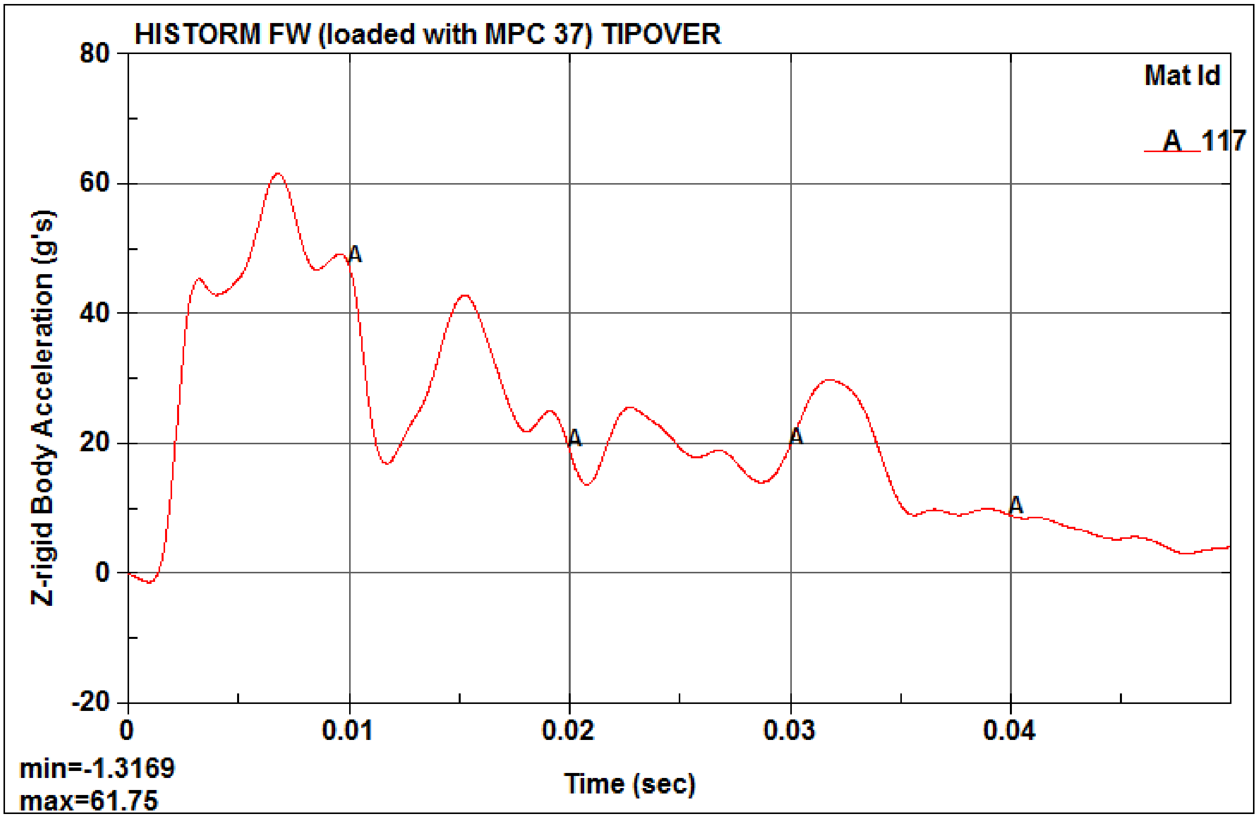


Figure 3.4.19A: Vertical Rigid Body Deceleration Time History –
Cask Lid Concrete (for HI-STORM FW Loaded with MPC-37)

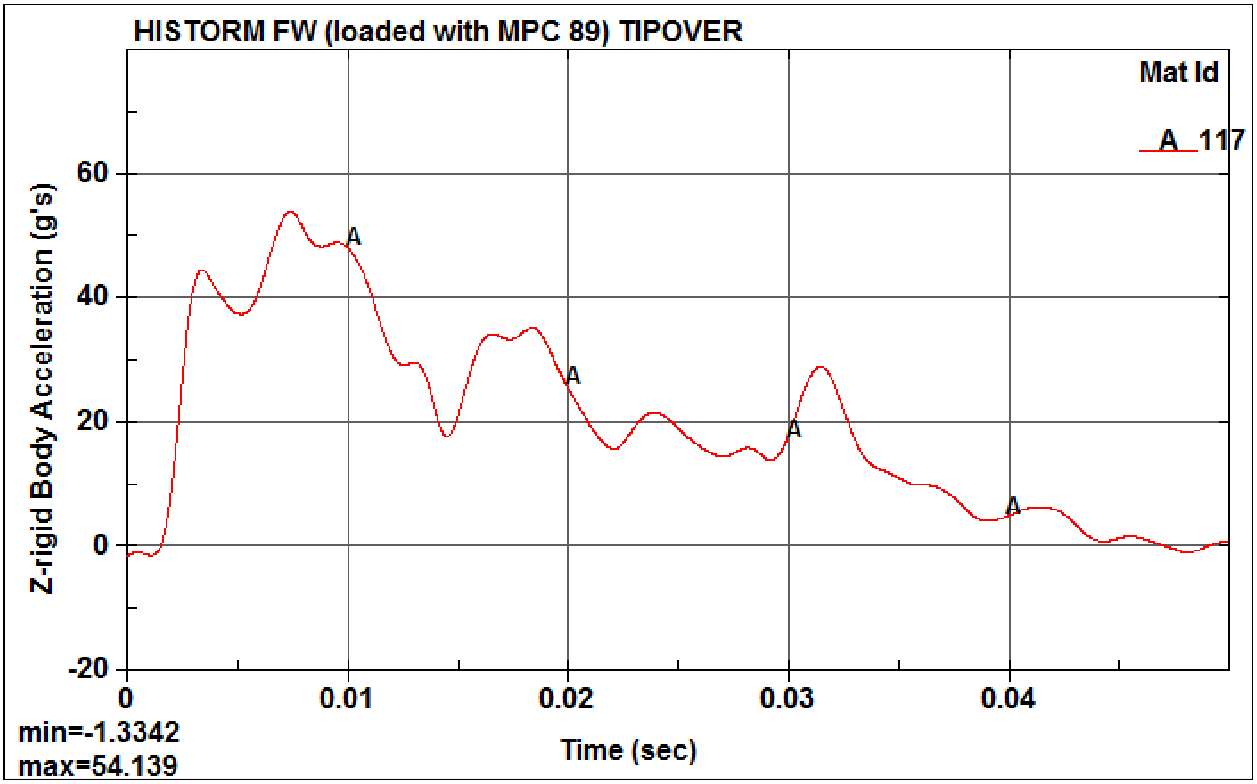


Figure 3.4.19B: Vertical Rigid Body Deceleration Time History –
Cask Lid Concrete (for HI-STORM FW Loaded with MPC-89)

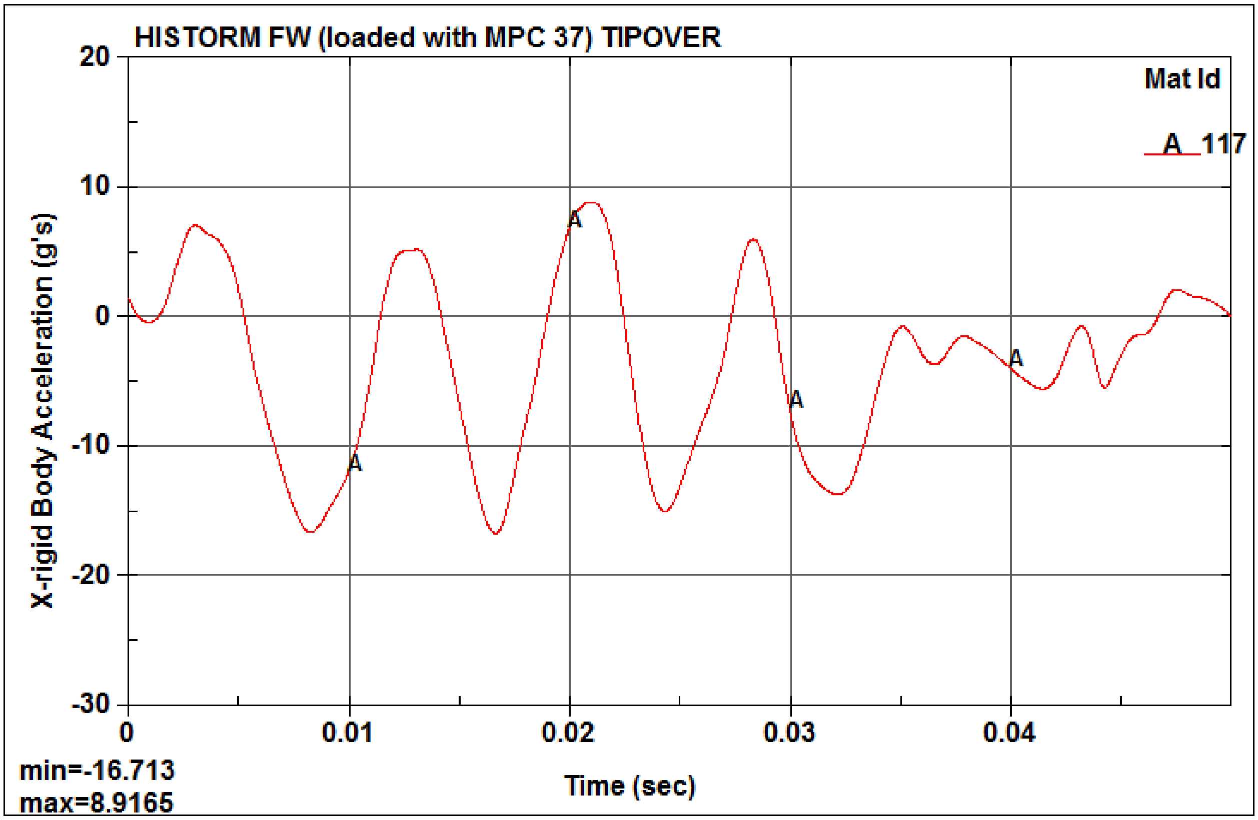


Figure 3.4.20A: Horizontal Rigid Body Deceleration Time History –
Cask Lid Concrete (for HI-STORM FW Loaded with MPC-37)

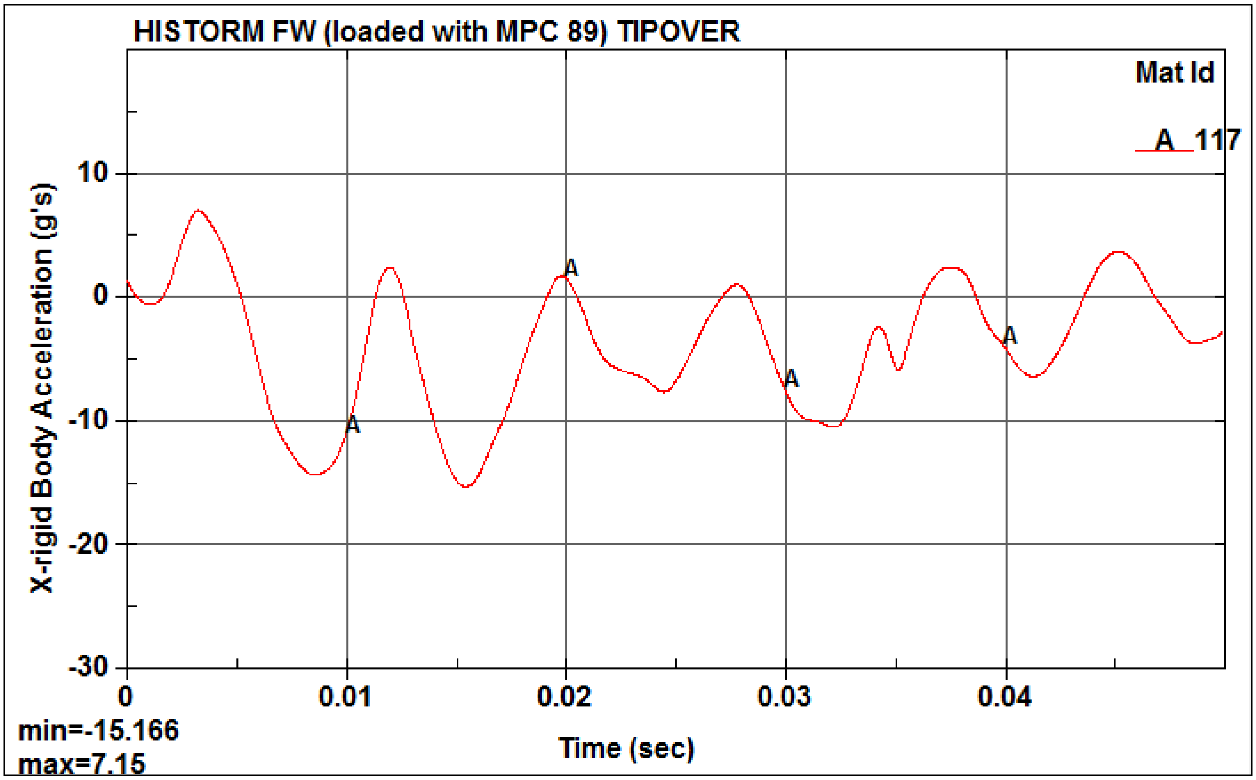
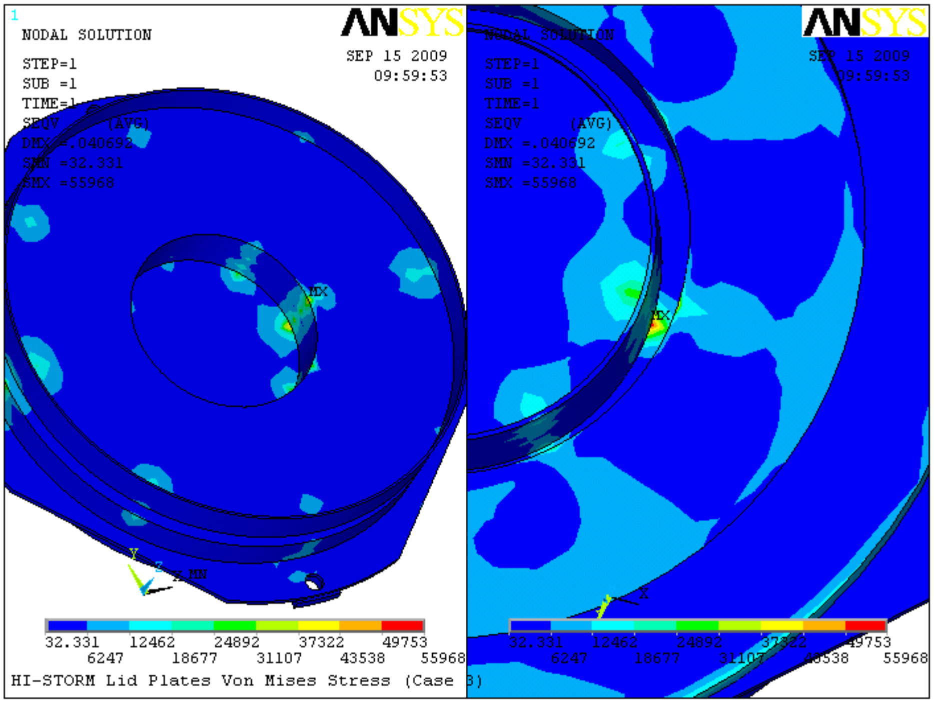
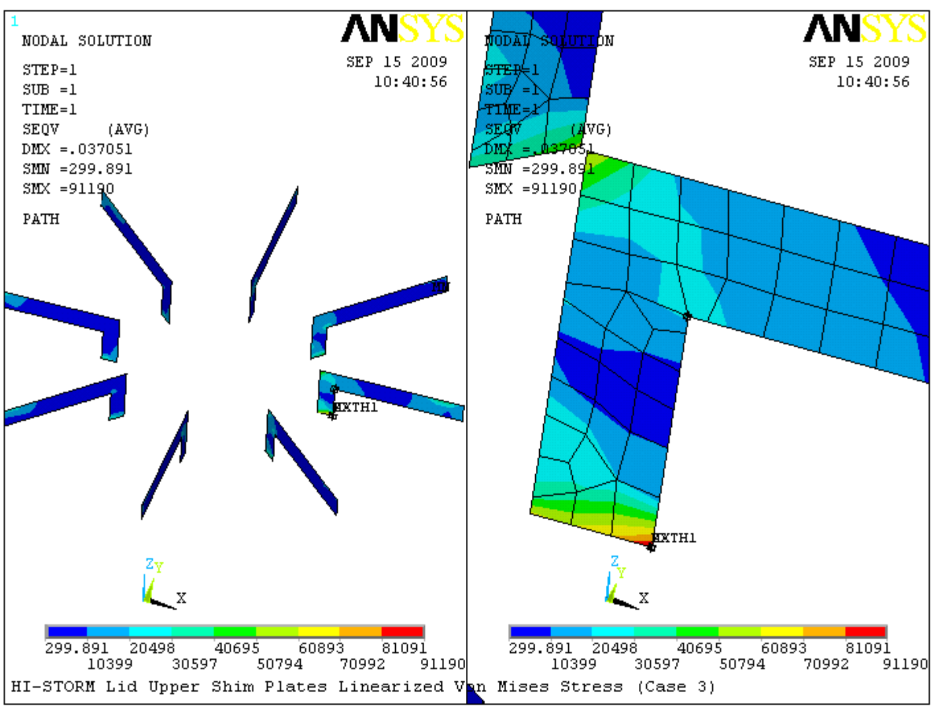


Figure 3.4.20B: Horizontal Rigid Body Deceleration Time History –
Cask Lid Concrete (for HI-STORM FW Loaded with MPC-89)



(a) Steel Weldment (Excluding Upper Shim Plates)



(b) Upper Shim Plates

Figure 3.4.21: Stress Distribution in HI-STORM FW Lid – Non-Mechanistic Tipover

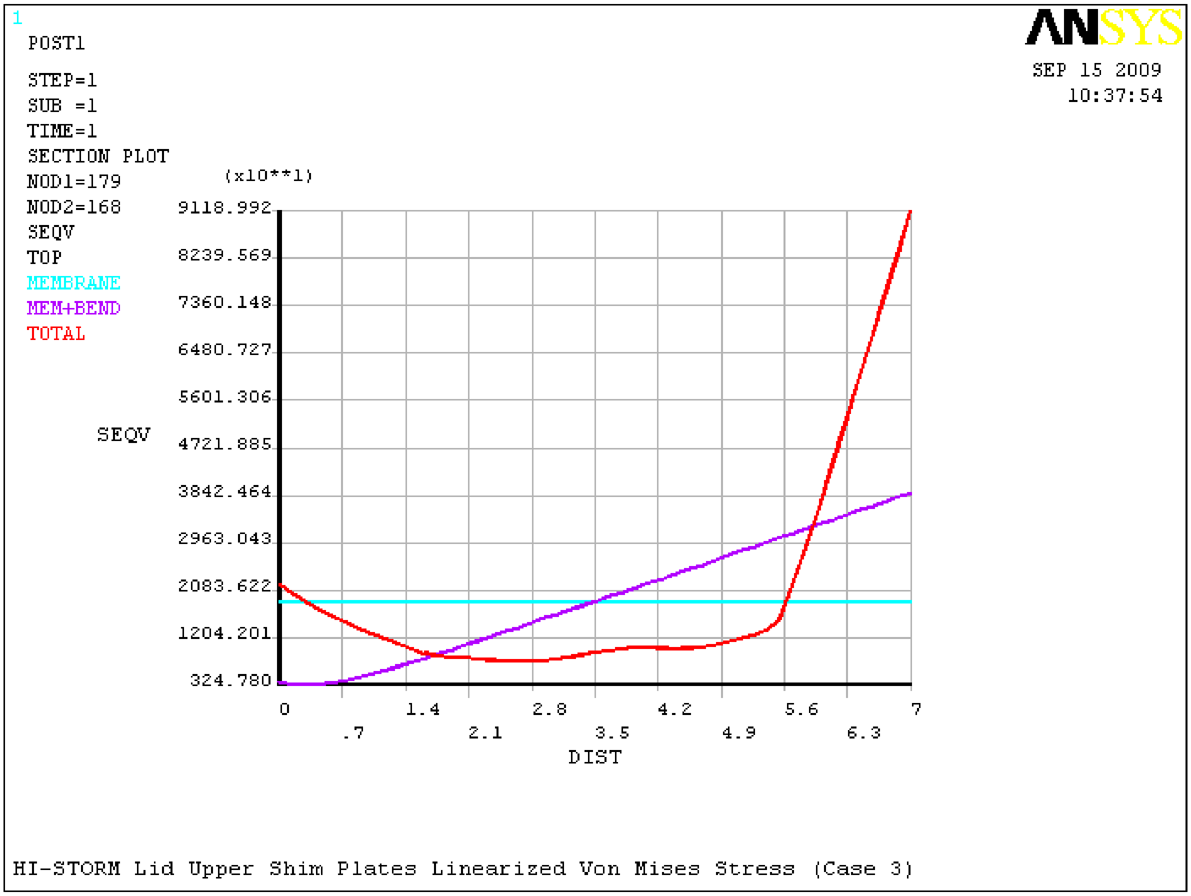


Figure 3.4.22: Linearized Stress Results for Upper Shim Plate – Non-Mechanistic Tipover

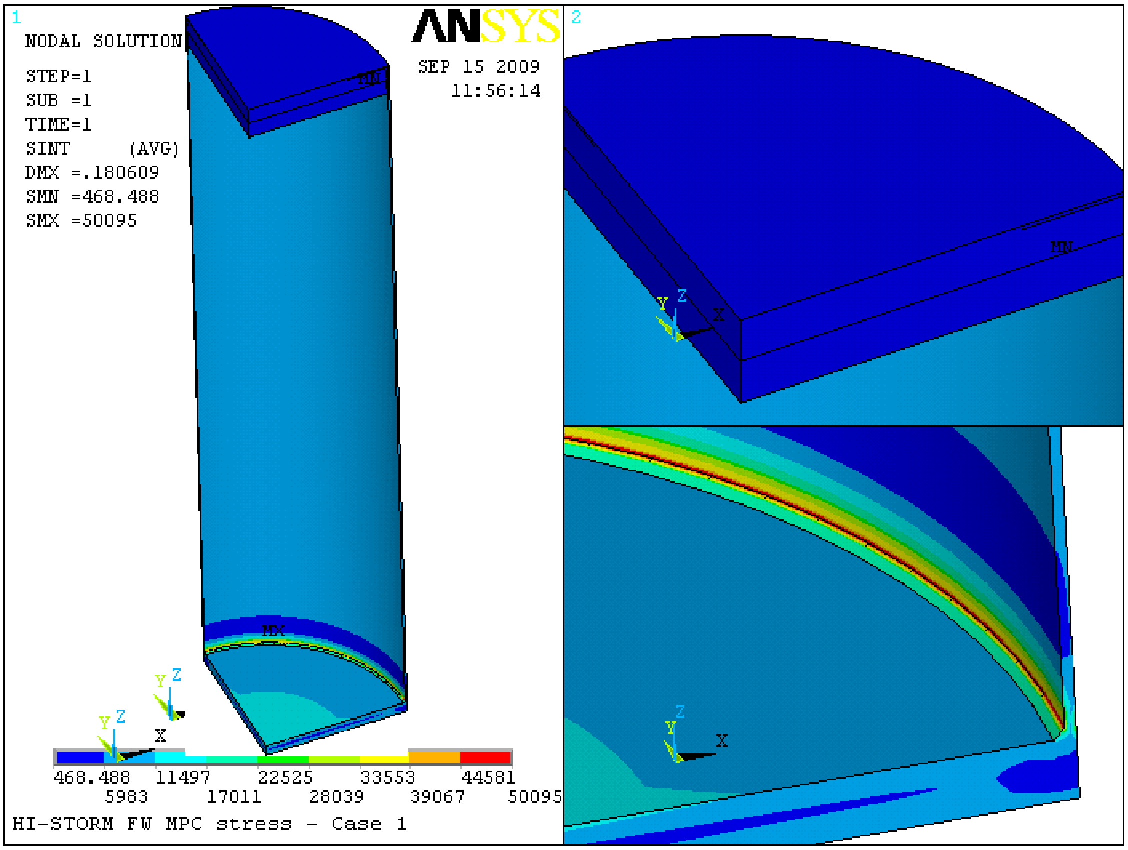


Figure 3.4.23: Stress Intensity Distribution in MPC Enclosure Vessel – Design Internal Pressure

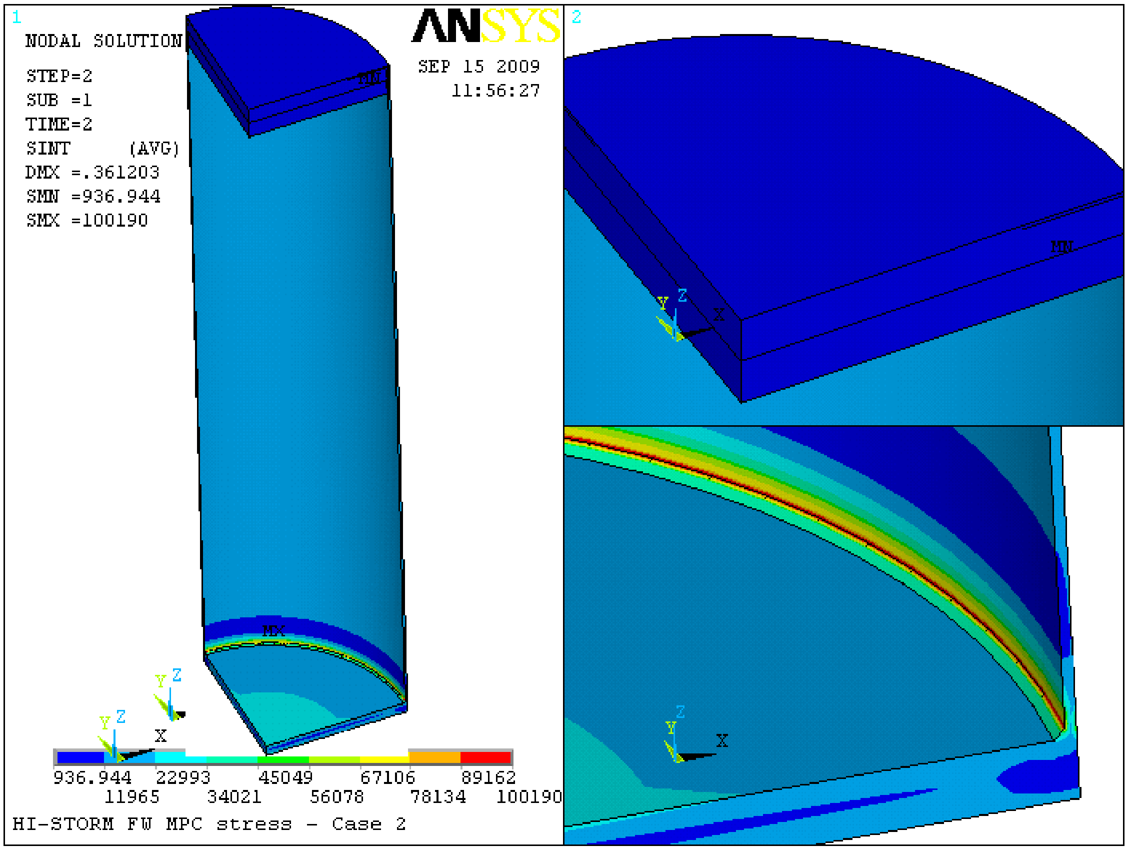
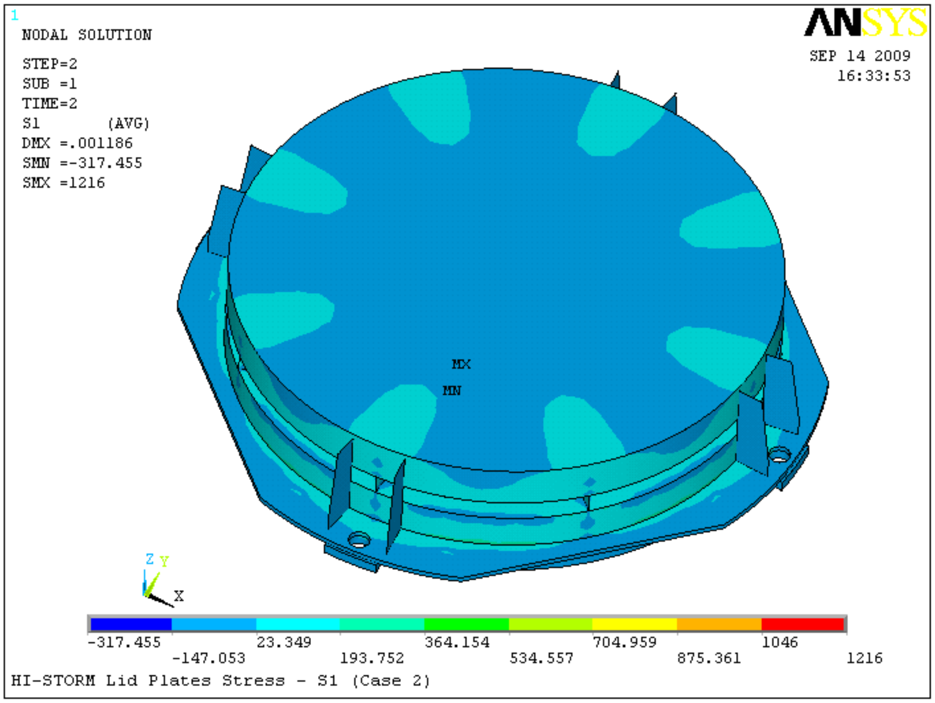
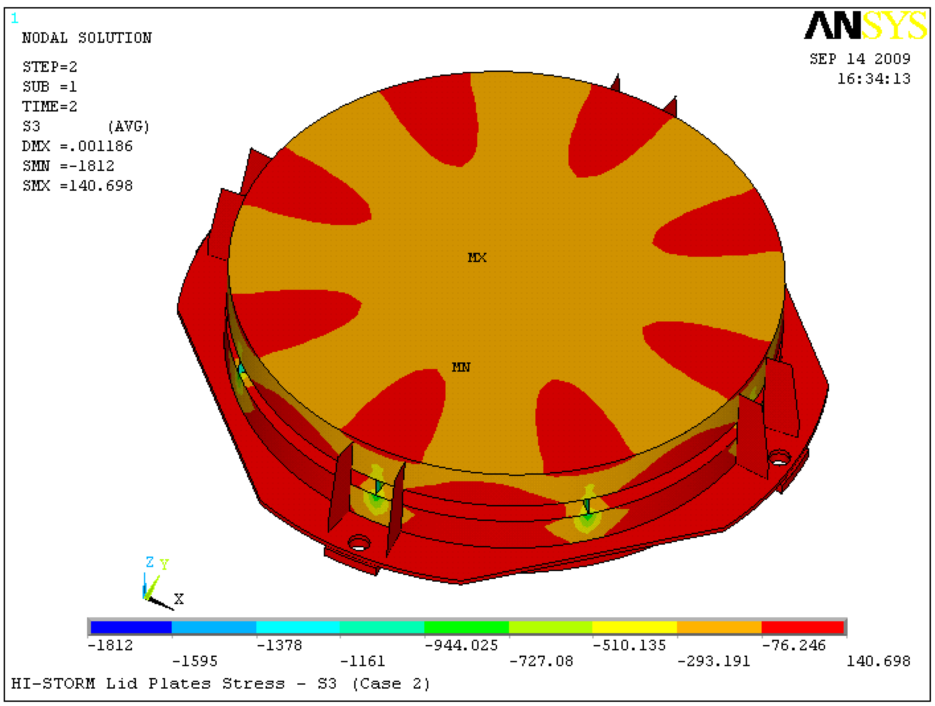


Figure 3.4.24: Stress Intensity Distribution in MPC Enclosure Vessel –
Accident Internal Pressure



(a) S1 Principal Stress



(b) S3 Principal Stress

Figure 3.4.25: Stress Distribution in HI-STORM FW Lid – Snow Load

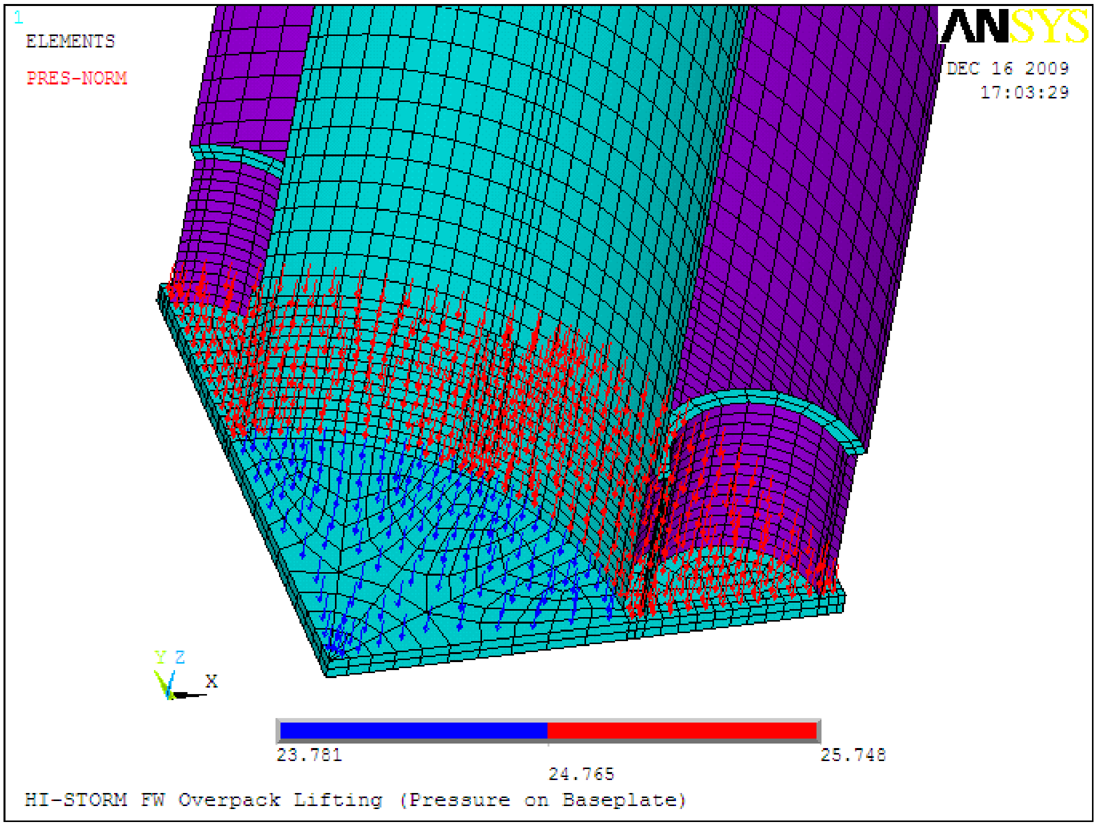


Figure 3.4.26: Applied Pressure on HI-STORM Baseplate
Simulating Concrete Shielding and Loaded MPC

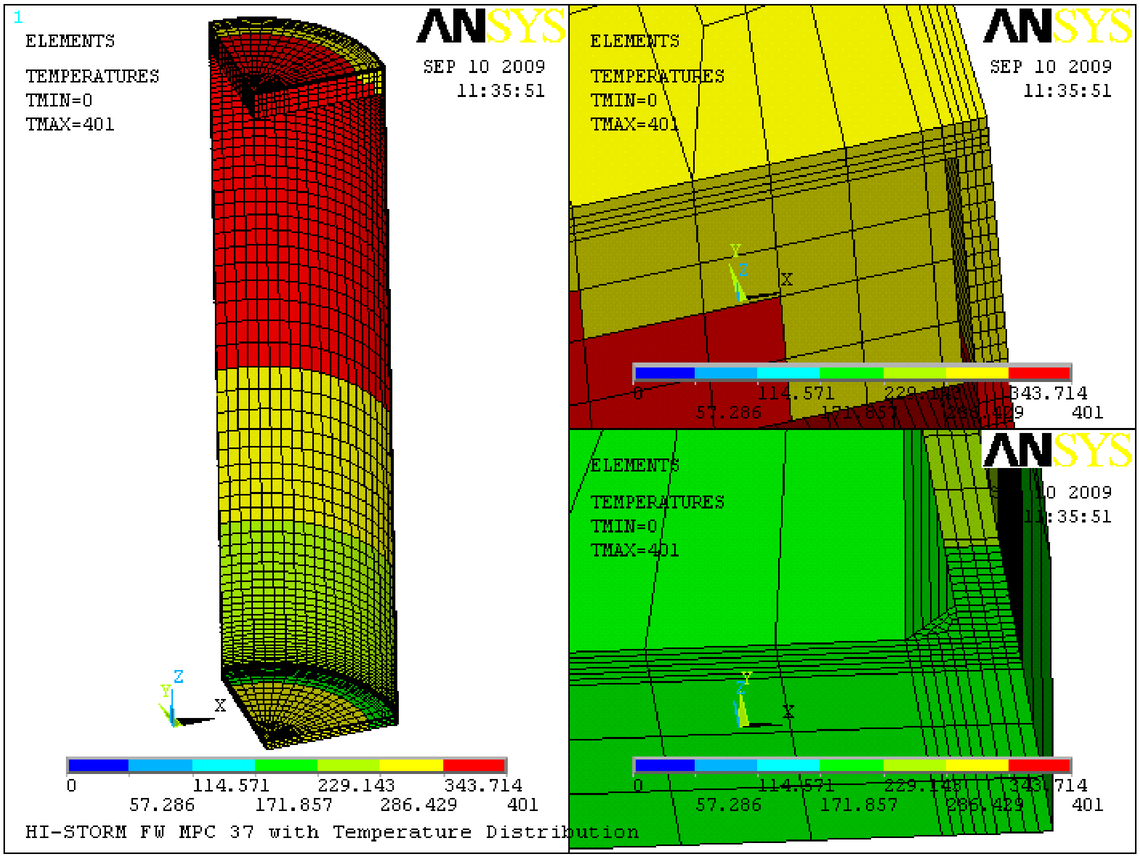


Figure 3.4.27: Normal Operating Temperature Distribution in MPC Enclosure Vessel

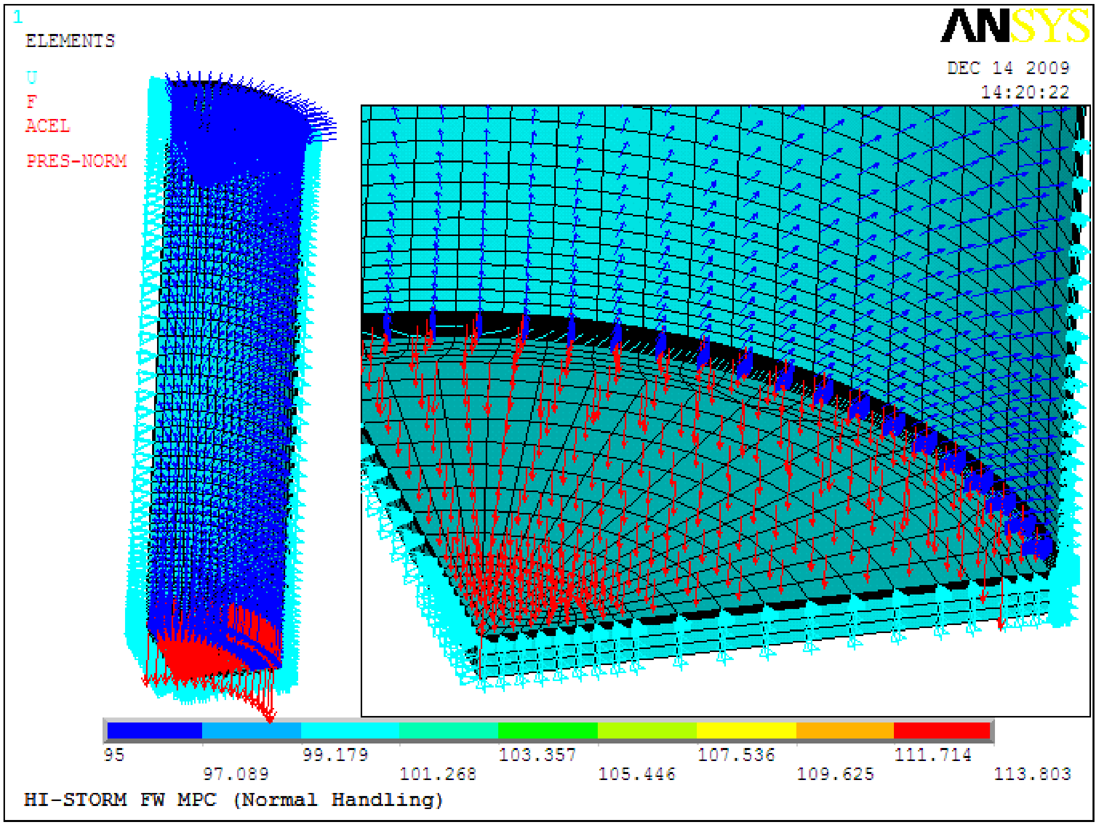


Figure 3.4.28: Normal Handling of MPC Enclosure Vessel –
Boundary Conditions and Applied Loads

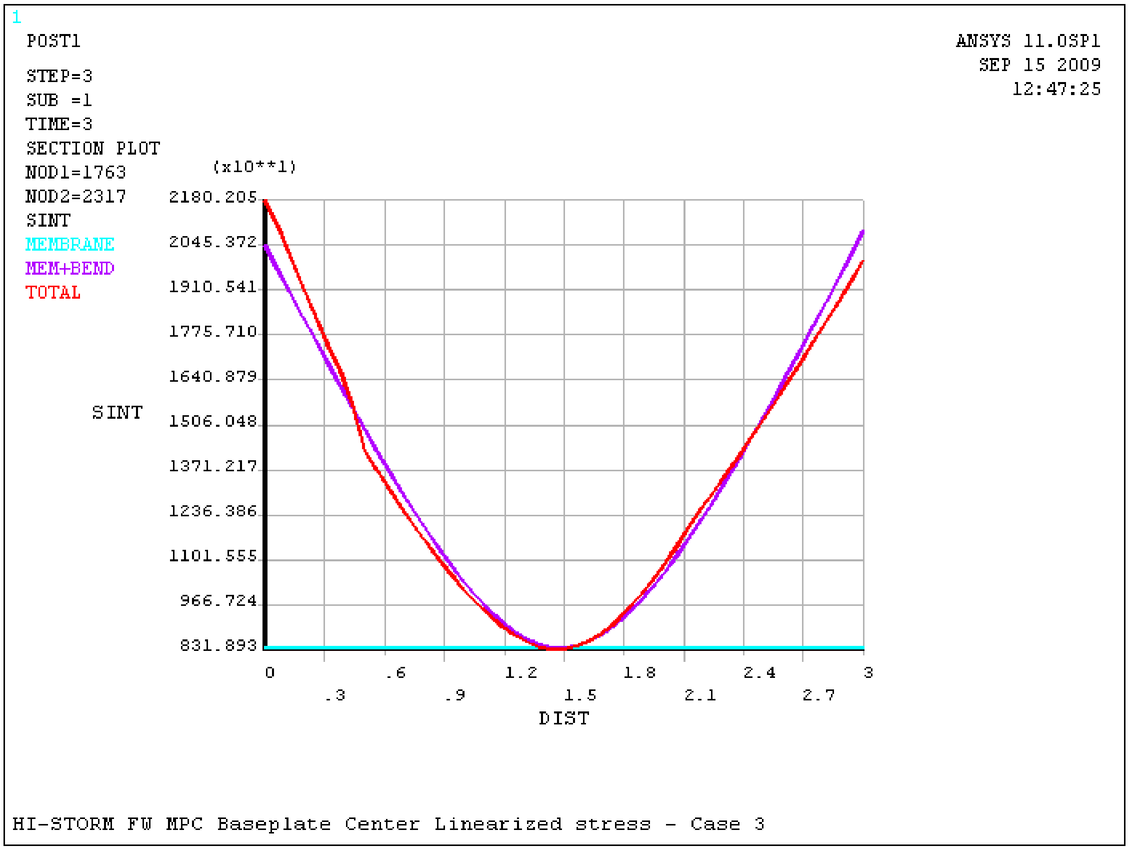


Figure 3.4.29: Normal Handling of MPC Enclosure Vessel –
Thru-Thickness Stress Intensity Plot at Baseplate Center

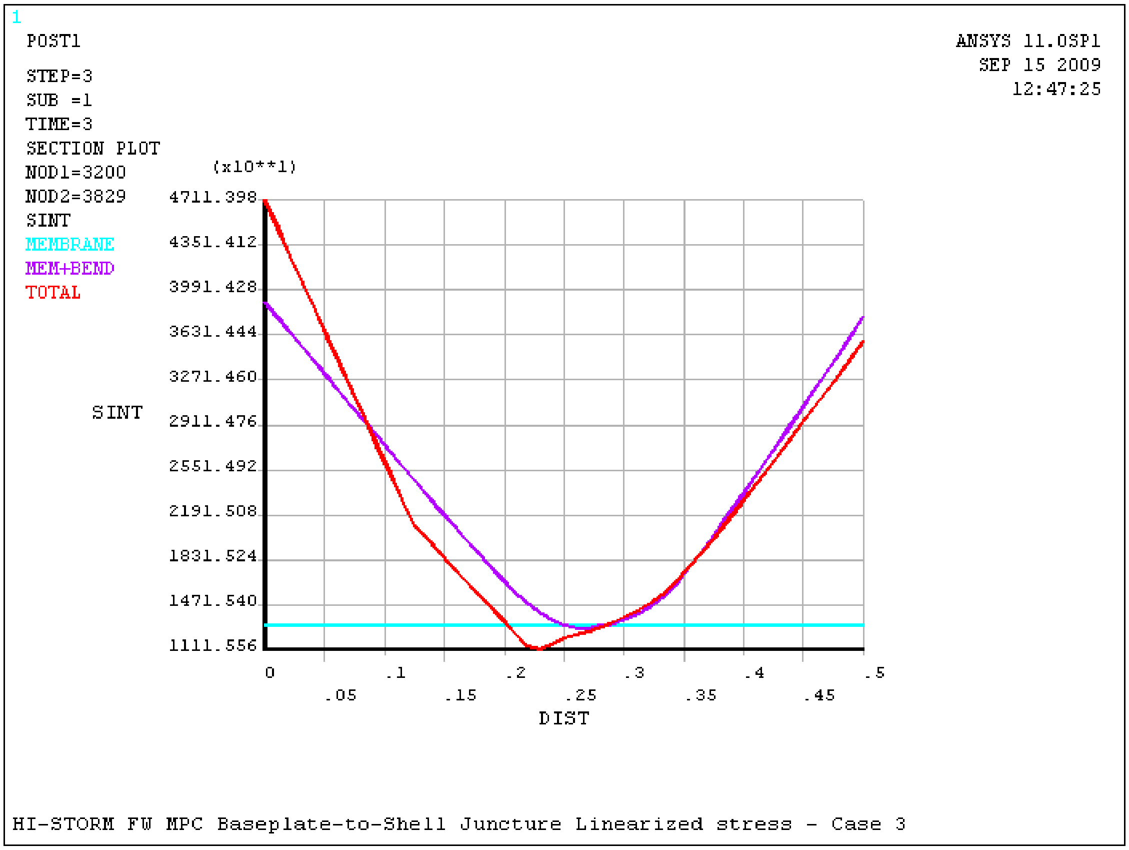


Figure 3.4.30: Normal Handling of MPC Enclosure Vessel –
Thru-Thickness Stress Intensity Plot at Baseplate-to-Shell Juncture

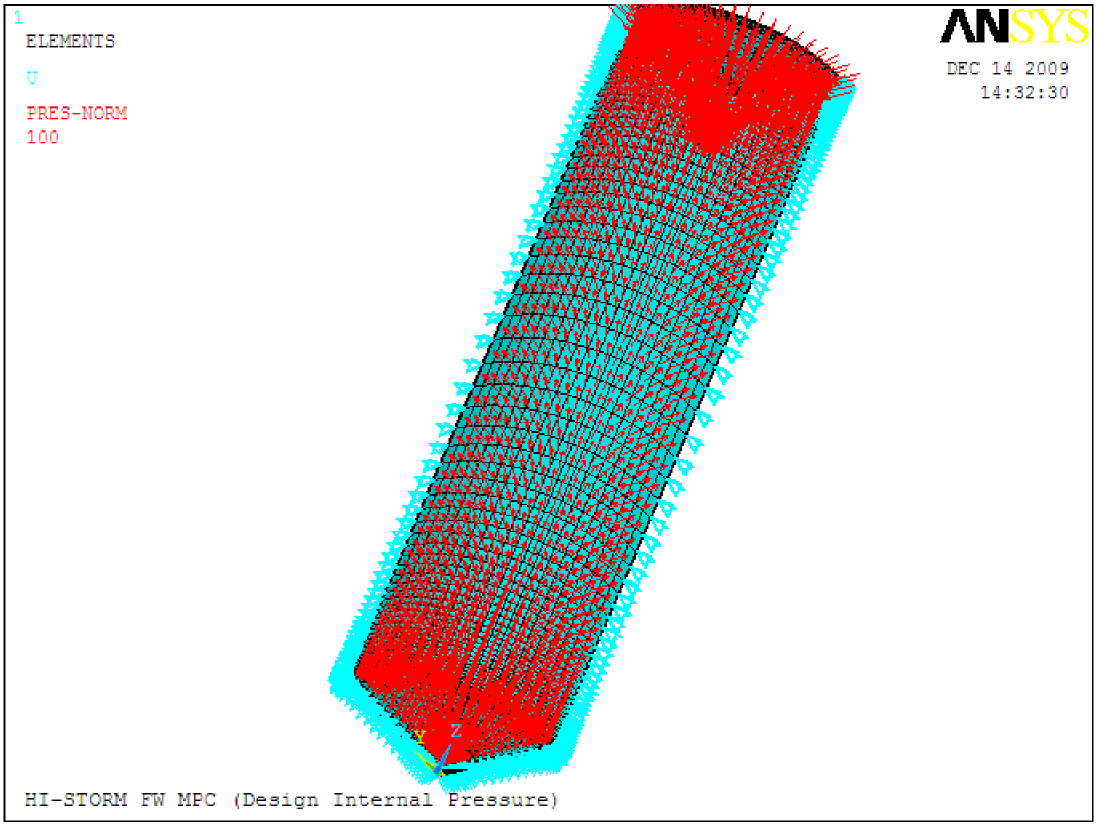


Figure 3.4.31: MPC Design Internal Pressure (Load Case 5) –
Boundary Conditions and Applied Loads

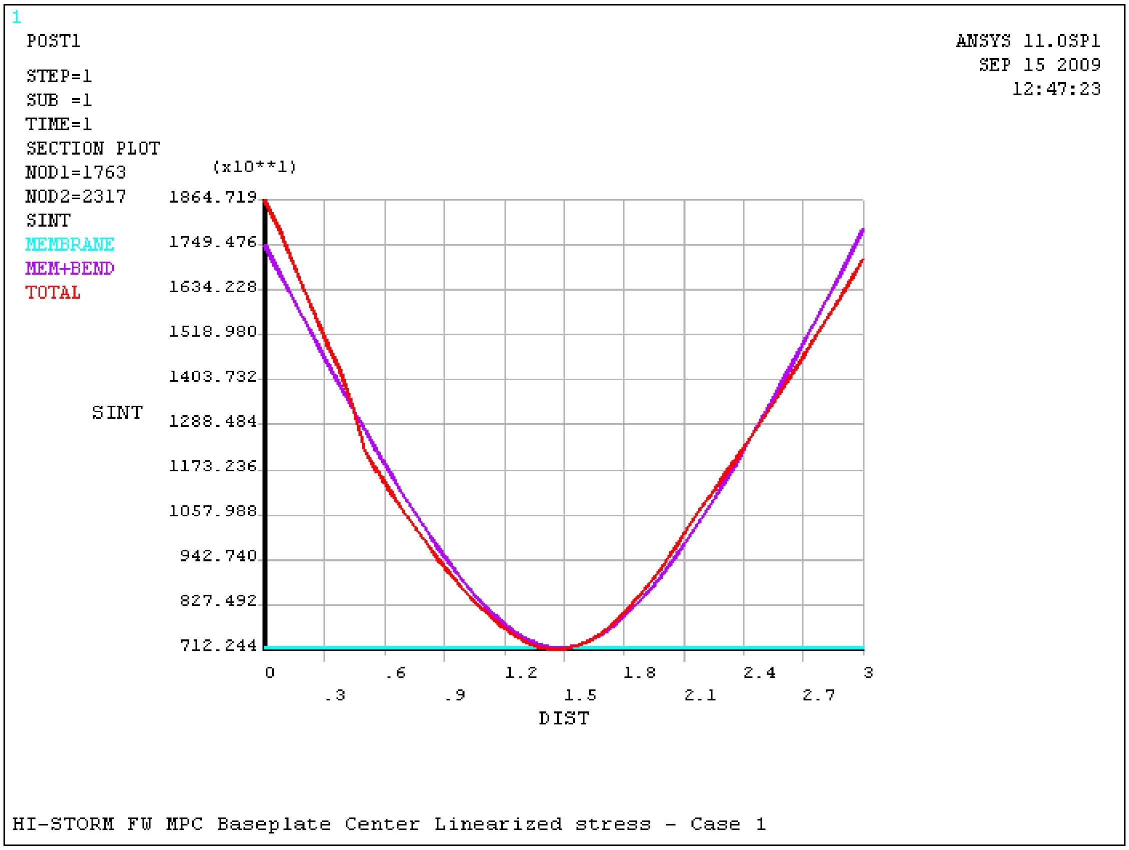


Figure 3.4.32: MPC Design Internal Pressure (Load Case 5) –
Thru-Thickness Stress Intensity Plot at Baseplate Center

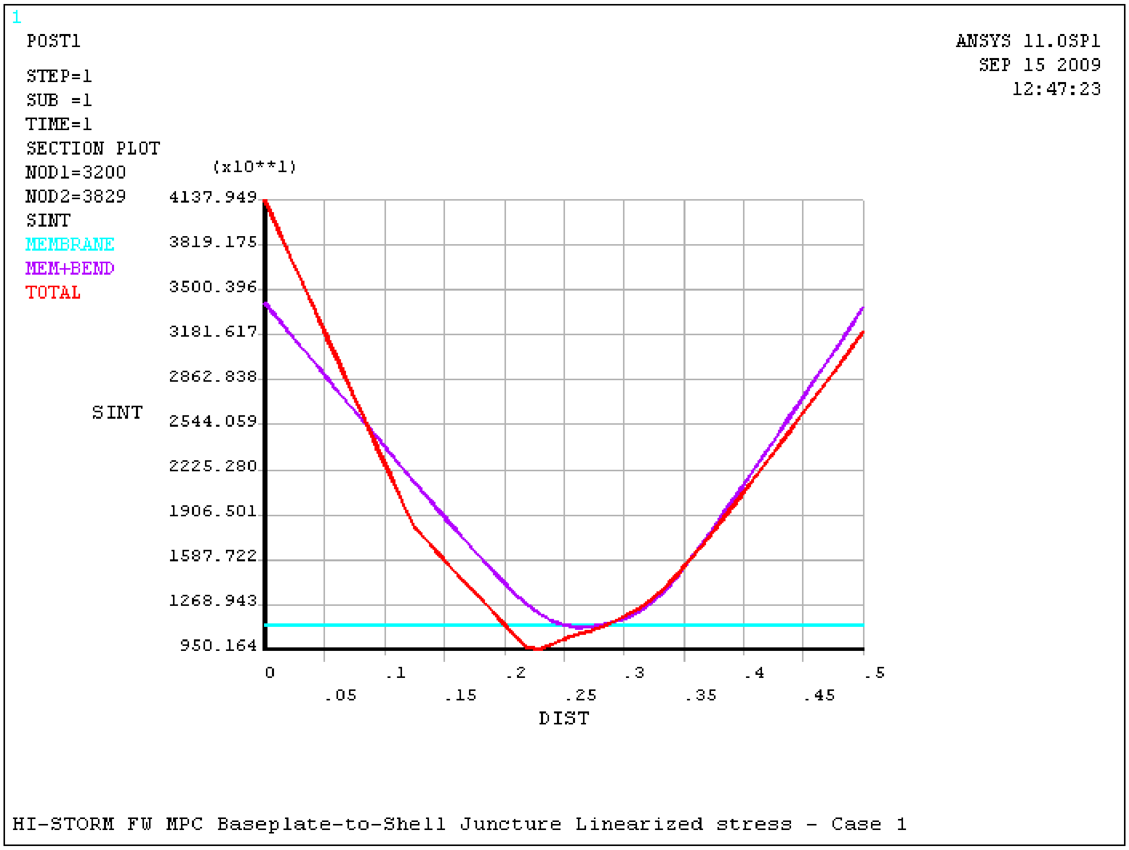


Figure 3.4.33: MPC Design Internal Pressure (Load Case 5) –
Thru-Thickness Stress Intensity Plot at Baseplate-to-Shell Juncture

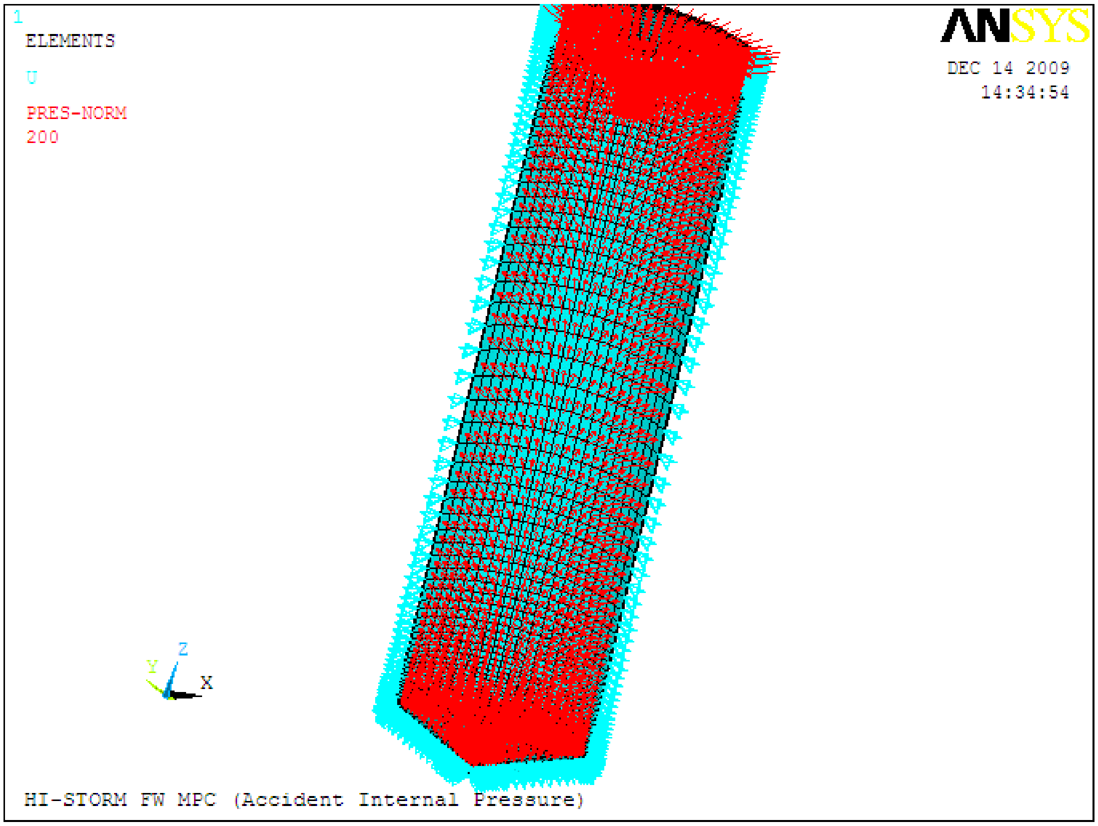


Figure 3.4.34: MPC Accident Internal Pressure (Load Case 6) –
Boundary Conditions and Applied Loads

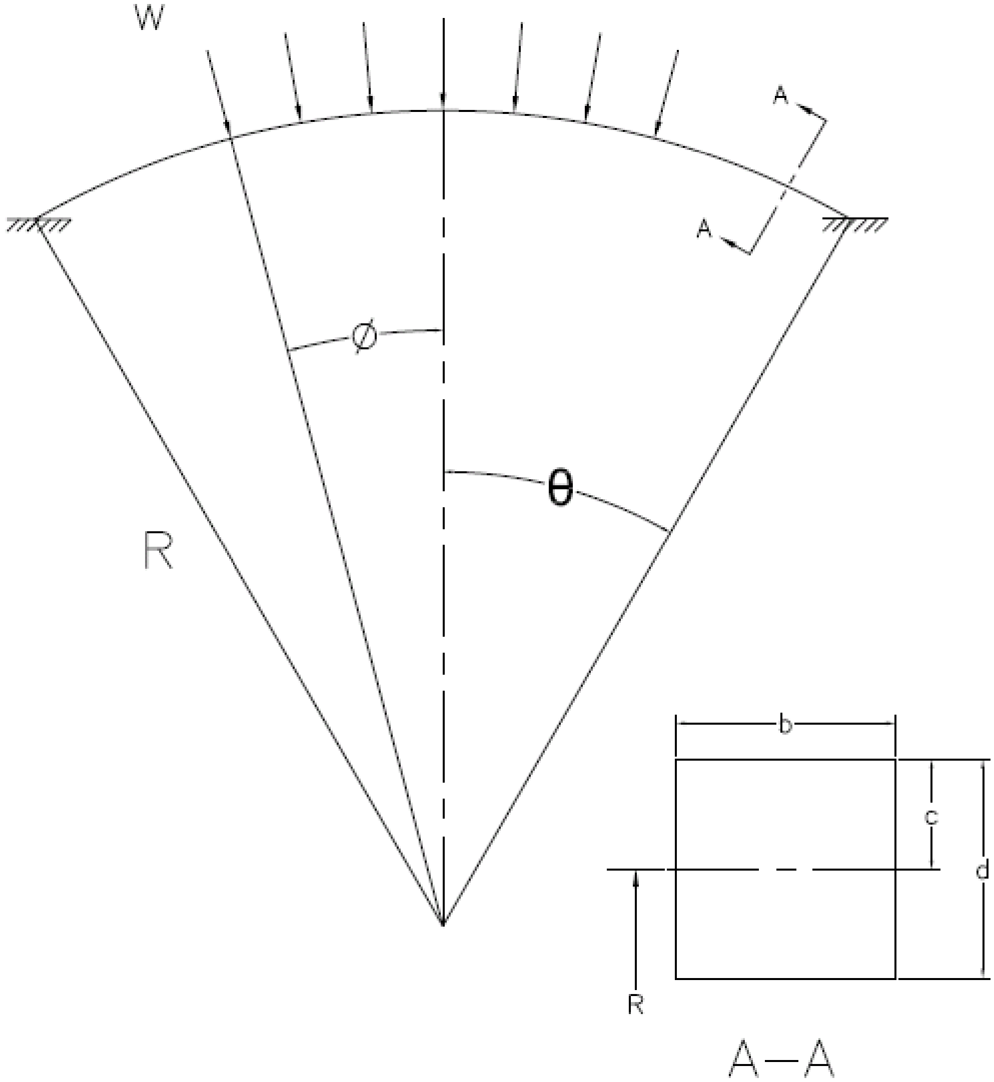


Figure 3.4.35: Analytical Model of HI-TRAC Water Jacket Shell (Load Case 8)

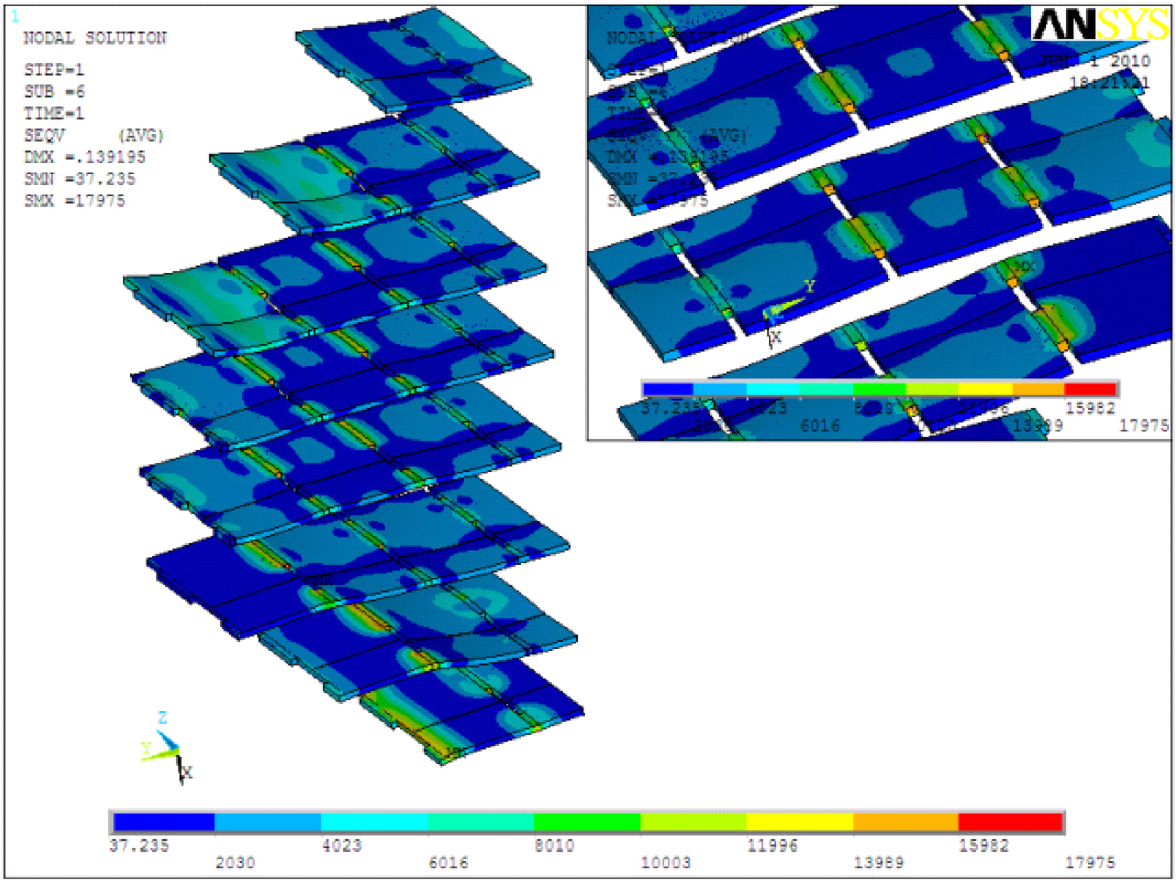


Figure 3.4.36: Stress Distribution in MPC-37 Fuel Basket (Horizontal Panels Only) under 65-g Static Load

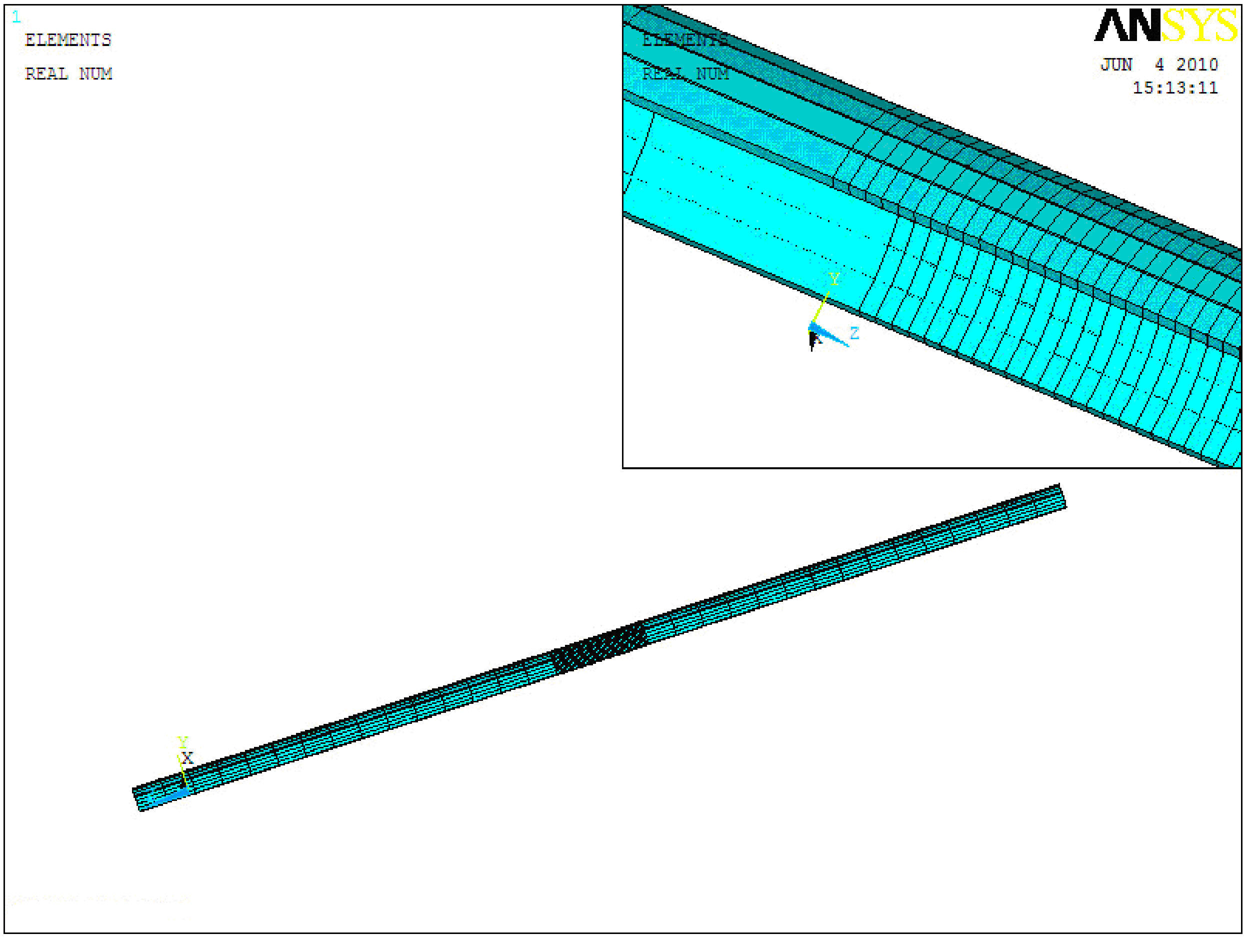


Figure 3.4.37: Finite Element Model for Fuel Rod Integrity Analysis (Load Case 11)

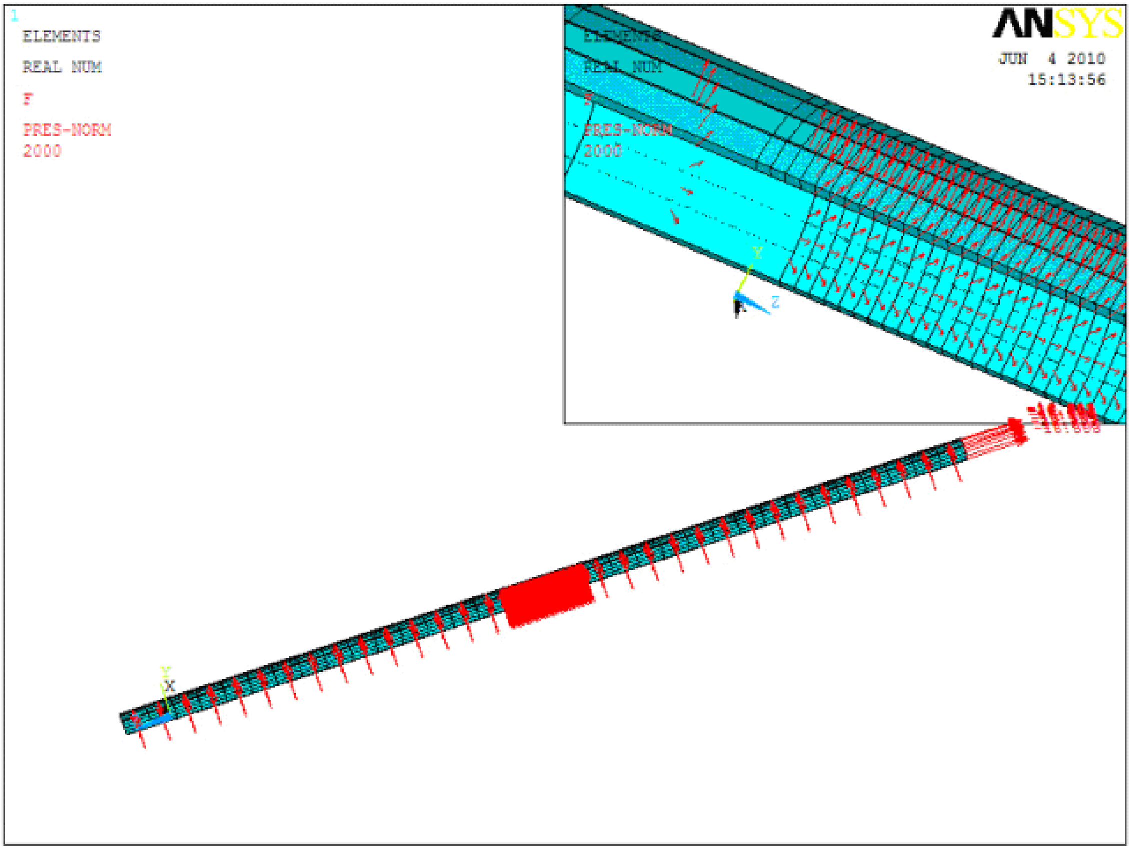


Figure 3.4.38: Applied Loads for Fuel Rod Integrity Analysis (Load Case 11)

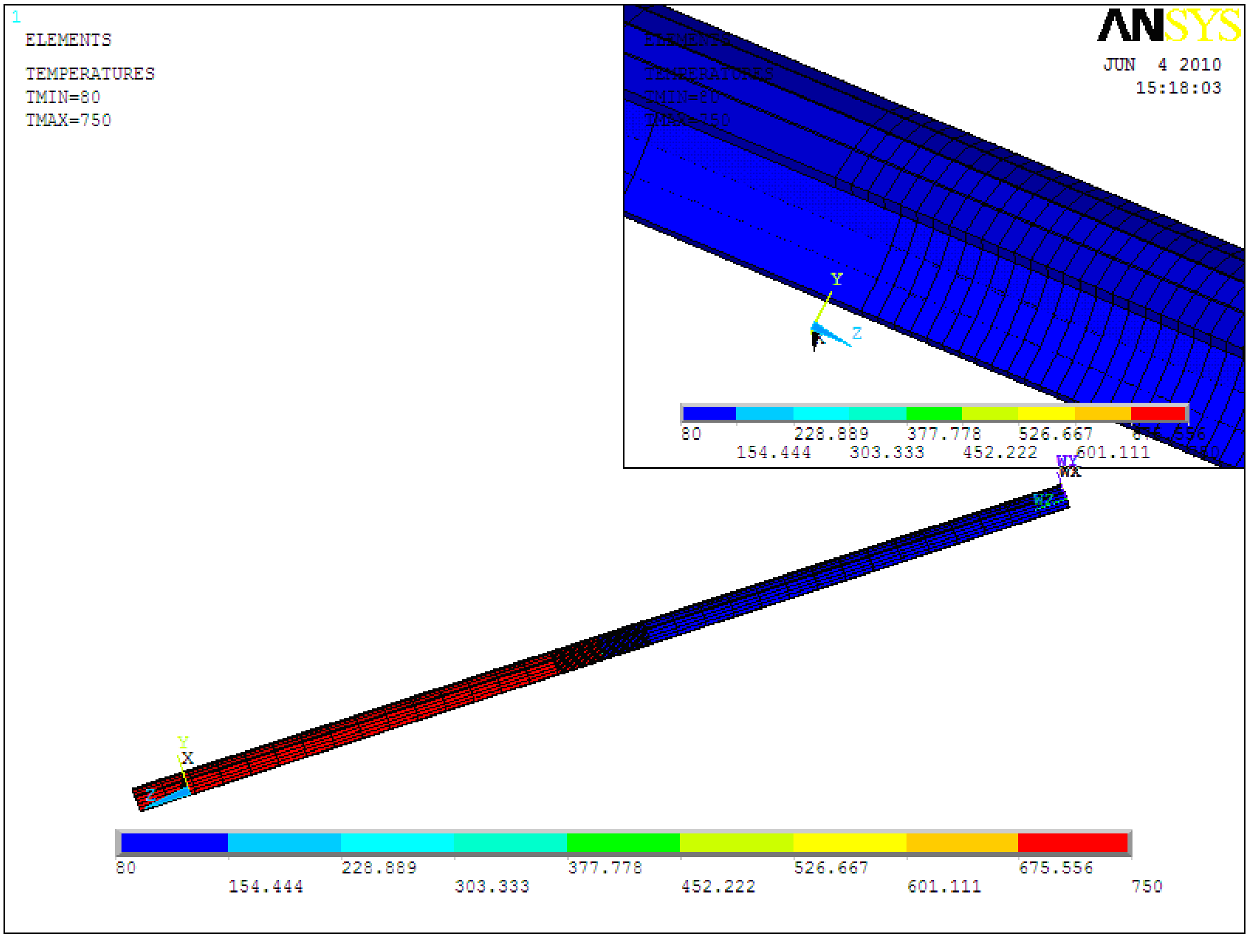


Figure 3.4.39: Applied Temperatures for Fuel Rod Integrity Analysis (Load Case 11)

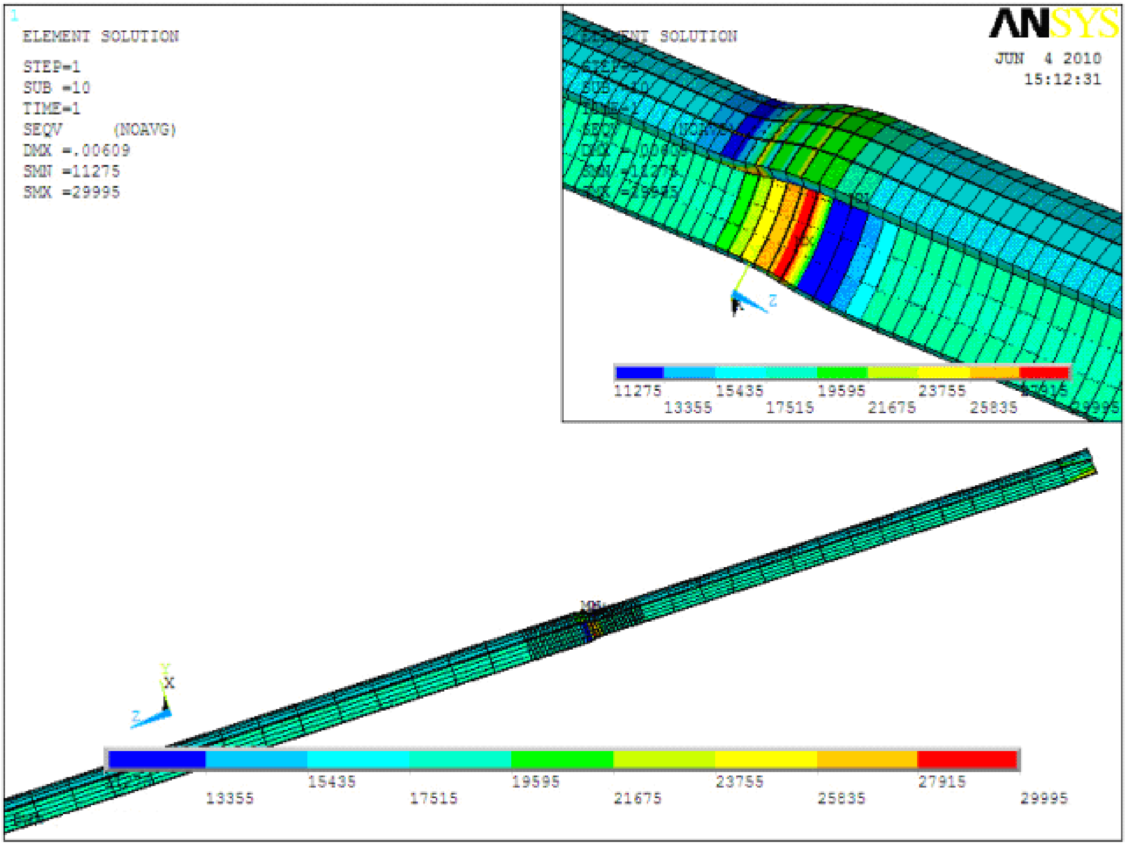


Figure 3.4.40: Stress Distribution in Fuel Rod Due to MPC Reflood (Load Case 11)

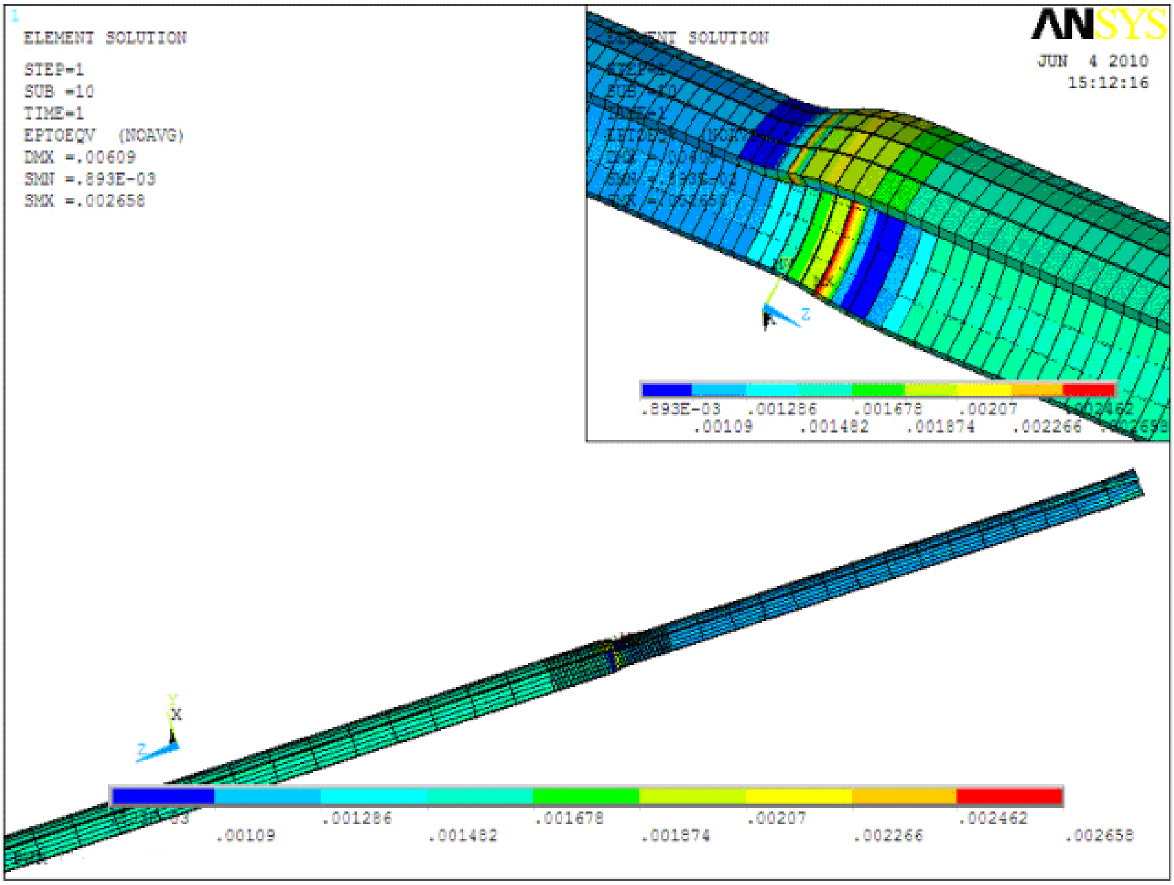


Figure 3.4.41: Strain Distribution in Fuel Rod Due to MPC Reflood (Load Case 11)

3.5 FUEL RODS

The regulations governing spent fuel storage cask approval and fabrication (10 CFR 72.236) require that a storage cask system "will reasonably maintain confinement of radioactive material under normal, off-normal, and credible accident conditions" (§72.236(l)). Although the cladding of intact fuel rods does provide a barrier against the release of radioactive fission products, the confinement evaluation for the HI-STORM FW system (Chapter 7) takes no credit for fuel cladding integrity in satisfying the regulatory confinement requirement.

As described in Section 7.1, the Confinement Boundary in the HI-STORM FW system consists of the MPC Enclosure Vessel. The Enclosure Vessel is designed and, to the extent practicable, manufactured in accordance with the most stringent ASME B&PV Code (Section III, Subsection NB). As required by NB, all materials are 100% UT inspected and all butt welds are subjected to 100% volumetric inspection. The field closure features redundant barriers (the MPC lid and port cover plates are the primary barriers, the closure ring is the secondary barrier). Section 7.1 further describes that the MPC design, welding, testing and inspection requirements meet the guidance of ISG-18 [7.1.2] such that leakage from the Confinement Boundary is non-credible. Section 7.2 addresses confinement for normal and off-normal conditions, and concludes that since the MPC confinement vessel remains intact, and the design bases temperatures and pressure are not exceeded, leakage from the MPC Confinement Boundary is not credible. Confinement for accident conditions is addressed in Section 7.3, which concludes that there is no mechanistic failure mode that could result in a breach of the Confinement Boundary, and escape of radioactive materials to the environment.

Since fuel rod cladding is not considered in the design criteria for the confinement of radioactive material under normal, off-normal, or accident conditions of storage, no specific analysis or test results are required to demonstrate cladding integrity.

3.6 SUPPLEMENTAL DATA

3.6.1 Calculation Packages

In addition to the calculations presented in Chapter 3, supporting calculation packages have been prepared to document other information pertinent to the analyses. Supporting calculation packages back up the summary results reported in the FSAR. The Calculation Packages are referenced in the body of the FSAR and are maintained as proprietary documents in Holtec's Configuration Control system.

3.6.2 Computer Programs

Two computer programs, all with a well established history of usage in the nuclear industry, have been utilized to perform structural and mechanical analyses documented in this FSAR. These codes are ANSYS and LS-DYNA. A third computer program, Visual Nastran, is also described below even though it is not explicitly used in this FSAR. It may, however, be used to perform the seismic stability evaluation of HI-STORM FW casks for a specific ISFSI site where NUREG/CR-6865 is not applicable (see Subsection 3.4.4.1.2).

i. ANSYS Mechanical

ANSYS is the original (and commonly used) name for ANSYS Mechanical general-purpose finite element analysis software. ANSYS Mechanical is the version of ANSYS commonly used for structural applications. It is a self contained analysis tool incorporating pre-processing (geometry creation, meshing), solver, and post processing modules in a unified graphical user interface. ANSYS Mechanical is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems. These problems include: static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems.

ANSYS Mechanical has been independently QA validated by Holtec International and used for structural analysis of casks, fuel racks, pressure vessels, and a wide variety of SSCs, for over twenty years.

ii. LS-DYNA

LS-DYNA is a general purpose finite element code for analyzing the large deformation static and dynamic response of structures including structures coupled to fluids. The main solution methodology is based on explicit time integration and is therefore well suited for the examination of the response to shock loading. A contact-impact algorithm allows difficult contact problems to be easily treated. Spatial discretization is achieved by the use of four node tetrahedron and eight node solid elements, two node beam elements, three and four node shell elements, eight node solid shell

elements, truss elements, membrane elements, discrete elements, and rigid bodies. A variety of element formulations are available for each element type. Adaptive re-meshing is available for shell elements. LS-DYNA currently contains approximately one hundred constitutive models and ten equations-of-state to cover a wide range of material behavior.

In this safety analysis report, LS-DYNA is used to analyze all loading conditions that involve short-time dynamic effects.

LS-DYNA is maintained in a QA-validated status in Holtec's Configuration Control system.

iii. Visual Nastran

Visual Nastran [3.6.1] is used for rigid body motion simulation of the cask components, where a simplified analysis is appropriate. VisualNastran is a kinematics simulation code that includes large orientation change capability, simulation of impacts, and representation of contact and friction behavior. Visual Nastran Desktop (VN) performs time history dynamic analysis of freestanding structures using the acceleration time-histories in the three orthogonal directions as the input. It provides a complete articulation of the dynamic response of the rigid body, including sliding, precession, and tipping (and combinations thereof). Visual Nastran is maintained in a QA-validated status by Holtec International.

All three computer codes have been benchmarked and QA-validated to establish their veracity.

The compliance matrix below provides the necessary information to document their validation status, and the measures employed pursuant to ISG-21 and Holtec's QA program, to ensure error-free solutions.

ISG-21 and QA Compliance Matrix for Computer Codes				
	Item	ANSYS	LS-DYNA	Visual Nastran
1.	Benchmark and QA-validation are documented in Holtec Report No.(s) (Proprietary Reports)	HI-2012627	HI-961519	HI-2022896
2.	Computer Program Type (Public or Private Domain)	Public Domain	Public Domain	Public Domain
3.	Does Holtec maintain a system evaluating error notices if any are issued by the Code provider to evaluate their effect on the safety analyses carried out using the Code, including Part 21 notification? (Yes/No)	Yes	Yes	Yes
4.	Is the use of the Code restricted to personnel qualified under the Company's personnel qualification program? (Yes/No)	Yes	Yes	Yes
5.	Has benchmarking been performed against sample problems with known independently obtained numerical solutions (Yes/No)	Yes	Yes	Yes
6.	Have element types used in the safety analyses herein also employed in the benchmarking effort? (Yes/No)	Yes	Yes	N/A
7.	Are the element types used in this FSAR also used in other Holtec dockets that support other CoCs? (Yes/No)	Yes	Yes	N/A
8.	Is each update of the Code vetted for backwards consistency with prior updates? (Yes/No)	Yes	Yes	Yes
9.	Is the use of the Code limited to the range of parameters specified in the User Manual provided by the Code Developer? (Yes/No)	Yes	Yes	Yes
10.	Are the element aspect ratios, where applicable, used in the simulation model within the limit recommended by the Code Developer or Holtec's successful experience in other safety analyses? (Yes/No)	Yes	Yes	N/A
11.	Are element sizes used in the simulation models consistent with past successful analyses in safety significant applications? (Yes/No)	Yes	Yes	N/A
12.	Was every computer run in this chapter free of an error warning (i.e., in hidden warnings in the Code that indicate a possible error in the solution? (Yes/No)	Yes	Yes	N/A
13.	If the answer to the above is No, then is the annotated warning discussed in the discussion of the result in this report?	N/A	N/A	N/A

3.7 COMPLIANCE WITH THE STRUCTURAL REQUIREMENTS IN PART 72

Supporting information to provide reasonable assurance with respect to the adequacy of the HI-STORM FW system to store spent nuclear fuel in accordance with the stipulations of 10CFR72 is presented throughout this FSAR. The following statements are applicable to an affirmative structural safety evaluation:

- The design and structural analysis of the HI-STORM FW system is in compliance with the provisions of Chapter 3 of NUREG-1536 as applicable.

- The HI-STORM FW structures, systems, and components (SSC) that are important to safety (ITS) are identified in the licensing drawings in Section 1.5. The licensing drawings present the HI-STORM FW SSCs in adequate detail and the explanatory narratives in Sections 3.1 and 3.4 provide sufficient textual details to allow an independent evaluation of their structural effectiveness.

- The requirements of 10CFR72.24 with regard to information pertinent to structural evaluation is provided in Chapters 2, 3, and 12.

- Technical Specifications pertaining to the structures of the HI-STORM FW system have been provided in Chapter 13 herein pursuant to the requirements of 10CFR72.26.

- A series of analyses to demonstrate compliance with the requirements of 10CFR72.122(b) and (c), and 10CFR72.24(c)(3) have been performed which show that SSCs in the HI-STORM FW system designated as ITS possess an adequate margin of safety with respect to all load combinations applicable to normal, off-normal, accident, and natural phenomenon events. In particular, the following information is provided:

    i. Load combinations for the fuel basket, enclosure vessel, and the HI-STORM FW/HI-TRAC VW overpacks for normal, off-normal, accident, and natural phenomenon events are provided in Subsection 3.1.2.2.

    ii. Stress limits applicable to the Code materials are found in Section 3.3.

    iii. The stress and displacement response of the fuel basket, the enclosure vessel, and the HI-STORM FW/HI-TRAC VW overpacks for all applicable loads have been computed by analysis and reported in Subsections 3.4.3 and 3.4.4. Descriptions of stress analysis models are presented in Subsection 3.1.3.

- The structural design and fabrication details of the fuel baskets whose safety function

in the HI-STORM FW system is to maintain nuclear criticality safety, are provided in the drawings in Section 1.5. The structural factors of safety, summarized in Section 3.4 for all credible load combinations under normal, off-normal, accident, and natural phenomenon events demonstrate that the acceptance criteria are satisfied in all cases. In particular, the maximum lateral deflection in the fuel basket panels under accident events has been determined to be within the limit used in the criticality analysis (see Subsection 3.4.4.1.4). Thus, the requirement of 10CFR72.124(a), with respect to structural margins of safety for SSCs important to nuclear criticality safety are fully satisfied.

- Structural margins of safety during handling, packaging, and transfer operations, under the provisions of 10CFR Part 72.236(b), imply that the lifting and handling devices be engineered to comply with the stipulations of ANSI N14.6, NUREG-0612. The requirements of the governing standards for handling operations are summarized in Subsection 3.4.3 herein. Factors of safety for all ITS components under lifting and handling operations are summarized in tables in Section 3.4, which show that adequate structural margins exist in all cases.

- Consistent with the provisions of 10CFR72.236(i), the Confinement Boundary for the HI-STORM FW system has been engineered to maintain confinement of radioactive materials under normal, off-normal, and postulated accident conditions. This assertion of confinement integrity is made on the strength of the following information provided in this FSAR.

  i. The MPC Enclosure Vessel which constitutes the Confinement Boundary is designed and fabricated in accordance with Section III, Subsection NB (Class 1 nuclear components) of the ASME Code to the maximum extent practicable.

  ii. The primary lid of the MPC Enclosure Vessel is welded using a strength groove weld and is subjected to multiple liquid penetrant examinations and pressure testing to establish a maximum confidence in weld joint integrity.

  iii. The closure system of the MPC Enclosure Vessel consists of *two* independent isolation barriers.

  iv. The Confinement Boundary is constructed from stainless steel alloys with a proven history of material integrity under the environmental conditions of an ISFSI.

  v. The load combinations for normal, off-normal, accident, and natural phenomena events have been compiled and applied on the MPC Enclosure Vessel (Confinement Boundary). The results, summarized in Section 3.4, show that the factor of safety (with respect to the appropriate limits) is greater

than one in all cases. Design Basis natural phenomena events such as tornado-borne missiles (large, intermediate, or small) have also been analyzed to evaluate their potential for reaching and breaching the Confinement Boundary. Analyses presented in Section 3.4 and supplemented by Appendices 3.A and 3.B show that the integrity of the Confinement Boundary is preserved under all design basis projectile impact scenarios.

- The information on structural design included in this FSAR complies with the requirements of 10CFR72.120 and 10CFR72.122.

- The structural design features in the HI-STORM FW system are in compliance with the specific requirements of 10CFR72.236(e), (f), (g), (h), (i), (j), (k), and (m).

3.8 REFERENCES

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[3.4.3] ASME Boiler & Pressure Vessel Code, Section III, Appendices, 2007.

[3.4.4] ASME Boiler & Pressure Vessel Code, Section III, Subsection NB, 2007.

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APPENDIX 3.A - RESPONSE OF HI-STORM FW AND HI-TRAC VW
TO TORNADO WIND LOAD AND LARGE MISSILE IMPACT

Withheld in Accordance with 10 CFR 2.390

APPENDIX 3.B - MISSILE PENETRATION ANALYSES
FOR HI-STORM FW AND HI-TRAC VW

Withheld in Accordance with 10 CFR 2.390

APPENDIX 3.C - CODE CASE N-284-2 STABILITY CALCULATIONS FOR MPC SHELL

Withheld in Accordance with 10 CFR 2.390