comparable to its counterpart in the HI-STORM 100 system. The material of construction of the pressure retaining components is also identical (options of stainless steels, denoted as Alloy X, are explained in Appendix 1.A herein as derived from the HI-STORM 100 FSAR with appropriate ASME Code edition updates). There are no gasketed joints in the MPCs.

ii. The top lid of the MPCs contains the same attachment provisions for lifting and handling the loaded canister as the HI-STORM 100 counterparts.

iii. The drain pipe and sump in the bottom baseplate of the MPCs (from which the drain pipe extracts the water during the dewatering operation) are also similar to those in the HI-STORM 100 counterparts.

iv. The fuel basket is assembled from a rectilinear gridwork of plates so that there are no bends or radii at the cell corners. This structural feature eliminates the source of severe bending stresses in the basket structure by eliminating the offset between the cell walls which transfer the inertia load of the stored SNF to the basket/MPC interface during the various postulated accident events (such as non-mechanistic tipover). This structural feature is shared with the HI-STORM 100 counterparts. Figures 1.1.6 and 1.1.7 show the PWR and BWR fuel baskets, respectively, in perspective view.

v. Precision extruded and/or machined blocks of aluminum alloy with axial holes (basket shims) are installed in the peripheral space between the fuel basket and the enclosure vessel to provide conformal contact surfaces between the basket shims and the fuel basket and between the basket shims and the enclosure vessel shell. The axial holes in the basket shims serve as the passageway for the downward flow of the helium gas under the thermosiphon action. This thermosiphon action is common to all MPCs including those of the HI-STORM 100. Various options are available to install these extruded shims in the basket periphery as summarized in Table 1.2.9.

vi. To facilitate an effective convective circulation inside the MPC, the operating pressure is set the same as that in the HI-STORM 100 counterparts.

vii. Like the high capacity baskets in the HI-STORM 100 MPCs, the fuel baskets do not contain flux traps (with the exception of the MPC-31C fuel basket).

Because of the above commonalities, the HI-STORM FW System is loaded in the same manner as the HI-STORM 100 system, and will use similar ancillary equipment, (e.g., lift attachments, lift yokes, lid welding machine, weld removal machine, cask transporter, mating device, low profile transporter or zero profile transporter, drying system, the hydrostatic pressure test system).

Lifting lugs, attached to the inside surface of the MPC shell, are used to place the empty MPC into the HI-TRAC VW transfer cask. The lifting lugs also serve to axially locate the MPC lid prior to welding. These internal lifting lugs cannot be used to handle a loaded MPC. The MPC lid is installed prior to any handling of a loaded MPC and there is no access to the internal lifting lugs once the MPC lid is installed.

The MPC incorporates a redundant closure system. The MPC lid is edge-welded (welds are depicted in the licensing drawing in Section 1.5) to the MPC outer shell. The lid is equipped with vent and drain ports that are utilized to remove moisture from the MPC and backfill the MPC with a specified amount of inert gas (helium). The vent and drain ports are closed tight and covered with a port cover (plate) that is seal welded before the closure ring is installed. The closure ring is a circular ring edge-welded to the MPC shell and lid; it covers the MPC lid-to shell weld and the vent and drain port cover plates. The MPC lid provides sufficient rigidity to allow the entire MPC loaded with SNF to be lifted by the suitably sized threaded anchor locations (TALs) in the MPC lid.

As discussed later in this section, the height of the MPC cavity plays a direct role in setting the amount of shielding available in the transfer cask. To maximize shielding and achieve ALARA within the constraints of a nuclear plant (such as crane capacity), it is necessary to minimize the cavity height of the MPC to the length of the fuel to be stored in it. Accordingly, the height of the MPC cavity is customized for each fuel type listed in Section 2.1. Table 3.2.1 provides the data to set the MPC cavity length as a small adder to the nominal fuel length (with any applicable NFH) to account for manufacturing tolerance, irradiation growth and thermal expansion effects.

For fuel assemblies that are shorter than the MPC cavity length (such as those without a control element in PWR SNF) a fuel shim may be utilized (as appropriate) to reduce the axial gap between the fuel assembly and the MPC cavity to approximately 1.5-2.5 inches. A small axial clearance is provided to account for manufacturing tolerances and the irradiation and thermal growth of the fuel assemblies. The actual length of fuel shims (if required) will be determined on a site-specific and fuel assembly-specific basis.

All components of the MPC assembly that may come into contact with spent fuel pool water or the ambient environment are made from stainless steel alloy or aluminum/aluminum alloy materials. Prominent among the aluminum based materials used in the MPC is the Metamic–HT neutron absorber lattice that comprises the fuel basket. As discussed in Chapter 8, concerns regarding interaction of coated carbon steel materials and various MPC operating environments [1.2.1] are not applicable to the HI-STORM FW MPCs. All structural components in an MPC enclosure vessel shall be made of Alloy X, a designation whose origin, as explained in the HI-STORM 100 FSAR [1.1.3], lies in the U.S. DOE's repository program.

As explained in Appendix 1.A, Alloy X (as defined in this FSAR) may be one of the following materials.

- Type 316
- Type 316LN
- Type 304
- Type 304LN
- Duplex Stainless Alloy S31803

Any stainless steel part in an MPC may be fabricated from any of the acceptable Alloy X materials listed above.

## 1.2.3 Cask Contents

This sub-section contains information on the cask contents pursuant to 10 CFR72, paragraphs 72.2(a)(1),(b) and 72.236(a),(c),(h),(m).

The HI-STORM FW System is designed to house both BWR and PWR spent nuclear fuel assemblies. Tables 1.2.1 and 1.2.2 provide key system data and parameters for the MPCs. A description of acceptable fuel assemblies for storage in the MPCs is provided in Section 2.1. This includes fuel assemblies classified as damaged fuel assemblies and fuel debris in accordance with the definitions of these terms in the Glossary. All fuel assemblies, non-fuel hardware, and neutron sources authorized for packaging in the MPCs must meet the fuel specifications provided in Section 2.1. All fuel assemblies classified as damaged fuel or fuel debris must be stored in damaged fuel containers (DFC).

As shown in Figure 1.2.1a (MPC-37) and Figure 1.2.2 (MPC-89), each storage location is assigned to one of three regions, denoted as Region 1, Region 2, and Region 3 with an associated cell identification number. For example, cell identified as 2-4 is Cell 4 in Region 2. A DFC can be stored in the outer peripheral locations of the MPC-37/MPC-32ML/MPC-31C and MPC-89 as shown in Figures 2.1.1 and 2.1.2, respectively. The permissible heat loads for each cell, region, and the total canister are given in Tables 1.2.3 and 1.2.4 for MPC-37/MPC-32ML/MPC-31C and MPC-89, respectively. The sub-design heat loads for each cell, region and total canister are in Table 4.4.11.

As an alternative to the loading patterns discussed above, fuel storage in the MPC-37 and MPC-89 is permitted to use the heat load patterns shown in Figure 1.2.3 through Figure 1.2.5 (MPC-37) and Figure 1.2.6 (MPC-89).

TABLE 1.2.1

KEY SYSTEM DATA FOR HI-STORM FW SYSTEM

| ITEM | QUANTITY | NOTES |
|---|---|---|
| Types of MPCs† | 4 | 3 for PWR<br>1 for BWR |
| MPC storage capacity: | MPC-37 | Up to 37 undamaged ZR clad PWR fuel assemblies with or without non-fuel hardware, of classes specified in Table 2.1.1a. Up to 12 damaged fuel containers containing PWR damaged fuel and/or fuel debris may be stored in the locations denoted in Figure 2.1.1a with the remaining basket cells containing undamaged fuel assemblies, up to a total of 37. Alternative damaged fuel patterns are shown in Figures 1.2.3 through 1.2.5. |
| MPC storage capacity: | MPC-89 | Up to 89 undamaged ZR clad BWR fuel assemblies. Up to 16 damaged fuel containers containing BWR damaged fuel and/or fuel debris may be stored in locations denoted in Figure 2.1.2 with the remaining basket cells containing undamaged fuel assemblies, up to a total of 89. Alternative damaged fuel patterns are shown in Figure 1.2.6. |
| MPC storage capacity: | MPC-32ML | Up to 32 undamaged ZR clad PWR fuel assemblies, of classes specified in Table 2.1.1b. Up to 8 damaged fuel containers containing PWR damaged fuel and/or fuel debris may be stored in the locations denoted in Figure 2.1.1b with the remaining basket cells containing undamaged fuel assemblies, up to a total of 32. |
| MPC storage capacity: | MPC-31C | Up to 31 undamaged ZR clad PWR fuel assemblies, of classes specified in Table 2.1.1c. Up to 6 damaged fuel containers containing PWR damaged fuel and/or fuel debris may be stored in the locations denoted in Figure 2.1.1c with the remaining basket cells containing undamaged fuel assemblies, up to a total of 31 (additional restrictions apply to total storage capacity, see Chapter 2). |

† See Chapter 2 for a complete description of authorized cask contents and fuel specifications.

| TABLE 1.2.3a<br>MPC-37 HEAT LOAD DATA (See Figure 1.2.1a for regions) | | | | | |
|---|---|---|---|---|---|
| Number of Regions: 3 | | | | | |
| Number of Storage Cells: 37 | | | | | |
| Maximum Design Basis Heat Load (kW): 44.09 (Pattern A); 45.0 (Pattern B); (Note 3) | | | | | |
| Region No. | Decay Heat Limit per Cell, kW (Notes 1 and 2) | | Number of Cells per Region | Decay Heat Limit per Region, kW | |
| | Pattern A | Pattern B | | Pattern A | Pattern B |
| 1 | 1.05 | 1.0 | 9 | 9.45 | 9.0 |
| 2 | 1.70 | 1.2 | 12 | 20.4 | 14.4 |
| 3 | 0.89 | 1.35 | 16 | 14.24 | 21.6 |

Notes:

(1) See Chapter 4 for decay heat limits per cell when vacuum drying high burnup fuel.

(2) Decay heat limit per cell for cells containing damaged fuel or fuel debris is equal to the decay heat limit per cell of the region where the damaged fuel or fuel debris is permitted to be stored.

(3) Alternative heat load patterns for the MPC-37 are included in Table 1.2.3d.

| TABLE 1.2.3d<br>ALTERNATIVE LOADING PATTERNS FOR THE MPC-37 | | | | |
|---|---|---|---|---|
| MPC Type | | Permissible Heat Load Per Storage Cell | | Maximum Heat Load, kW |
| MPC-37 | Short Fuel (Note 1) | Undamaged Only | Figure 1.2.3a | 37.4 |
| | | Undamaged and Damaged | Figure 1.2.3b | 34.4 |
| | | Undamaged, Damaged, and/or Fuel Debris | Figure 1.2.3c | 34.4 |
| | Standard Fuel (Note 1) | Undamaged Only | Figure 1.2.4a | 39.95 |
| | | Undamaged and Damaged | Figure 1.2.4b | 36.65 |
| | | Undamaged, Damaged, and/or Fuel Debris | Figure 1.2.4c | 36.65 |
| | Long Fuel (Note 1) | Undamaged Only | Figure 1.2.5a | 44.85 |
| | | Undamaged and Damaged | Figure 1.2.5b | 40.95 |
| | | Undamaged, Damaged, and/or Fuel Debris | Figure 1.2.5c | 40.95 |

Notes:

1. See Table 1.2.10 for fuel length data.

| TABLE 1.2.4a<br>MPC-89 HEAT LOAD DATA (See Figure 1.2.2 for regions) | | | |
|---|---|---|---|
| Number of Regions: 3 | | | |
| Number of Storage Cells: 89 | | | |
| Maximum Design Basis Heat Load: 46.36 kW (Note 3) | | | |
| Region No. | Decay Heat Limit per Cell, kW (Notes 1 and 2) | Number of Cells per Region | Decay Heat Limit per Region, kW |
| 1 | 0.44 | 9 | 3.96 |
| 2 | 0.62 | 40 | 24.80 |
| 3 | 0.44 | 40 | 17.60 |

Note:

(1) See Chapter 4 for decay heat limits per cell when loading high burnup fuel and using vacuum drying of the MPC.

(2) Decay heat limit per cell for cells containing damaged fuel or fuel debris is equal to the decay heat limit per cell of the region where the damaged fuel or fuel debris is permitted to be stored.

(3) Alternative heat load patterns for the MPC-89 are included in Table 1.2.4b.

| TABLE 1.2.4b<br>ALTERNATIVE LOADING PATTERNS FOR THE MPC-89 | | | |
|---|---|---|---|
| MPC Type | Permissible Heat Load Per Storage Cell | | Maximum Heat Load, kW |
| MPC-89 | Undamaged Only | Figure 1.2.6a | 46.2 |
| | Undamaged, Damaged, and/or Fuel Debris | Figure 1.2.6b | 44.92 |

TABLE 1.2.8b
INVARIANT PROPERTIES OF METAMIC-HT USED IN SAFETY ANALYSIS

| | Property | Temperature, °C | Property Value (Note 1) | Property Type |
|---|---|---|---|---|
| 1. | Thermal conductivity, k (W/m°k) | Ambient<br>200/300/350<br>450/500 | 180/180/180/180<br>180/180 | Invariant |
| 2. | Emissivity (dimensionless), e | 150≤T≤500 | 0.85 | Invariant |
| 3. | Nominal specific gravity, (dimensionless) s | Ambient | 2.705 | Invariant |
| 4. | Average thermal expansion, coefficient, Γ ($^oC^{-1}$) | 30≤T≤500 | $21x10^{-6}$ | Invariant |
| 5. | Specific Heat, $C_p$ (J/kg-$^o$C) | 100/200/350<br>350≤T≤500 | 823.3/914.1/1024.2<br>Note 3 | Invariant |

Note 1: Properties can be interpolated, use 40$^o$C for ambient when interpolating.

Note 2: Intentionally Deleted

**Note 3: Heat Capacity Function**

T: Temperature ($^o$C)

Cp = 1024.2 + 0.493(T-350)

| TABLE 1.2.10<br><br>PWR FUEL LENGTH CATEGORIES | |
|---|---|
| Category | Length Range |
| Short Fuel | 128 inches ≤ L < 144 inches |
| Standard Fuel | 144 inches ≤ L < 168 inches |
| Long Fuel | L ≥ 168 inches |
| Notes:<br><br>1. "L" means "nominal active fuel length". The nominal, unirradiated active fuel length of the PWR fuel assembly is used to designate it as "short", "standard" and "long". | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.45 | 0.45 | 0.45 | | |
| | 0.45 | 3.2 | 0.5 | 3.2 | 0.45 | |
| 0.6 | 2.4 | 0.5 | 0.6 | 0.5 | 2.4 | 0.6 |
| 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 |
| 0.6 | 2.4 | 0.5 | 0.6 | 0.5 | 2.4 | 0.6 |
| | 0.45 | 3.2 | 0.5 | 3.2 | 0.45 | |
| | | 0.45 | 0.45 | 0.45 | | |

Figure 1.2.3a: Alternative MPC-37 Loading Pattern for MPCs Containing Only Undamaged Fuel, "Short" Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

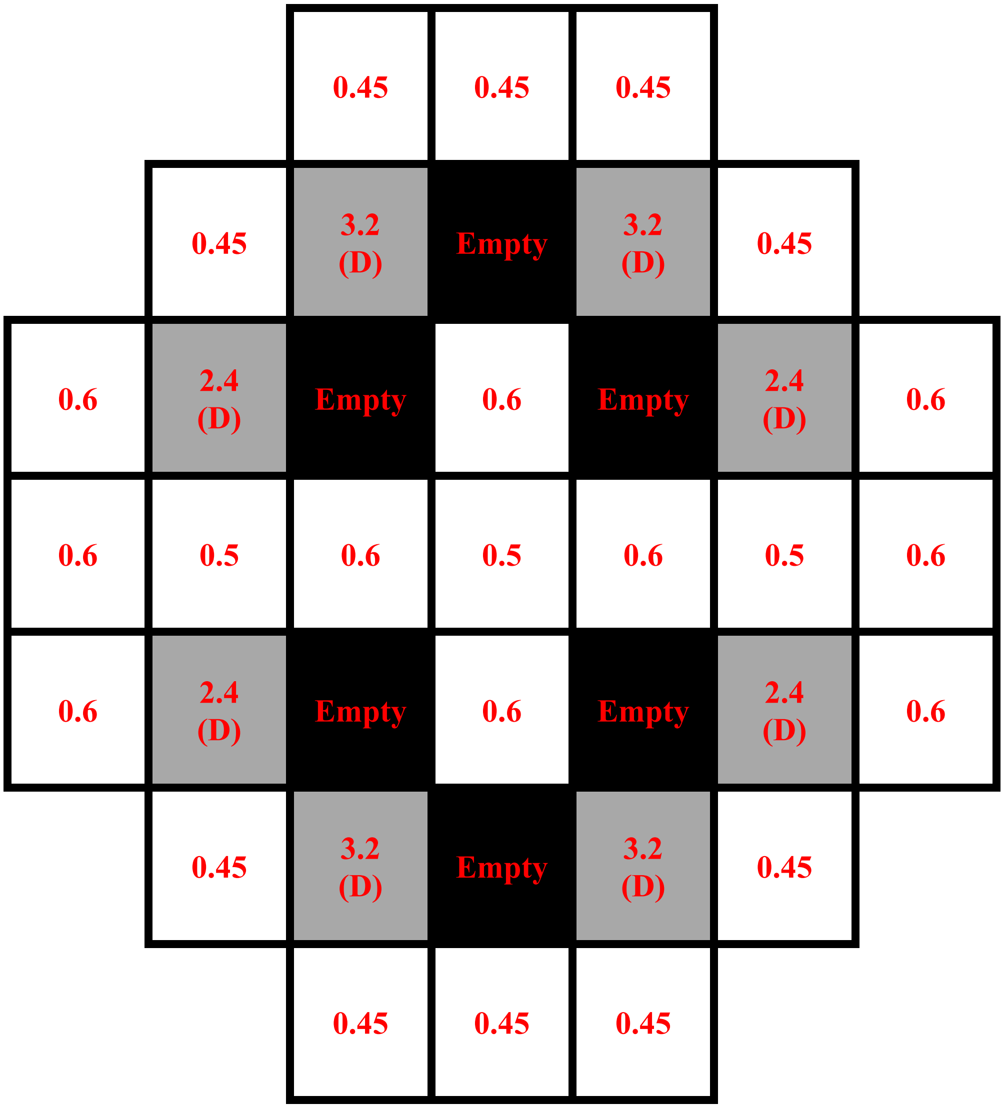


Figure 1.2.3b: Alternative MPC-37 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel in DFCs, "Short" Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel or damaged fuel in a DFC may be stored in cells denoted by "D". Cells denoted as "Empty" must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.45 | 0.45 | 0.45 | | |
| | 0.45 | 3.2 (D/F) | Empty | 3.2 (D/F) | 0.45 | |
| 0.6 | 2.4 | Empty | 0.6 | Empty | 2.4 | 0.6 |
| 0.6 | 0.5 | 0.6 | 0.5 | 0.6 | 0.5 | 0.6 |
| 0.6 | 2.4 | Empty | 0.6 | Empty | 2.4 | 0.6 |
| | 0.45 | 3.2 (D/F) | Empty | 3.2 (D/F) | 0.45 | |
| | | 0.45 | 0.45 | 0.45 | | |

Figure 1.2.3c: Alternative MPC-37 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel and/or Fuel Debris in DFCs, "Short" Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel, damaged fuel in a DFC, or fuel debris in a DFC may be stored in cells denoted by "D/F". Cells denoted as "Empty" must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.55 | 0.55 | 0.55 | | |
| | 0.55 | 3.2 | 0.55 | 3.2 | 0.55 | |
| 0.75 | 2.4 | 0.55 | 0.65 | 0.55 | 2.4 | 0.75 |
| 0.75 | 0.55 | 0.65 | 0.55 | 0.65 | 0.55 | 0.75 |
| 0.75 | 2.4 | 0.55 | 0.65 | 0.55 | 2.4 | 0.75 |
| | 0.55 | 3.2 | 0.55 | 3.2 | 0.55 | |
| | | 0.55 | 0.55 | 0.55 | | |

Figure 1.2.4a: Alternative MPC-37 Loading Pattern for MPCs Containing Only Undamaged Fuel, "Standard" Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.55 | 0.55 | 0.55 | | |
| | 0.55 | 3.2 (D) | Empty | 3.2 (D) | 0.55 | |
| 0.75 | 2.4 (D) | Empty | 0.65 | Empty | 2.4 (D) | 0.75 |
| 0.75 | 0.55 | 0.65 | 0.55 | 0.65 | 0.55 | 0.75 |
| 0.75 | 2.4 (D) | Empty | 0.65 | Empty | 2.4 (D) | 0.75 |
| | 0.55 | 3.2 (D) | Empty | 3.2 (D) | 0.55 | |
| | | 0.55 | 0.55 | 0.55 | | |

Figure 1.2.4b: Alternative MPC-37 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel in DFCs, “Standard” Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel or damaged fuel in a DFC may be stored in cells denoted by “D”. Cells denoted as “Empty” must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.55 | 0.55 | 0.55 | | |
| | 0.55 | 3.2 (D/F) | Empty | 3.2 (D/F) | 0.55 | |
| 0.75 | 2.4 | Empty | 0.65 | Empty | 2.4 | 0.75 |
| 0.75 | 0.55 | 0.65 | 0.55 | 0.65 | 0.55 | 0.75 |
| 0.75 | 2.4 | Empty | 0.65 | Empty | 2.4 | 0.75 |
| | 0.55 | 3.2 (D/F) | Empty | 3.2 (D/F) | 0.55 | |
| | | 0.55 | 0.55 | 0.55 | | |

Figure 1.2.4c: MPC-37 Heat Load Chart for MPCs Containing Undamaged Fuel and Damaged Fuel and/or Fuel Debris in DFCs, “Standard” Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel, damaged fuel in a DFC, or fuel debris in a DFC may be stored in cells denoted by “D/F”. Cells denoted as “Empty” must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.65 | 0.65 | 0.65 | | |
| | 0.65 | 3.5 | 0.65 | 3.5 | 0.65 | |
| 0.85 | 2.6 | 0.65 | 0.75 | 0.65 | 2.6 | 0.85 |
| 0.85 | 0.65 | 0.75 | 0.65 | 0.75 | 0.65 | 0.85 |
| 0.85 | 2.6 | 0.65 | 0.75 | 0.65 | 2.6 | 0.85 |
| | 0.65 | 3.5 | 0.65 | 3.5 | 0.65 | |
| | | 0.65 | 0.65 | 0.65 | | |

Figure 1.2.5a: Alternative MPC-37 Loading Pattern for MPCs Containing Only Undamaged Fuel, “Long” Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.65 | 0.65 | 0.65 | | |
| | 0.65 | 3.5 (D) | Empty | 3.5 (D) | 0.65 | |
| 0.85 | 2.6 (D) | Empty | 0.75 | Empty | 2.6 (D) | 0.85 |
| 0.85 | 0.65 | 0.75 | 0.65 | 0.75 | 0.65 | 0.85 |
| 0.85 | 2.6 (D) | Empty | 0.75 | Empty | 2.6 (D) | 0.85 |
| | 0.65 | 3.5 (D) | Empty | 3.5 (D) | 0.65 | |
| | | 0.65 | 0.65 | 0.65 | | |

Figure 1.2.5b: Alternative MPC-37 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel in DFCs, “Long” Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel or damaged fuel in a DFC may be stored in cells denoted by “D”. Cells denoted as “Empty” must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.65 | 0.65 | 0.65 | | |
| | 0.65 | 3.5 (D/F) | Empty | 3.5 (D/F) | 0.65 | |
| 0.85 | 2.6 | Empty | 0.75 | Empty | 2.6 | 0.85 |
| 0.85 | 0.65 | 0.75 | 0.65 | 0.75 | 0.65 | 0.85 |
| 0.85 | 2.6 | Empty | 0.75 | Empty | 2.6 | 0.85 |
| | 0.65 | 3.5 (D/F) | Empty | 3.5 (D/F) | 0.65 | |
| | | 0.65 | 0.65 | 0.65 | | |

Figure 1.2.5c: Alternative MPC-37 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel and/or Fuel Debris in DFCs, “Long” Fuel per Cell Heat Load Limits

(All storage cell heat loads are in kW)

Note that undamaged fuel, damaged fuel in a DFC, or fuel debris in a DFC may be stored in cells denoted by “D/F”. Cells denoted as “Empty” must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.25 | 0.25 | 0.25 | | | | |
| | | 0.25 | 0.25 | 0.25 | 1.45 | 0.25 | 0.25 | 0.25 | | |
| | 0.25 | 0.25 | 1.45 | 0.9 | 0.9 | 0.9 | 1.45 | 0.25 | 0.25 | |
| | 0.25 | 1.45 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 1.45 | 0.25 | |
| 0.25 | 0.25 | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 0.25 | 0.25 |
| 0.25 | 1.45 | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 1.45 | 0.25 |
| 0.25 | 0.25 | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 0.25 | 0.25 |
| | 0.25 | 1.45 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 1.45 | 0.25 | |
| | 0.25 | 0.25 | 1.45 | 0.9 | 0.9 | 0.9 | 1.45 | 0.25 | 0.25 | |
| | | 0.25 | 0.25 | 0.25 | 1.45 | 0.25 | 0.25 | 0.25 | | |
| | | | | 0.25 | 0.25 | 0.25 | | | | |

Figure 1.2.6a: Alternative MPC-89 Loading Pattern for MPCs Containing Only Undamaged Fuel, per Cell Heat Load Limits

(All Storage cell heat loads are in kW)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.25 | 0.25 | 0.25 | | | | |
| | | 0.25 | 0.25 | 0.25 | 1.45 (D/F) | 0.25 | 0.25 | 0.25 | | |
| | 0.25 | 0.25 | 1.45 (D/F) | 0.9 | 0.9 | 0.9 | 1.45 (D/F) | 0.25 | 0.25 | |
| | 0.25 | 1.45 (D/F) | Empty | 0.32 | 0.32 | 0.32 | Empty | 1.45 (D/F) | 0.25 | |
| 0.25 | 0.25 | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 0.25 | 0.25 |
| 0.25 | 1.45 (D/F) | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 1.45 (D/F) | 0.25 |
| 0.25 | 0.25 | 0.9 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.9 | 0.25 | 0.25 |
| | 0.25 | 1.45 (D/F) | Empty | 0.32 | 0.32 | 0.32 | Empty | 1.45 (D/F) | 0.25 | |
| | 0.25 | 0.25 | 1.45 (D/F) | 0.9 | 0.9 | 0.9 | 1.45 (D/F) | 0.25 | 0.25 | |
| | | 0.25 | 0.25 | 0.25 | 1.45 (D/F) | 0.25 | 0.25 | 0.25 | | |
| | | | | 0.25 | 0.25 | 0.25 | | | | |

Figure 1.2.6b: Alternative MPC-89 Loading Pattern for MPCs Containing Undamaged Fuel and Damaged Fuel and/or Fuel Debris in DFCs, per Cell Heat Load Limits
(All Storage cell heat loads are in kW)

Note that undamaged fuel, damaged fuel in a DFC, or fuel debris in a DFC may be stored in cells denoted by “D/F”. Cells denoted as “Empty” must remain empty (i.e. are not permitted to store fuel) regardless of the contents of the adjacent cell.

# APPENDIX 1.A: ALLOY X DESCRIPTION

## 1.A.1 Introduction

Alloy X is used within this licensing application to designate a group of stainless steel alloys. Alloy X can be any one of the following alloys:

- Type 316
- Type 316LN
- Type 304
- Type 304LN
- Duplex Stainless Alloy S31803 [1.A.3]

Qualification of structures made of Alloy X is accomplished by using the least favorable mechanical and thermal properties of the entire group for all MPC mechanical, structural, neutronic, radiological, and thermal conditions. The Alloy X approach is conservative because no matter which material is ultimately utilized, the Alloy X approach guarantees that the performance of the MPC will meet or exceed the analytical predictions.

Duplex stainless steels (DSS) are sensitive to the manufacturing processes employed in welding operations. Control of microstructure stability plays a vital role. The intermetallic microstructure is a complex function of the attendant parameters. For example, Cr and Mo promote ferrite and intermetallic phases, whereas N and Ni promote austenite.

During welding the balance between the ferritic and austenitic phases may be disturbed due to ferritization at high temperatures associated with welding operations. Ferrite content over 70% will lead to lower ductility and reduced corrosion resistance. Coarse ferritic grains are harmful for DSS toughness besides of impairing the austenite reformation at the heat affected zone (HAZ) [1.A.5]. The best metallurgical condition for welding is achieved by the most rapid quenching from the annealing temperature that produces a fine grained DSS structure with the required ferrite content (less than 70%).

Besides the austenite-ferrite phase balance, the second major concern with duplex steels and their chemical composition is the formation of detrimental intermetallic phases, precipitating preferentially in the ferrite, at elevated temperatures in the range of approximately 600 - 1750°F reaching an uncertain state of fragility at 887°F [1.A.4] and above. The mechanical (toughness) and corrosion properties of the weld and HAZ are deteriorated due to the presence of intermetallic phases.

Welding of DSS is associated with problems in the HAZ which can be loss of corrosion, toughness, or post-weld cracking. The heat input and cooling rates in welding are important as they control ferrite to austenite transformation. Exceedingly low heat input may result in fusion zones and HAZ which are excessively ferritic (above 70%) [1.A.6]. Exceedingly high heat input increases the danger of forming intermetallic phases [1.A.6]. In both cases the impact toughness and corrosion resistance

of the DSS will be seriously affected. Hence, heat input must be 0.6 – 2.6 kJ/mm to retain the phase balance, limit the width of the HAZ, and obtain a sigma phase free product [1.A.5]. Further, cooling rate from the solution annealing temperature must exceed 0.3°C/s to avoid sigma phase and satisfy the generally accepted toughness requirements [1.A.8]. The maximum interpass temperature is limited to 150°C (302°F) [1.A.6].

DSS have chloride stress corrosion cracking (CSCC) resistance significantly greater than that of the austenitic stainless steels, but they are not completely immune. Experimental results indicate that DSS is prone to stress corrosion cracking at temperatures above 100°C [1.A.9]. Poor welding practice, a low pH, presence of Hydrogen in welds, and/or high ferrite (>70%) can contribute to failures at temperatures below 100°C.

Holtec will make sure that this material shall be used *only* if the metal temperature of the MPC shell can be assured to remain below the limit in Table 1.A.6 under all *normal operating* modes [1.A.3]. Likewise, under short term and accident conditions, such as the “inlet duct blockage” scenario, the maximum metal temperature of duplex stainless steel must be held below the limit in Table 1.A.6.

To confirm that the required properties are achieved in production, Holtec will implement a test program to insure that the weldments are tested for the absence of detrimental intermetallic phases. The test program will comply with ASTM A923 and will use metallographic examination, impact testing and corrosion testing to demonstrate the absence of such detrimental phases. The test will be intended to determine the presence or absence of intermetallic phase to the extent that it is detrimental to the toughness and corrosion resistance of the material. The test *shall* be implemented to products during weld procedure qualification as well as during fabrication which will provide the assurance that the weldments are *free* from detrimental intermetallic phases, and *provide* the required corrosion resistance and fracture toughness [1.A.7].

For other stainless steels listed as members of Alloy X above, the design temperature limits in Table 2.2.3 remain unmodified.

This appendix defines the least favorable material properties of Alloy X.

## 1.A.2 Common Material Properties

Several material properties do not vary significantly from one Alloy X constituent to the next. These common material properties are as follows:

- density
- specific heat
- Young's Modulus (Modulus of Elasticity)
- Poisson's Ratio

The comparative values for Modulus of Elasticity at different temperatures are provided in Table 1.A.7. The values utilized for this licensing application are provided in their appropriate chapters.

## 1.A.3 Least Favorable Material Properties

The following material properties vary between the Alloy X constituents:

- Design Stress Intensity ($S_m$)
- Tensile (Ultimate) Strength ($S_u$)
- Yield Strength ($S_y$)
- Coefficient of Thermal Expansion ($\alpha$)
- Coefficient of Thermal Conductivity (k)

Each of these material properties are provided in the ASME Code Section II [1.A.10]. Tables 1.A.1 through 1.A.5 provide the ASME Code values for each constituent of Alloy X along with the least favorable value utilized in this licensing application. The ASME Code only provides values from -20°F. The lower bound service temperature of the MPC is -40°F, which is below -20°F. Most of the above-mentioned properties improve as the temperature drops. For this reason, the values at the lowest design temperature for the HI-STORM FW System have been assumed to be equal to the lowest value stated in the ASME Code. The lone exceptions are the coefficient of thermal expansion and thermal conductivity. As they decrease with the decreasing temperature, their values for -40°F are linearly extrapolated from the 70°F value with the slope based on data from 70°F to 100°F.

The Alloy X material properties are the minimum values of the group for the design stress intensity, tensile strength, yield strength, and coefficient of thermal conductivity. Using minimum values of design stress intensity is conservative because lower design stress intensities lead to lower allowables that are based on design stress intensity. Similarly, using minimum values of tensile strength and yield strength is conservative because lower values of tensile strength and yield strength lead to lower allowables that are based on tensile strength and yield strength. When compared to calculated values, these lower allowables result in factors of safety that are conservative for any of the constituent materials of Alloy X. Using the minimum value of thermal conductivity has the effect of reducing the heat rejection rate from the canister, which is conservative. The maximum and minimum values are used for the coefficient of thermal expansion of Alloy X. The maximum and minimum coefficients of thermal expansion are used as appropriate in this submittal to support a conservative safety evaluation. However, for any internal interference assessment the actual values of coefficients of thermal expansion from the ASME Code or Table 1.A.4 will be used.

## 1.A.4 References

[1.A.1] ASME Boiler & Pressure Vessel Code, Section II, Materials (2007).
[1.A.2] ASME Boiler & Pressure Vessel Code Section II, 2013 ed. with Addenda through 2014
[1.A.3] ASME Code Case N-635-1 (2013)
[1.A.4] C. Örnek, D. Engelberg, S. Lyon and T. Ladwein, "Effect of "475°C Embrittlement" on the Corrosion Behaviour of Grade 2205 Duplex Stainless Steel Investigated Using Local Probing Techiques," *Corrosion Management Magazine,* no. 115, pp. 9-11, 2013.
[1.A.5] C.R. Xavier, H.G. Delgado Jr., J.A de Castro, "An Experimental and Numerical Approach for the Welding Effects on the Duplex Stainless Steel Microstructure" – Materials Research Vol. 18(3) pp. 489-502, 2015.
[1.A.6] "Practical guidelines for Fabrication of Duplex Stainless Steels" – International Molybdenum Association, 2014.
[1.A.7] ASTM A923-14, "Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels" – W Conshohocken, PA, ASTM International 2014.
[1.A.8] J. Charles, "Duplex Stainless Steels, A Review After DSS '07 held in GRADO" – Steel Research International Vol. 79(6) pp. 455-465, 2008.
[1.A.9] A. Leonard, "Review of external stress corrosion cracking of 22%Cr duplex stainless steel, Phase 1 – Operational data acquisition," – HSE RR 129, Her Majesty's Stationery Office, Norwich, UK, 2003.
[1.A.10] ASME Boiler & Pressure Vessel Code Section II, Part D, 2015.

TABLE 1.A.1

DESIGN STRESS INTENSITY ($S_m$) vs. TEMPERATURE FOR THE ALLOY-X MATERIALS

| Temp. ($^oF$) | Type 304 | Type 304LN | Type 316 | Type 316LN | Duplex Stainless Steel S31803 [Notes 3 and 4] | Alloy X (minimum of constituent values) |
|---|---|---|---|---|---|---|
| -40 | 20.0 | 20.0 | 20.0 | 20.0 | 30.0 | 20.0 |
| 100 | 20.0 | 20.0 | 20.0 | 20.0 | 30.0 | 20.0 |
| 200 | 20.0 | 20.0 | 20.0 | 20.0 | 30.0 | 20.0 |
| 300 | 20.0 | 20.0 | 20.0 | 20.0 | 28.9 | 20.0 |
| 400 | 18.6 | 18.6 | 19.3 | 18.9 | 27.8 | 18.6 |
| 500 | 17.5 | 17.5 | 18.0 | 17.5 | 27.2 | 17.5 |
| 600 | 16.6 | 16.6 | 17.0 | 16.5 | 26.9 | 16.5 |
| 650 | 16.2 | 16.2 | 16.6 | 16.0 | - | 16.0 |
| 700 | 15.8 | 15.8 | 16.3 | 15.6 | - | 15.6 |
| 750 | 15.5 | 15.5 | 16.1 | 15.2 | - | 15.2 |
| 800 | 15.2 | 15.2 | 15.9 | 14.8 | - | 14.8 |

Notes:

1. Source: Table 2A on pages 308, 312, 316, and 320 of [1.A.1] for Type 316/316LN/304/304LN.
2. Units of design stress intensity values are ksi.
3. Design stress intensity values have been derived based on the basis established in Mandatory Appendix 2 page 924 and 925 which essentially states that the stress intensity value at temperature is the minimum of one-third of the tensile strength or two-thirds of the yield strength at temperature.
4. Maximum temperature of use for duplex stainless steel under both long term storage and short term / accident conditions is noted in Table 1.A.6.

TABLE 1.A.2

TENSILE STRENGTH ($S_u$) vs. TEMPERATURE OF ALLOY-X MATERIALS

| Temp. ($^oF$) | Type 304 | Type 304LN | Type 316 | Type 316LN | Duplex Stainless Steel S31803 [Note 4] | Alloy X (minimum of constituent values) |
|---|---|---|---|---|---|---|
| -40 | 75.0 (70.0) | 75.0 (70.0) | 75.0 (70.0) | 75.0 (70.0) | 90 (90) | 75.0 (70.0) |
| 100 | 75.0 (70.0) | 75.0 (70.0) | 75.0 (70.0) | 75.0 (70.0) | 90 (90) | 75.0 (70.0) |
| 200 | 71.0 (66.3) | 71.0 (66.3) | 75.0 (70.0) | 75.0 (70.0) | 90 (90) | 71.0 (66.3) |
| 300 | 66.2 (61.8) | 66.2 (61.8) | 72.9 (68.0) | 70.7 (66.0) | 86.8 (86.8) | 66.2 (61.8) |
| 400 | 64.0 (59.7) | 64.0 (59.7) | 71.9 (67.1) | 67.1 (62.6) | 83.5 (83.5) | 64.0 (59.7) |
| 500 | 63.4 (59.2) | 63.4 (59.2) | 71.8 (67.0) | 64.6 (60.3) | 81.6 (81.6) | 63.4 (59.2) |
| 600 | 63.4 (59.2) | 63.4 (59.2) | 71.8 (67.0) | 63.3 (59.0) | 80.7 (80.7) | 63.3 (59.0) |
| 650 | 63.4 (59.2) | 63.4 (59.2) | 71.8 (67.0) | 62.8 (58.6) | - | 62.8 (58.6) |
| 700 | 63.4 (59.2) | 63.4 (59.2) | 71.8 (67.0) | 62.4 (58.3) | - | 62.4 (58.3) |
| 750 | 63.3 (59.0) | 63.3 (59.0) | 71.5 (66.7) | 62.1 (57.9) | - | 62.1 (57.9) |
| 800 | 62.8 (58.6) | 62.8 (58.6) | 70.8 (66.1) | 61.7 (57.6) | - | 61.7 (57.6) |

Notes:

1. Source: Table U on pages 514, 516, 518, 520, and 522 of [1.A.1] for Type 304/304LN/316/316LN.
2. Units of tensile strength are ksi.
3. 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) or SA-182 forged material (S31803), which are used solely for the one-piece construction MPC lids. All other values correspond to SA-240 plate material.
4. Source: Table U on page 521 of [1.A.10] for DSS UNS S31803.
5. Maximum temperature of use for duplex stainless steel under both long term storage and short term / accident conditions is noted in Table 1.A.6.

| TABLE 1.A.3<br><br>YIELD STRESSES ($S_y$) vs. TEMPERATURE OF ALLOY-X MATERIALS | | | | | | |
|---|---|---|---|---|---|---|
| Temp. (°F) | Type 304 | Type 304LN | Type 316 | Type 316LN | Duplex Stainless Steel S31803 [Note 3] | Alloy X (minimum of constituent values) |
| -40 | 30.0 | 30.0 | 30.0 | 30.0 | 65.0 (65.0) | 30.0 |
| 100 | 30.0 | 30.0 | 30.0 | 30.0 | 65.0 (65.0) | 30.0 |
| 200 | 25.0 | 25.0 | 25.9 | 25.5 | 57.8 (57.8) | 25.0 |
| 300 | 22.4 | 22.4 | 23.4 | 22.9 | 53.7 (53.7) | 22.4 |
| 400 | 20.7 | 20.7 | 21.4 | 21.0 | 51.2 (51.2) | 20.7 |
| 500 | 19.4 | 19.4 | 20.0 | 19.5 | 49.6 (49.6) | 19.4 |
| 600 | 18.4 | 18.4 | 18.9 | 18.3 | 47.9 (47.9) | 18.3 |
| 650 | 18.0 | 18.0 | 18.5 | 17.8 | - | 17.8 |
| 700 | 17.6 | 17.6 | 18.2 | 17.3 | - | 17.3 |
| 750 | 17.2 | 17.2 | 17.9 | 16.9 | - | 16.9 |
| 800 | 16.9 | 16.9 | 17.7 | 16.5 | - | 16.5 |

Notes:

1. Source: Table Y-1 on pages 634, 638, 646, and 650 of [1.A.1] for Type 304/304LN/316/316LN.
2. Units of yield stress are ksi.
3. Source: Table Y-1 on page 672 and 673 of [1.A.10] for DSS UNS S31803. Values in parentheses are based on SA-182 forged material (S31803) which is used solely for the one-piece construction MPC lids. All other values correspond to SA-240 plate material.
4. Maximum temperature of use for duplex stainless steel under both long term storage and short term / accident conditions is noted in Table 1.A.6.

TABLE 1.A.4

COEFFICIENT OF THERMAL EXPANSION
vs. TEMPERATURE OF ALLOY-X MATERIALS

| Temp. (°F) | Type 304, 304LN, 316, 316LN (Alloy X Maximum) | Duplex Stainless Steel S31803 [Note 3] (Alloy X Minimum) |
|---|---|---|
| -40 | -- | 6.63 |
| 100 | 8.6 | 7.1 |
| 150 | 8.8 | 7.3 |
| 200 | 8.9 | 7.5 |
| 250 | 9.1 | 7.6 |
| 300 | 9.2 | 7.8 |
| 350 | 9.4 | 7.9 |
| 400 | 9.5 | 8.0 |
| 450 | 9.6 | 8.1 |
| 500 | 9.7 | 8.3 |
| 550 | 9.8 | 8.4 |
| 600 | 9.8 | 8.4 |
| 650 | 9.9 | - |
| 700 | 10.0 | - |
| 750 | 10.0 | - |
| 800 | 10.1 | - |
| 850 | 10.2 | - |
| 900 | 10.2 | - |
| 950 | 10.3 | - |
| 1000 | 10.3 | - |
| 1050 | 10.4 | - |
| 1100 | 10.4 | - |

Notes:

1. Source: Group 3 alloys from Table TE-1 on pages 749 and 751 of [1.A.1] for Type 304/304LN/316/316LN.
2. Units of mean coefficient of thermal expansion are in./in./°F x $10^{-6}$.
3. Source: Group 2 alloys from Table TE-1 on page 753 of [1.A.10] for SS UNS S31803.
4. Maximum temperature of use for duplex stainless steel under both long term storage and short term / accident conditions is noted in Table 1.A.6.

TABLE 1.A.5

THERMAL CONDUCTIVITY vs. TEMPERATURE OF ALLOY-X MATERIALS

| Temp. ($^{o}$F) | Type 304 and Type 304LN | Type 316 and Type 316LN | Duplex Stainless Steel S31803 [Note 3] | Alloy X (minimum of constituent values) |
|---|---|---|---|---|
| -40 | -- | -- | 7.83 | -- |
| 70 | 8.6 | 8.2 | 8.2 | 8.2 |
| 100 | 8.7 | 8.3 | 8.3 | 8.3 |
| 150 | 9.0 | 8.6 | 8.6 | 8.6 |
| 200 | 9.3 | 8.8 | 8.8 | 8.8 |
| 250 | 9.6 | 9.1 | 9.1 | 9.1 |
| 300 | 9.8 | 9.3 | 9.3 | 9.3 |
| 350 | 10.1 | 9.5 | 9.5 | 9.5 |
| 400 | 10.4 | 9.8 | 9.8 | 9.8 |
| 450 | 10.6 | 10.0 | 10.0 | 10.0 |
| 500 | 10.9 | 10.2 | 10.2 | 10.2 |
| 550 | 11.1 | 10.5 | 10.5 | 10.5 |
| 600 | 11.3 | 10.7 | 10.7 | 10.7 |
| 650 | 11.6 | 10.9 | - | 10.9 |
| 700 | 11.8 | 11.2 | - | 11.2 |
| 750 | 12.0 | 11.4 | - | 11.4 |
| 800 | 12.3 | 11.6 | - | 11.6 |
| 850 | 12.5 | 11.9 | - | 11.9 |
| 900 | 12.7 | 12.1 | - | 12.1 |
| 950 | 12.9 | 12.3 | - | 12.3 |
| 1000 | 13.1 | 12.5 | - | 12.5 |
| 1050 | 13.4 | 12.8 | - | 12.8 |
| 1100 | 13.6 | 13.0 | - | 13.0 |

Notes:

1. Source: Material groups J and K in Table TCD on page 765, 766, and 775 of [1.A.1] for Type 304/304LN/316/316LN.
2. Units of thermal conductivity are Btu/hr-ft-°F.
3. Source: Table TCD on page 773 of [1.A.10] for DSS UNS S31803.
4. Maximum temperature of use for duplex stainless steel under both long term storage and short term / accident conditions is noted in Table 1.A.6.

Table 1.A.6

DUPLEX STAINLESS STEEL TEMPERATURE LIMITS [Note 1]

| Parameter | Value |
|---|---|
| Long Term, Normal Condition Design Temperature Limits (Long-Term Events) ($^{o}$ F) | 550 |
| Short-Term Events, Off-Normal, and Accident Condition Temperature Limits ($^{o}$ F) | 600 |

Notes:
1. These temperature limits take precedence over those in Table 2.2.3

Table 1.A.7

ALLOY X MODULI OF ELASTICITY (E) vs. TEMPERATURE

| **Temp. (Deg. F)** | **Moduli of Elasticity (E)** | |
|---|---|---|
| | **Austenitic stainless steels (304, 304LN, 316, 316LN)** | **Duplex stainless steel (UNS S31803)** |
| -40 | 28.82 | 29.78 |
| 100 | 28.14 | 28.82 |
| 150 | 27.87 | 28.51 |
| 200 | 27.6 | 28.2 |
| 250 | 27.3 | 27.85 |
| 300 | 27.0 | 27.5 |
| 350 | 26.75 | 27.25 |
| 400 | 26.5 | 27.0 |
| 450 | 26.15 | 26.7 |
| 500 | 25.8 | 26.4 |
| 550 | 25.55 | 26.2 |
| 600 | 25.3 | 26.0 |
| 650 | 25.05 | - |
| 700 | 24.8 | - |
| 750 | 24.45 | - |
| 800 | 24.1 | - |

Definitions:

E = Young's Modulus (psi x $10^6$)

Notes:

1. Source for E values of austenitic stainless steels is material group G in Table TM-1 of [3.3.1].
2. Source for E values of duplex stainless steel is material group H in Table TM-1 of [1.A.10].

To achieve compliance with the above criteria, certain design and operational changes are necessary, as summarized below.

i. The peak fuel cladding temperature limit (PCT) for long term storage operations and short term operations is generally set at 400ºC (752ºF). However, for MPCs containing all moderate burnup fuel, the fuel cladding temperature limit for short-term operations is set at 570ºC (1058ºF) because the nominal fuel cladding stress is shown to be less than 90 MPa [2.0.2]. Appropriate analyses have been performed as discussed in Chapter 4 and operating restrictions have been added to ensure these limits are met.

ii. A method of drying, such as forced helium dehydration (FHD) is used if the above temperature limits for short-term operations cannot be met.

iii. The off-normal and accident condition PCT limit remains unchanged at 570 ºC (1058ºF).

The MPC cavity is dried, either with FHD or vacuum drying, and then it is backfilled with high purity helium to promote heat transfer and prevent cladding degradation.

The normal condition design temperatures for the stainless steel components in the MPC are provided in Table 2.2.3.

The MPC-37 and MPC-89 models allow for regionalized storage where the basket is segregated into three regions as shown in Figures 1.2.1a and 1.2.2. Decay heat limits for regionalized loading are presented in Tables 1.2.3a and 1.2.4 for MPC-37 and MPC-89 respectively. Specific requirements, such as approved locations for DFCs and non-fuel hardware are given in Section 2.1.

As an alternative to the regionalized storage patterns, The MPC-37 and MPC-89 models allow for the use of the heat load charts shown in Figures 1.2.3 through 1.2.5 (MPC-37) and 1.2.6 (MPC-89).

Shielding

The dose limits for an ISFSI using the HI-STORM FW System are delineated in 10CFR72.104 and 72.106. Compliance with these regulations for any particular array of casks at an ISFSI is necessarily site-specific and must be demonstrated by the licensee. Dose for a single cask and a representative cask array is illustrated in Chapter 5.

The MPC provides axial shielding at the top and bottom ends to maintain occupational exposures ALARA during canister closure and handling operations. The HI-TRAC VW bottom lid also contains shielding. The occupational doses are controlled in accordance with plant-specific procedures and ALARA requirements (discussed in Chapter 9).

Table 2.1.1a

MATERIAL TO BE STORED

| **PARAMETER** | **VALUE** | |
|---|---|---|
| | MPC-37 | MPC-89 |
| Fuel Type | Uranium oxide undamaged fuel assemblies, damaged fuel assemblies, and fuel debris meeting the limits in Table 2.1.2 for the applicable array/class. | Uranium oxide undamaged fuel assemblies, damaged fuel assemblies, with or without channels, fuel debris meeting the limits in Table 2.1.3 for the applicable array/class. |
| Cladding Type | ZR (see Glossary for definition) | ZR (see Glossary for definition) |
| Maximum Initial Rod Enrichment | Depending on soluble boron levels or burnup credit and assembly array/class as specified in Table 2.1.6 and Table 2.1.7. | ≤ 5.0 wt. % U-235 |
| Post-irradiation cooling time and average burnup per assembly | Minimum Cooling Time: 2 years<br><br>Maximum Assembly Average Burnup: 68.2 GWd/mtU | Minimum Cooling Time: 2 years<br><br>Maximum Assembly Average Burnup: 65 GWd/mtU |
| Non-fuel hardware post-irradiation cooling time and burnup | Minimum Cooling Time: 2 years<br><br>Maximum Burnup†:<br>- BPRAs, WABAs and vibration suppressors: 60 GWd/mtU<br>- TPDs, NSAs, APSRs, RCCAs, CRAs, CEAs, water displacement guide tube plugs and orifice rod assemblies: 630 GWd/mtU<br>- ITTRs: not applicable | N/A |
| Decay heat per fuel storage location | Regionalized Loading: See Table 1.2.3 | Regionalized Loading: See Table 1.2.4 |

† Burnups for non-fuel hardware are to be determined based on the burnup and uranium mass of the fuel assemblies in which the component was inserted during reactor operation. Burnup not applicable for ITTRs since installed post-irradiation.

Table 2.1.1a (continued)

MATERIAL TO BE STORED

| PARAMETER | VALUE | |
|---|---|---|
| | MPC-37 | MPC-89 |
| Other Limitations | ▪ Quantity is limited to 37 undamaged ZR clad PWR fuel assemblies with or without non-fuel hardware. Up to 12 damaged fuel containers containing PWR damaged fuel and/or fuel debris may be stored in the locations denoted in Figure 2.1.1 with the remaining basket cells containing undamaged ZR fuel assemblies, up to a total of 37. Alternative damaged fuel patterns are shown in Figures 1.2.3, 1.2.4, and 1.2.5.<br>▪ One NSA.<br>▪ Up to 30 BPRAs.<br>▪ BPRAs, TPDs, WABAs, water displacement guide tube plugs, orifice rod assemblies, and/or vibration suppressor inserts, with or without ITTRs, may be stored with fuel assemblies in any fuel cell location.<br>▪ CRAs, RCCAs, CEAs, NSAs, and/or APSRs may be stored with fuel assemblies in fuel cell locations specified in Figure 2.1.5. | ▪ Quantity is limited to 89 undamaged ZR clad BWR fuel assemblies. Up to 16 damaged fuel containers containing BWR damaged fuel and/or fuel debris may be stored in locations denoted in Figure 2.1.2 with the remaining basket cells containing undamaged ZR fuel assemblies, up to a total of 89. Alternative damaged fuel patterns are shown in Figure 1.2.6. |

Table 2.1.3 (continued)

BWR FUEL ASSEMBLY CHARACTERISTICS (Note 1)

| **Fuel Assembly Array and Class** | **10x10 C** | **10x10 F** | **10x10 G** | **10x10 I** | **11x11 A** |
|---|---|---|---|---|---|
| Maximum Planar-Average Initial Enrichment (wt.% $^{235}$U) (Note 14) | $\leq$ 4.8 | $\leq$ 4.7 (Note 13) | $\leq$ 4.6 (Note 12) | $\leq$ 4.8 | $\leq$ 4.8 |
| Maximum Planar-Average Initial Enrichment with Gadolinium Credit (wt.% $^{235}$U) (Note 15) | $\leq$ 5.0 | $\leq$ 5.0 | $\leq$ 5.0 | N/A | N/A |
| No. of Fuel Rod Locations | 96 | 92/78 (Note 7) | 96/84 | 91/79 | 112/92 |
| Fuel Clad O.D. (in.) | $\geq$ 0.3780 | $\geq$ 0.4035 | $\geq$ 0.387 | $\geq$ 0.4047 | $\geq$ 0.3701 |
| Fuel Clad I.D. (in.) | $\leq$ 0.3294 | $\leq$ 0.3570 | $\leq$ 0.340 | $\leq$ 0.3559 | $\leq$ 0.3252 |
| Fuel Pellet Dia. (in.) | $\leq$ 0.3224 | $\leq$ 0.3500 | $\leq$ 0.334 | $\leq$ 0.3492 | $\leq$ 0.3193 |
| Fuel Rod Pitch (in.) | $\leq$ 0.488 | $\leq$ 0.510 | $\leq$ 0.512 | $\leq$ 0.5100 | $\leq$ 0.4705 |
| Design Active Fuel Length (in.) | $\leq$ 150 | $\leq$ 150 | $\leq$ 150 | $\leq$ 150 | $\leq$ 150 |
| No. of Water Rods (Note 10) | 5 (Note 9) | 2 | 5 (Note 9) | 1 (Note 5) | 1 (Note 5) |
| Water Rod Thickness (in.) | $\geq$ 0.031 | $\geq$ 0.030 | $\geq$ 0.031 | $\geq$ 0.0315 | $\geq$ 0.0340 |
| Channel Thickness (in.) | $\leq$ 0.055 | $\leq$ 0.120 | $\leq$ 0.060 | $\leq$ 0.100 | $\leq$ 0.100 |

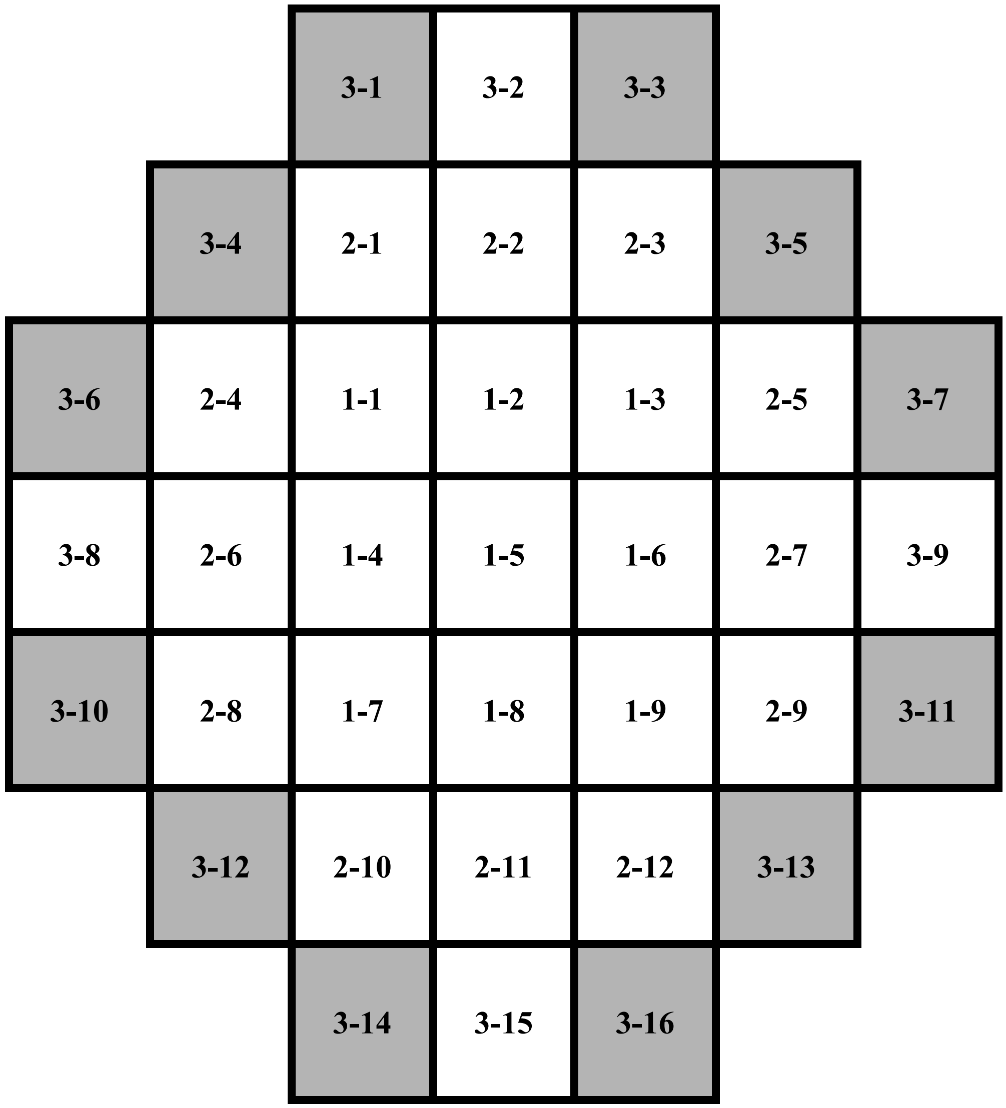


Figure 2.1.1a Location of DFCs for Damaged Fuel or Fuel Debris in the MPC-37 (Shaded Cells) under Patterns A and B

See Figures 1.2.3, 1.2.4, and 1.2.5 for the locations of DFCs for alternative damaged fuel and fuel debris loading patterns.

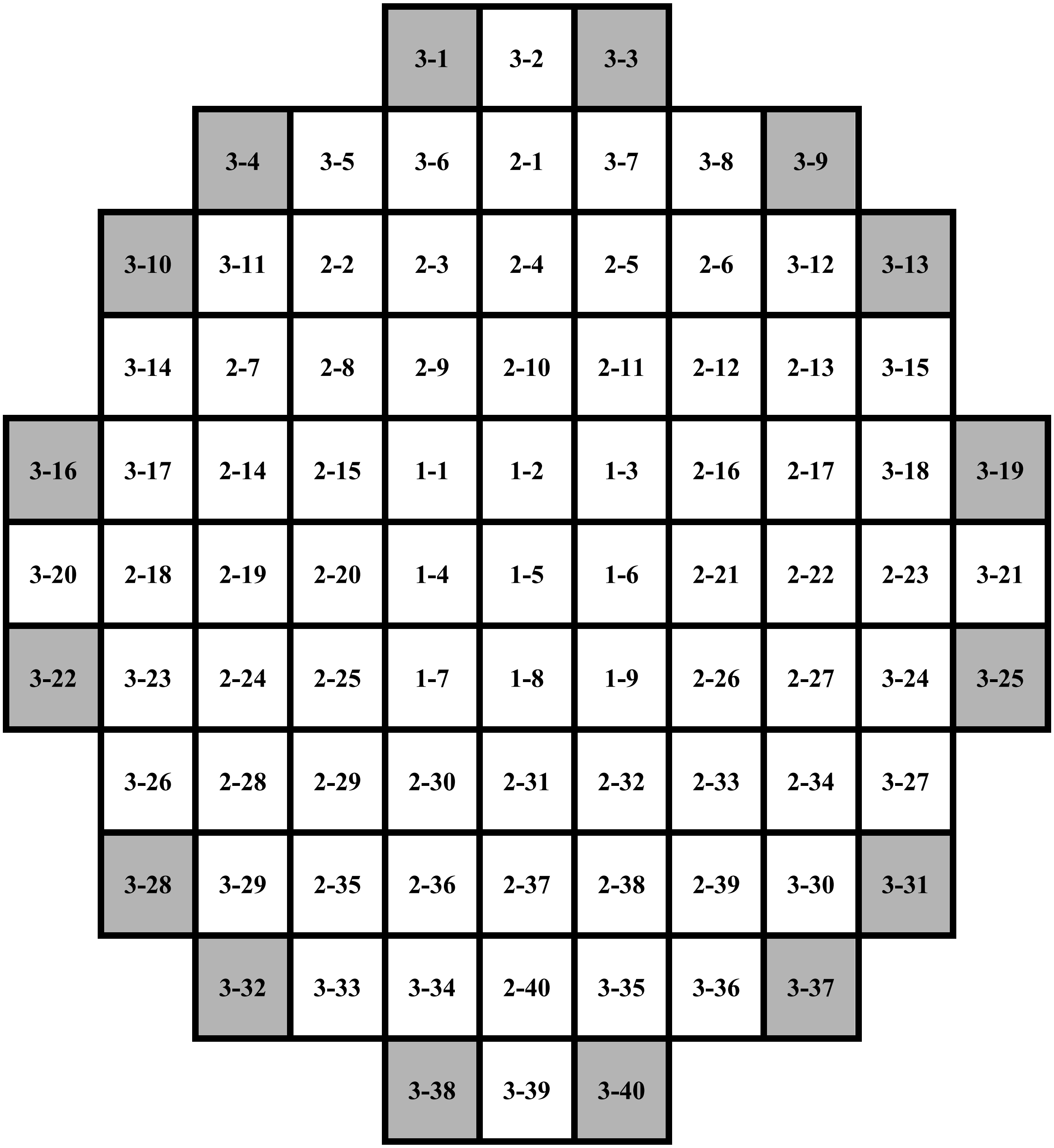


Figure 2.1.2 Location of DFCs for Damaged Fuel or Fuel Debris
in the MPC-89 (Shaded Cells)

See Figure 1.2.6 for the locations of DFCs for alternative damaged fuel and fuel debris loading patterns.

i. Level A Service Limits are used to establish allowables for normal condition load combinations.

ii. Level B Service Limits are used to establish allowables for off-normal conditions.

iii. Level C Service Limits are not used.

iv. Level D Service Limits are used to establish allowables for certain accident conditions.

The ASME Code service limits are used in the structural analyses for definition of allowable stresses and allowable stress intensities, as applicable. Allowable stresses and stress intensities for structural analyses are tabulated in Chapter 3. These service limits are matched with normal, off-normal, and accident condition loads combinations in the following subsections.

The MPC confinement boundary is required to meet Section III, Class 1, Subsection NB stress intensity limits. Table 2.2.10 lists the stress intensity limits for Design and Service Levels A, B, and D for Class 1 structures extracted from the ASME Code. Table 2.2.12 lists allowable stress limits for the steel structure of the HI-STORM FW overpack and HI-TRAC VW transfer cask which are analyzed to meet the stress limits of Subsection NF, Class 3 for loadings defined as service levels A, B, and D are applicable.

### 2.2.6 Loads

Subsections 2.2.1, 2.2.2, and 2.2.3 describe the design criteria for normal, off-normal, and accident conditions, respectively. The loads are listed in Tables 2.2.7 and 2.2.13, along with the applicable acceptance criteria.

### 2.2.7 Design Basis Loads

Where appropriate, for each loading type, a bounding value is selected in this FSAR to impute an additional margin for the associated loading events. Such bounding loads are referred to as Design Basis Loads (DBL) in this FSAR. For example, the Design Basis External Pressure on the MPC, set down in Table 2.2.1, is a DBL, as it grossly exceeds any credible external pressure that may be postulated for an ISFSI site.

### 2.2.8 Allowable Limits

The stress intensity limits for the MPC confinement boundary for the design condition and the service conditions are provided in Table 2.2.10. The MPC confinement boundary stress intensity limits are obtained from ASME Code, Section III, Subsection NB. The displacement limit for the MPC fuel basket is expressed as a dimensionless parameter θ defined as [2.2.11]

$$\theta = \frac{\delta}{w}$$

Table 2.2.1

PRESSURE LIMITS

| Pressure Location | Condition | Pressure (psig) |
|---|---|---|
| MPC Internal Pressure | Design / Long-Term Normal | 100 |
| | Short-Term Normal | 115 |
| | Off-Normal | 120 |
| | Accident | 200 |
| MPC External Pressure | Normal | (0) Ambient |
| | Off-Normal/Short-Term | (0) Ambient |
| | Accident | 55 |
| HI-TRAC Water Jacket Internal Pressure | Accident | 65 |
| Overpack External Pressure | Normal | (0) Ambient |
| | Off-Normal/Short-Term | (0) Ambient |
| | Accident | See Paragraph 3.1.2.1.d |

Table 2.2.3

TEMPERATURE LIMITS

| HI-STORM FW Component | Normal Condition Design Temperature Limits (°F) | Off-Normal and Accident Condition Temperature Limits † (°F) |
|---|---|---|
| MPC shell | 600* | 800* |
| MPC basket | 752 | 932 |
| MPC basket shims | 752 | 932 |
| MPC lid | 600* | 800* |
| MPC closure ring | 500* | 800* |
| MPC baseplate | 400* | 800* |
| HI-TRAC VW inner shell | 500 | 700 |
| HI-TRAC VW bottom lid | 500 | 700 |
| | | |
| HI-TRAC VW top flange | 400 | 650 |
| HI-TRAC VW bottom lid seals | 350 | N/A |
| HI-TRAC VW bottom lid bolts | 400 | 800 |
| HI-TRAC VW bottom flange | 350 | 700 |
| | | |
| HI-TRAC VW radial neutron shield | 311 | N/A |
| HI-TRAC VW radial lead gamma shield | 350 | 600 |
| Fuel Cladding | 752 (Storage)<br><br>752 or 1058 (Short Term Operations)†† | 1058 (Off-Normal and Accident Conditions) |
| Overpack concrete | 300 | 350 |
| Overpack Lid Top and Bottom Plate | 450 | 700 |
| Remainder of overpack steel structure | 350 | 700 |

† For accident conditions that involve heating of the steel structures and no mechanical loading (such as the blocked air duct accident), the permissible metal temperature of the steel parts is defined by Table 1A of ASME Section II (Part D) for Section III, Class 3 materials as 700°F. For the fire event, the structure is required to remain physically stable (no specific temperature limits apply)

†† Short term operations include MPC drying and onsite transport. The 1058°F temperature limit applies to MPCs containing all moderate burnup fuel. The limit for MPCs containing one or more high burnup fuel assemblies is 752°F.

* Temperature limits in Table 1.A.6 shall take precedence if duplex stainless steels are used for the fabrication of confinement boundary components, as described in Appendix 1.A.

| Table 2.2.7<br>LOADS APPLICABLE TO THE NORMAL AND OFF-NORMAL CONDITIONS OF STORAGE | | | | |
|---|---|---|---|---|
| Loading Case | Loading | Affected Item and Part | Magnitude of Loading | Acceptance Criterion |
| NA. | Snow and Ice | Top lid of HI-STORM FW overpack | Table 2.2.8 | The stress in the steel structure must meet NF Class 3 limits for linear structures |
| NB. | Internal Pressure‡‡ | MPC Enclosure Vessel | Table 2.2.1 | Meet "NB" stress intensity limits |
| | a. Design or Long-term Normal Condition | MPC Enclosure Vessel | Table 2.2.1 | Design condition limits on primary stress intensities |
| | b. Short-term Normal Condition | MPC Enclosure Vessel | Table 2.2.1 | Level A limits on primary and secondary stress intensities |
| | c. Short-term Normal Lifting Operation | MPC Enclosure Vessel | Table 2.2.1 | Level A limits on primary stress intensities |
| | d. Off-Normal Condition | MPC Enclosure Vessel | Table 2.2.1 | Level B limits on primary and secondary stress intensities. |

‡‡ Normal condition internal pressure is bounded by the Design Internal Pressure in Table 2.2.1. Because the top and bottom extremities of the MPC Enclosure Vessel are each at a uniform temperature due to the recirculating helium, thermal stresses are minimal. Therefore, the Design Internal Pressure envelops the case of the Normal Service condition for the MPC. The same remark applies to the Off-Normal Service condition.

| Table 2.2.10<br><br>MPC CONFINEMENT BOUNDARY STRESS INTENSITY LIMITS<br>FOR DIFFERENT LOADING CONDITIONS (ELASTIC ANALYSIS PER NB-3220)† | | | |
|---|---|---|---|
| Stress Category | Design | Level A* | Level D†† |
| Primary Membrane, $P_m$ | $S_m$ | $S_m$ | AMIN (2.4$S_m$, .7$S_u$) |
| Local Membrane, $P_L$ | 1.5$S_m$ | 1.5$S_m$ | 150% of $P_m$ Limit |
| Membrane plus Primary Bending | 1.5$S_m$ | 1.5$S_m$ | 150% of $P_m$ Limit |
| Primary Membrane plus Primary Bending | 1.5$S_m$ | N/A | 150% of $P_m$ Limit |
| Membrane plus Primary Bending plus Secondary | N/A | 3$S_m$ | N/A |
| Average Shear Stress†††† | 0.6$S_m$ | 0.6$S_m$ | 0.42$S_u$ |

† Stress combinations including F (peak stress) apply to fatigue evaluations only.

†† Governed by Appendix F, Paragraph F-1331 of the ASME Code, Section III.

†††† Governed by NB-3227.2 or F-1331.1(d).

* The values of Level A Service Limits shall apply for Level B Service Limits, except that for primary stress intensities generated by Level B Service Loadings, allowable stress intensity values of 110% of Level A limits shall apply per NB-3223.

| TABLE 2.2.14<br>List of ASME Code Alternatives for Multi-Purpose Canisters (MPCs) | | | |
|---|---|---|---|
| | | nominal thickness of the pressure retaining material.<br><br>NB-1132.2(e) requires that the first connecting weld of a welded nonstructural attachment to a component shall conform to NB-4430 if the connecting weld is within 2t from the pressure retaining portion of the component. | |
| MPC Enclosure Vessel | NB-2000 | Requires materials to be supplied by ASME-approved material supplier. | Materials will be supplied by Holtec approved suppliers with Certified Material Test Reports (CMTRs) in accordance with NB-2000 requirements. |
| MPC Enclosure Vessel | NB-2121 | Provides permitted material specification for pressure-retaining material, which must conform to Section II, Part D, Tables 2A and 2B. | Certain duplex stainless steels are not included in Section II, Part D, Tables 2A and 2B. UNS S31803 duplex stainless steel alloy is evaluated in the HI-STORM FW FSAR and meet the required design criteria for use in the HI-STORM FW system per ASME Code Case N-635-1. Appendix 1.A provides the required property data for the necessary safety analysis. |
| MPC Enclosure Vessel | NB-3100<br>NF-3100 | Provides requirements for determining design loading conditions, such as pressure, temperature, and mechanical loads. | These requirements are subsumed by the HI-STORM FW FSAR, serving as the Design Specification, which establishes the service conditions and load combinations for the storage system. |
| MPC Enclosure Vessel | NB-4120 | NB-4121.2 and NF-4121.2 provide requirements for repetition of tensile or impact tests for material subjected to heat treatment during fabrication or installation. | In-shop operations of short duration that apply heat to a component, such as plasma cutting of plate stock, welding, machining, and coating are not, unless explicitly stated by the Code, defined as heat treatment operations. |
| MPC Enclosure Vessel | NB-4220 | Requires certain forming tolerances to be met for cylindrical, conical, or spherical shells of a vessel. | The cylindricity measurements on the rolled shells are not specifically recorded in the shop travelers, as would be the case for a Code-stamped pressure vessel. Rather, the requirements on inter-component clearances (such as the MPC-to-transfer cask) are guaranteed through fixture-controlled manufacturing. The fabrication specification and shop procedures ensure that all dimensional design objectives, including inter-component annular |

enclosure vessels, carrying the PWR fuel types, are identical to the MPC-37 except for the length. The finite element models for the fuel baskets, the fuel assemblies and the basket shims, for all four basket types are shown in Figures 3.4.12, 3.4.13 and 3.4.14, respectively.

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 temperature distribution for the maximum length MPC as determined by the thermal analyses in Chapter 4 for short-term normal operations.

v. The fuel basket models (Figures 3.4.12A, 3.4.12B, 3.4.12C and 3.4.12D), 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. 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.

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<br>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)<br>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<br>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<br>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, Short-Term Normal and Off-Normal Internal Pressure<br>MPC under the Design, Short-term normal and Off-normal Internal Pressure | — | X | — | Demonstrate that the MPC meets "NB" stress intensity limits. | 2.2.1 |
| 6 | NB | Maximum Internal Pressure Under the Accident Condition<br>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 3.1.7

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** | | | | | |
|---|---|---|---|---|---|---|
| | $\mathbf{S_m}$ | $\mathbf{P_m}$ † | $\mathbf{P_L}$ † | $\mathbf{P_L + P_b}$ † | $\mathbf{P_L + P_b + Q}$ †† | $\mathbf{P_e}$ †† |
| -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 for austenitic stainless steels of Alloy X and Appendix 1.A for duplex stainless steel of Alloy X.
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.
6. Allowable primary stress intensities under Level B Service Loadings shall be 110% of allowable primary stress intensities under Level A Service Loading per NB-3223.

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

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 design, 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 3.2.4

HI-TRAC VW WEIGHT DATA (COMPUTED NOMINAL VALUES)

| **Item** | **BWR Fuel Based on length below** | | | **PWR Fuel Based on length below (see Note 1)** | | |
|---|---|---|---|---|---|---|
| | **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 | 78,000 | 99,600 |
| HI-TRAC VW Bottom Lid | 13,000 | 13,000 | 13,000 | 13,000 | 13,000 | 13,000 |
| MPC with Basket | 36,100 | 35,400 | 36,600 | 36,500 | 32,600 | 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) | 53,700 (1,450 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 | 7,600 | 9,900 |
| Displaced Water Mass by the Cask in the Pool (Excludes MPC) | 18,900 | 18,400 | 19,400 | 18,600 | 17,500 | 21,600 |

# 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] and Appendix 1.A, are used in all structural analyses. As is shown in Chapter 4, the maximum metal temperature for austenitic stainless steel grades of Alloy X used at or within the Confinement Boundary remains below 1000°F under all service modes and the maximum temperature of duplex stainless steel (UNS S31803) grade of Alloy X used for confinement boundary does not exceed 600°F under any condition. 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°F temperature for up to 10,000 hours. In addition, per ASME Code Case N-635-1 (Use of 22Cr-5Ni-3Mo-N (Alloy UNS S31803) Forgings, Plate, Bar, Welded and Seamless Pipe, and/or Tube, Fittings, and Fusion Welded Pipe with Additional of Filler Metal, Classes 1, 2, and 3, Section III, Division 1), the maximum permissible temperature for

duplex stainless steel grade of Alloy X is 600°F. 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.

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] for austenitic stainless steels of Alloy X and Appendix 1.A for duplex stainless steel of Alloy X.
2. Source for $S_u$ values is Table U of [3.3.1] for austenitic stainless steels of Alloy X and Appendix 1.A for duplex stainless steel of Alloy X.
3. Source for α values is Table TE-1 of [3.3.1] for austenitic stainless steels of Alloy X. Values of α for duplex stainless steel grade of Alloy X can be obtained from Appendix 1.A.
4. Source for E values is material group G in Table TM-1 of [3.3.1] for austenitic stainless steels of Alloy X and Appendix 1.A for duplex stainless steel of Alloy X.
5. Minimum values of $S_y$, $S_u$ and E from all candidate Alloy X materials are listed.
6. Duplex stainless steel grade of Alloy X is only used in fabrication of MPC confinement boundary components and its use is limited to 600 °F per Appendix 1.A.

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 during a lift 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 stresses (membrane and membrane plus bending) must be below the Level A service condition limit using ASME Code, Section III, Subsections NB and NF (2007 issues), as applicable, as the reference codes.

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

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 23.1 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 101.8 lbf/in. All internal surfaces of the MPC storage cavity are also subjected to a bounding normal condition internal pressure of 120 psig, which exceeds the normal operating pressures per Tables 4.4.5 and 4.5.5. 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 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 conservatively taken at 500°F for the MPC shell, 600°F for the MPC lids, 450°F for the MPC baseplate, and 450°F at the MPC baseplate-to-shell juncture. These temperatures bound the operating temperatures for these parts under normal operating conditions (Tables 4.4.3 and 4.5.2). 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

$D$ = 74.375 in

$W_{lid}$ = 11,500 lb

From Table 2.2.1, the bounding pressure inside the MPC cavity under normal operating conditions is

$P$ = 120 psig

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

$$F = 1.15 \cdot (W_{MPC} - W_{lid}) + P \cdot \left( \frac{\pi \cdot D^2}{4} \right) = 641{,}980 lb$$

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

$$A = \pi \cdot D \cdot \left( t_w - \frac{1}{8} in \right) \cdot 0.8 = 116.8 in^2$$

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

$$\tau = \frac{F}{A} = 5{,}495 psi$$

The MPC Enclosure Vessel is made from Alloy X material, whose mechanical properties are listed in Table 3.3.1. Based on a bounding normal condition temperature of 600ºF (Tables 4.4.3 and 4.5.2), 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

$$\tau_a = 0.3 \times S_u = 18{,}990 psi$$

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

$$SF = \frac{\tau_a}{\tau} = 3.46$$

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

3.4.4.1.5 Load Case 5: Design, Short-Term Normal and Off-Normal MPC 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 a bounding (design, long-term and short-term) internal pressure (Table 2.2.1) of 120 psig 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 bounding 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 stress intensities in the MPC Enclosure Vessel are compared with the applicable stress intensity limits from Subsection NB of the ASME Code (Fig. NB-3221-1). The allowable stress intensities are obtained at design temperature limits in Table 2.2.3 (600°F for the MPC shell and the MPC lid, 400°F for the baseplate, and 600°F at the baseplate-to-shell juncture, conservatively). 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.

Similar evaluations are performed for the MPC Enclosure Vessel under short-term normal (Level A) and off-normal (Level B) conditions. The applied loads are bounding internal pressure (120 psig) from Table 2.2.1 and conservatively bounding temperature contours based on thermal evaluations in Sections 4.5 and 4.6 for short-term normal and off-normal conditions, 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 (Fig. NB-3222-1 and Subsection NB-3223 for Level A and Level B, respectively). The allowable stress intensities are obtained at bounding bulk temperatures [3.4.13] from thermal evaluations. The maximum calculated stress intensities in the MPC Enclosure Vessel and their corresponding allowable limits, are summarized in Tables 3.4.7A and 3.4.7B for Level A and Level B, respectively.

3.4.4.1.6 Load Case 6: Maximum MPC 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 for design internal pressure. 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 800°F for the MPC shell, the MPC lid, the MPC baseplate, and the MPC baseplate-to-shell juncture. These temperatures are obtained from Table 2.2.3 for accident conditions and 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

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 | 9.47 | 16.5 | 1.74 |
| Lid – Local Membrane Plus Primary Bending Stress Intensity | 15.19 | 24.75 | 1.63 |
| Baseplate – Primary Membrane Stress Intensity | 11.00 | 18.05 | 1.64 |
| Baseplate – Local Membrane Plus Primary Bending Stress Intensity | 26.27 | 27.10 | 1.03 |
| Shell – Primary Membrane Stress Intensity | 15.92 | 17.50 | 1.10 |
| Shell – Local Membrane Plus Primary Bending Stress Intensity | 23.07 | 26.3 | 1.14 |

| Table 3.4.2<br><br>STRESS RESULTS FOR HI-TRAC VW –<br>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 | 9.33 | 57.5 | 6.16 |
| Bottom Lid – Primary Bending Stress | 3.81 | 29.4 | 7.71 |

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 | 6.42 | 16.50 | 2.57 |
| Lid – Local Membrane Plus Primary Bending Stress Intensity | 14.26 | 24.75 | 1.74 |
| Baseplate – Primary Membrane Stress Intensity | 9.00 | 18.60 | 2.07 |
| Baseplate – Local Membrane Plus Primary Bending Stress Intensity | 21.97 | 27.90 | 1.27 |
| Shell – Primary Membrane Stress Intensity | 13.76 | 16.50 | 1.20 |
| Shell – Local Membrane Plus Primary Bending Stress Intensity | 19.84 | 24.75 | 1.25 |

Table 3.4.7A

STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL – SHORT-TERM NORMAL INTERNAL PRESSURE

| Item | Calculated Value (ksi) | Allowable Limit (ksi) | Safety Factor |
|---|---|---|---|
| Lid – Primary Membrane Stress Intensity | 13.10 | 18.05 | 1.38 |
| Lid – Local Membrane Plus Primary Bending Stress Intensity | 21.56 | 27.1 | 1.26 |
| Baseplate – Primary Membrane Stress Intensity | 12.40 | 18.95 | 1.53 |
| Baseplate – Local Membrane Plus Primary Bending Stress Intensity | 28.25 | 28.425 | 1.01 |
| Shell – Primary Membrane Stress Intensity | 14.07 | 18.05 | 1.28 |
| Shell – Local Membrane Plus Primary Bending Stress Intensity | 23.12 | 27.1 | 1.17 |
| Shell – Local Membrane Plus Primary Bending Plus Secondary Stress Intensity | 49.81 | 56.85 | 1.14 |

| Table 3.4.7B<br><br>STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL – OFF-NORMAL INTERNAL PRESSURE | | | |
|---|---|---|---|
| Item | Calculated Value (ksi) | Allowable Limit (ksi) | Safety Factor |
| Lid – Primary Membrane Stress Intensity | 12.10 | 18.15 | 1.50 |
| Lid – Local Membrane Plus Primary Bending Stress Intensity | 16.45 | 27.225 | 1.66 |
| Baseplate – Primary Membrane Stress Intensity | 9.69 | 19.25 | 1.99 |
| Baseplate – Local Membrane Plus Primary Bending Stress Intensity | 26.15 | 28.93 | 1.11 |
| Shell – Primary Membrane Stress Intensity | 15.93 | 19.25 | 1.21 |
| Shell – Local Membrane Plus Primary Bending Stress Intensity | 26.00 | 28.93 | 1.11 |
| Shell – Local Membrane Plus Primary Bending Plus Secondary Stress Intensity | 48.92 | 54.15 | 1.11 |

| Table 3.4.8<br><br>STRESS INTENSITY RESULTS FOR MPC ENCLOSURE VESSEL – ACCIDENT INTERNAL PRESSURE | | | |
|---|---|---|---|
| Item | Calculated Value (ksi) | Allowable Limit (ksi) | Safety Factor |
| Lid – Primary Membrane Stress Intensity | 10.69 | 35.5 | 3.32 |
| Lid – Local Membrane Plus Primary Bending Stress Intensity | 13.60 | 53.25 | 3.92 |
| Baseplate – Primary Membrane Stress Intensity | 16.00 | 35.50 | 2.20 |
| Baseplate – Local Membrane Plus Primary Bending Stress Intensity | 36.61 | 53.25 | 1.45 |
| Shell – Primary Membrane Stress Intensity | 22.93 | 35.50 | 1.55 |

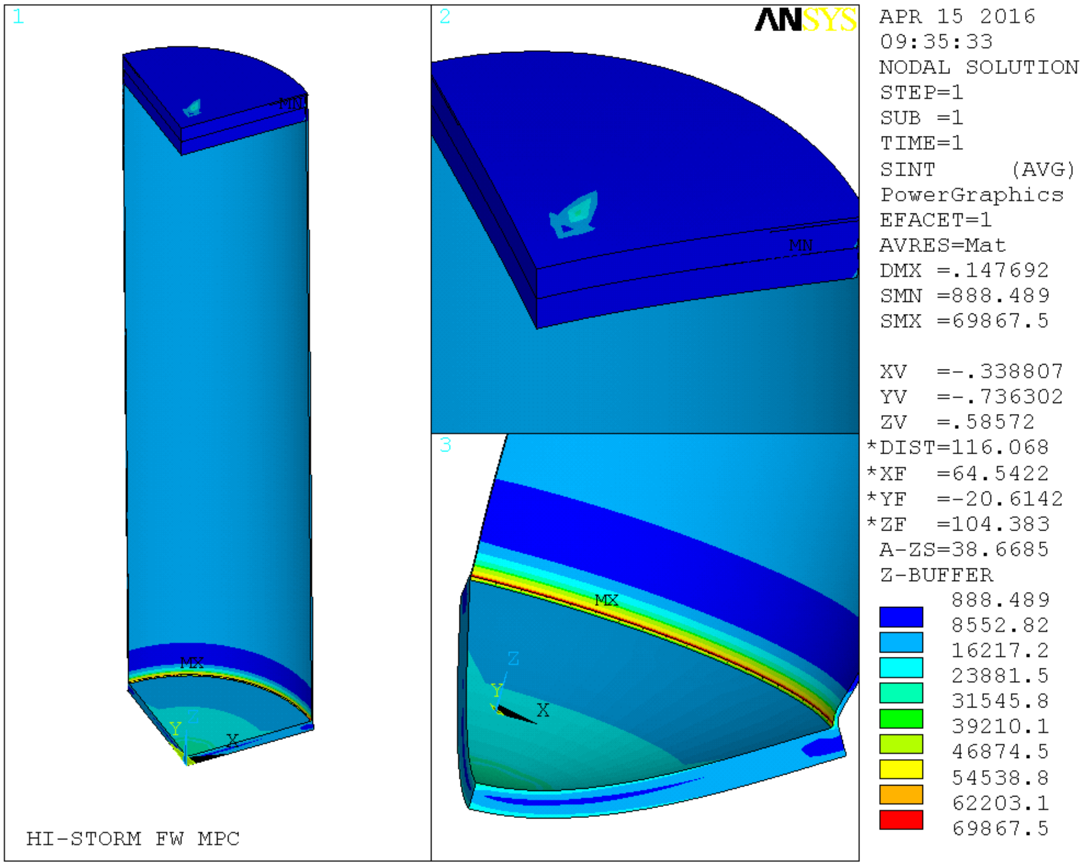


Figure 3.4.2: Stress Intensity Distribution in MPC Enclosure Vessel – Normal Handling

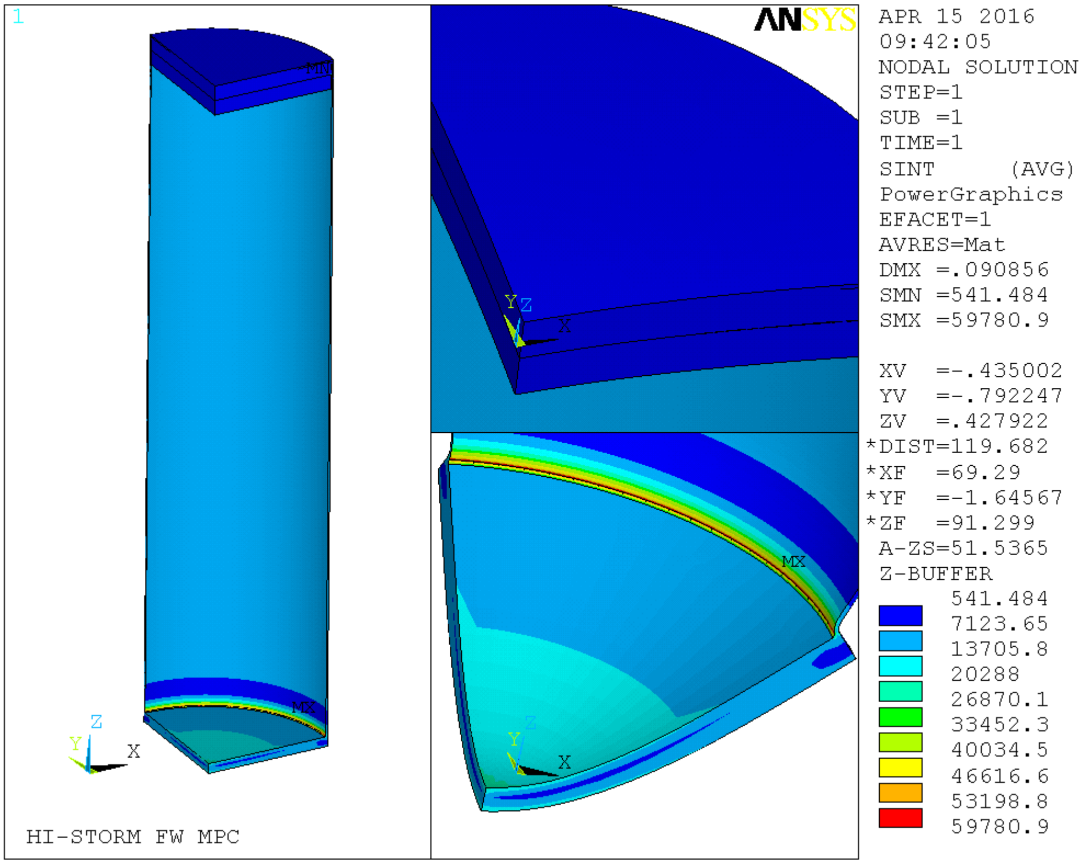


Figure 3.4.23: Stress Intensity Distribution in MPC Enclosure Vessel – Design Internal Pressure

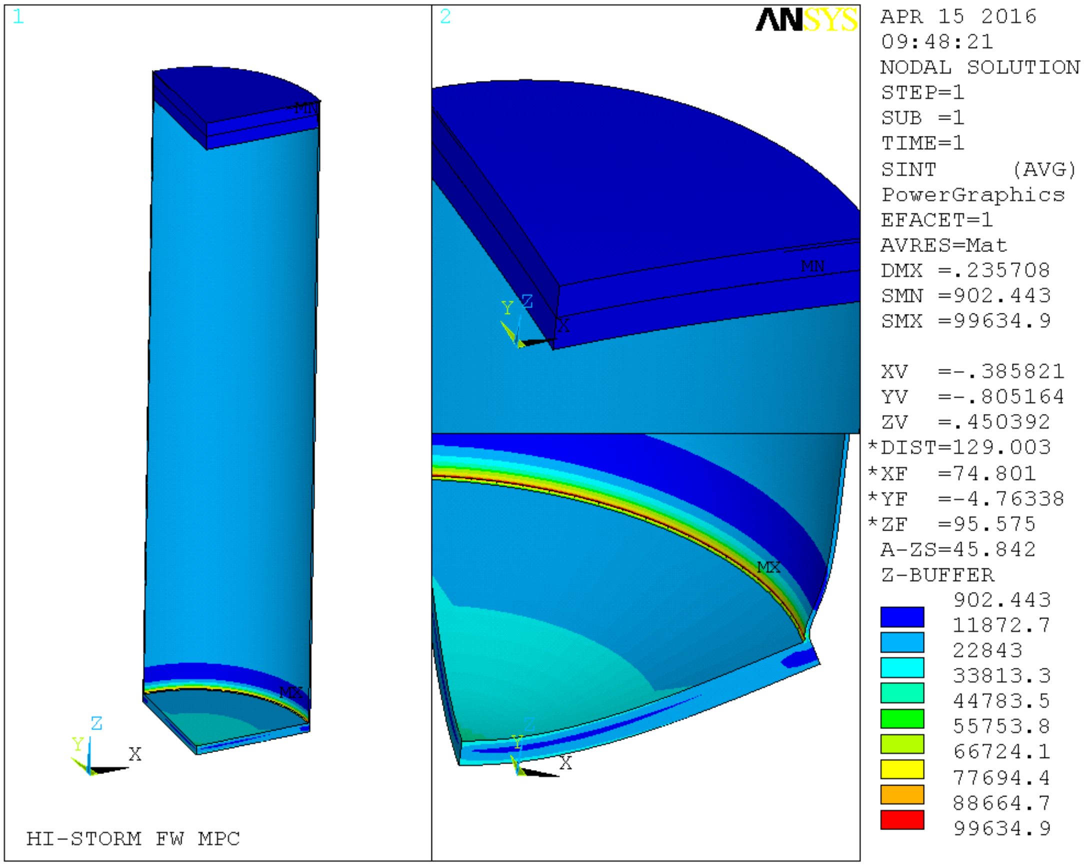


Figure 3.4.24: Stress Intensity Distribution in MPC Enclosure Vessel –
Accident Internal Pressure

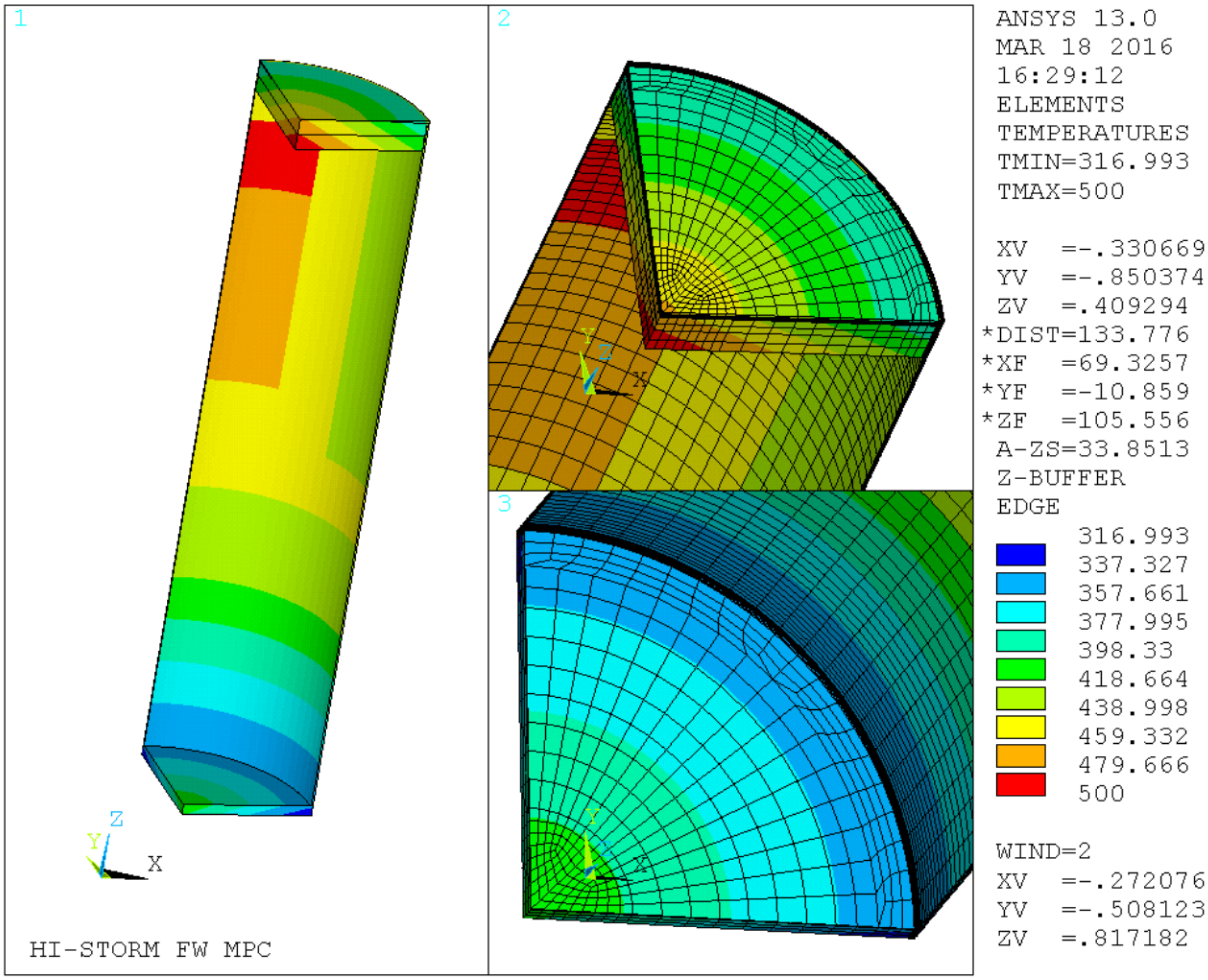


Figure 3.4.27: Short-Term Normal Condition Temperature Distribution in MPC Enclosure Vessel

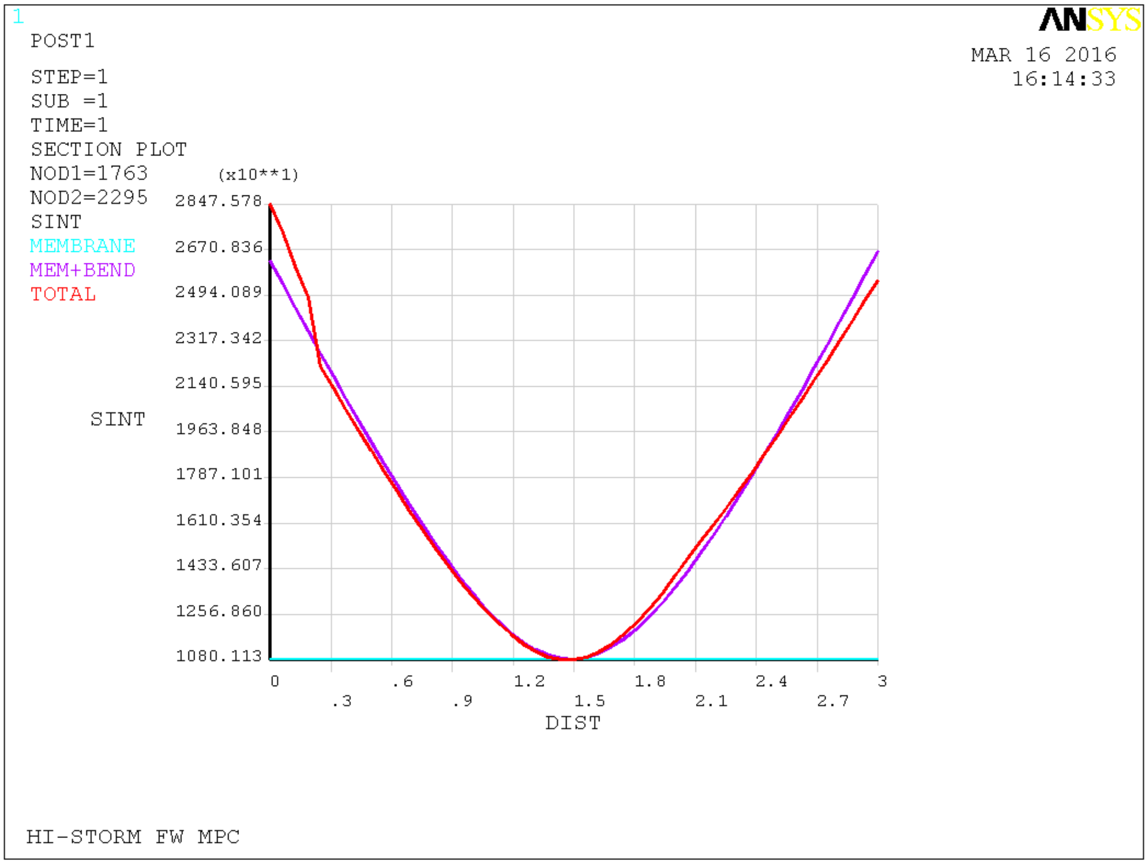


Figure 3.4.29: Normal Handling of MPC Enclosure Vessel –
Thru-Thickness Stress Intensity Plot at Baseplate Center

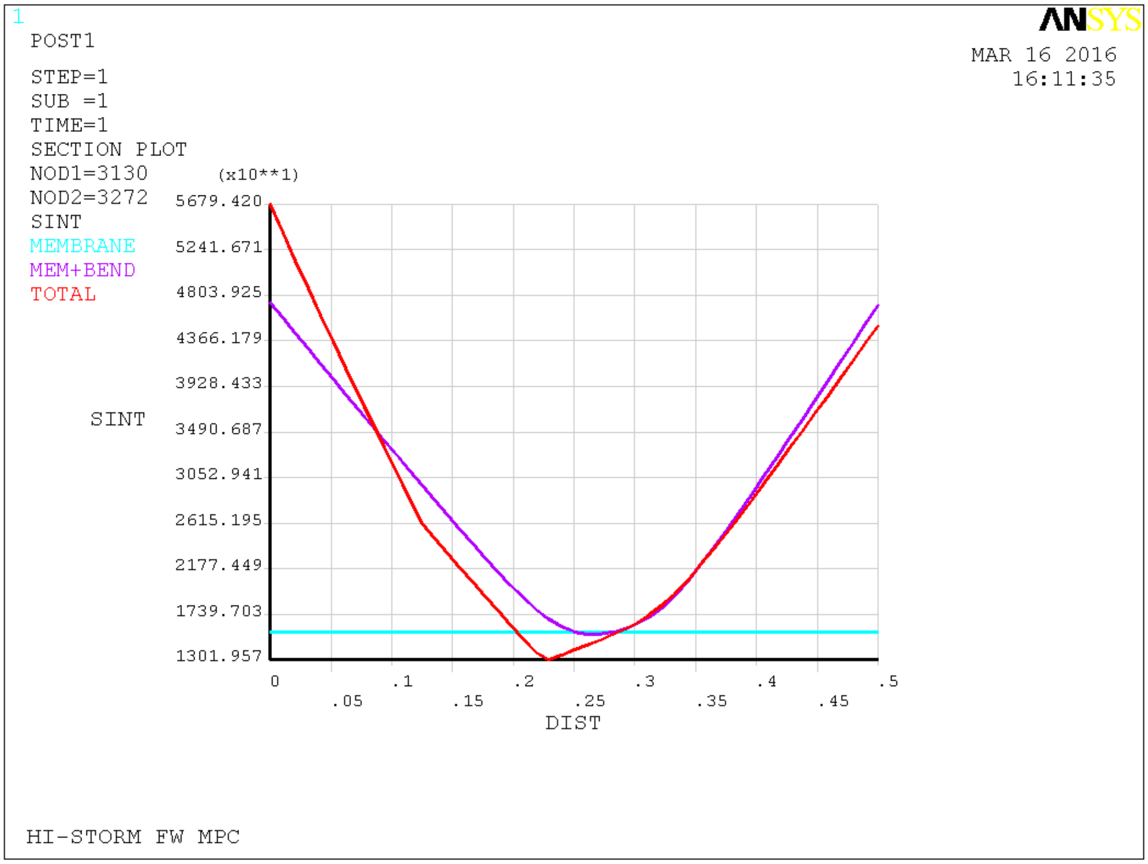


Figure 3.4.30: Normal Handling of MPC Enclosure Vessel –
Thru-Thickness Stress Intensity Plot at Baseplate-to-Shell Juncture

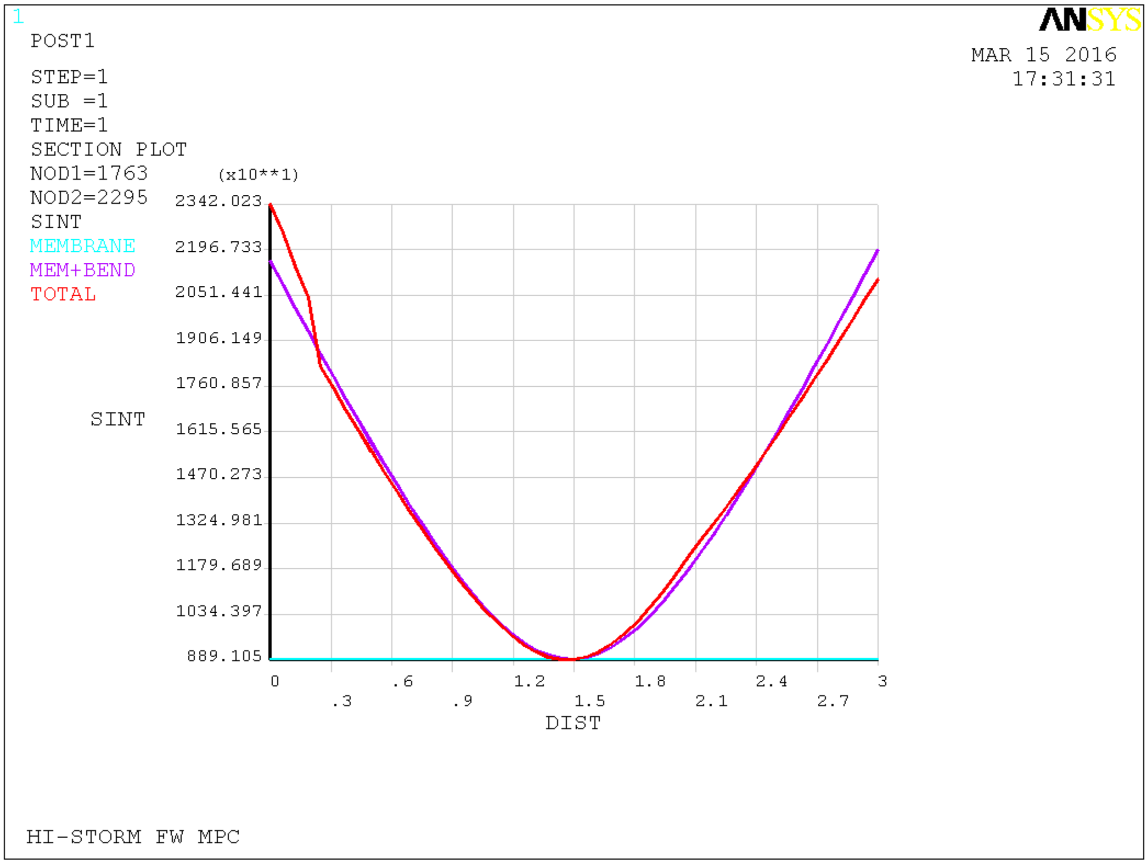


Figure 3.4.32: MPC Design Internal Pressure (Load Case 5) –
Thru-Thickness Stress Intensity Plot at Baseplate Center

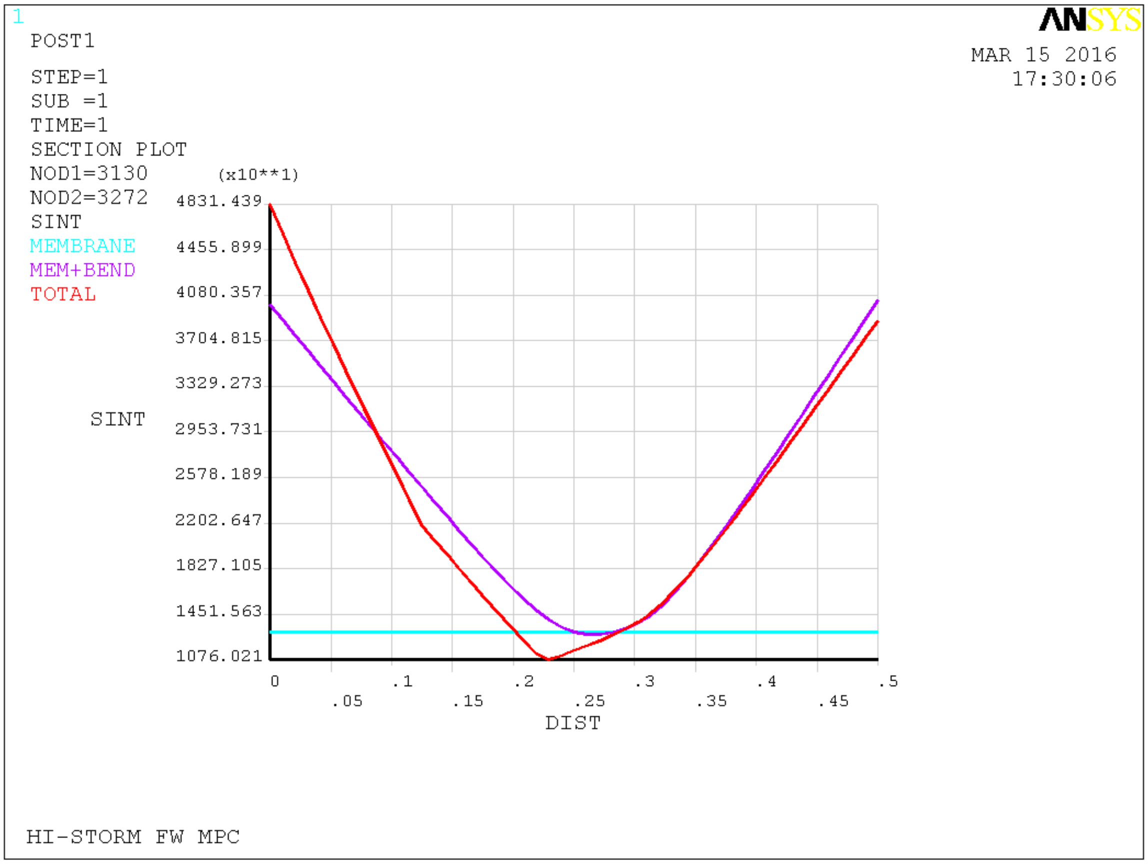


Figure 3.4.33: MPC Design Internal Pressure (Load Case 5) –
Thru-Thickness Stress Intensity Plot at Baseplate-to-Shell Juncture

compliance with ISG-11 and with NUREG-1536 guidelines, subject to the exceptions and clarifications discussed in Chapter 1, Table 1.0.3.

As explained in Section 1.2, the storage of SNF in the fuel baskets in the HI-STORM FW system is configured for a three-region storage system under regionalized storage and uniform storage. Figures 1.2.1a, 1.2.1b, 1.2.1c and 1.2.2 provide the information on the location of the regions and Tables 1.2.3a, 1.2.3b, 1.2.3c and 1.2.4 provide the permissible specific heat load (heat load per fuel assembly) in each region for the PWR and BWR MPCs, respectively. The Specific Heat Load (SHL) values under regionalized storage are defined for two patterns that in one case maximizes ALARA (Table 1.2.3a, Pattern A and Table 1.2.4) and in the other case maximizes heat dissipation (Table 1.2.3a, Pattern B). The ALARA maximized fuel loading is guided by the following considerations:

- Region 1: Located in the core region of the basket is permitted to store fuel with medium specific heat load.
- Region 2: This is the intermediate region flanked by the core region (Region I) from the inside and the peripheral region (Region III) on the outside. This region has the maximum SHL in the basket.
- Region 3: Located in the peripheral region of the basket, this region has the smallest SHL. Because a low SHL means a low radiation dose emitted by the fuel, the low heat emitting fuel around the periphery of the basket serves to block the radiation from the Region II fuel, thus reducing the total quantity of radiation emanating from the MPC in the lateral direction.

Thus, the 3-region arrangement defined above serves to minimize radiation dose from the MPC and peak cladding temperatures mitigated by avoiding placement of hot fuel in the basket core.

To address the needs of cask users having high heat load fuel inventories, fuel loading Pattern B is defined in Table 1.2.3a to maximize heat dissipation by locating hotter fuel in the cold peripheral Region 3 and in this manner minimize cladding temperatures. This has the salutary effect of minimizing core temperature gradients in the radial direction and thermal stresses in the fuel and fuel basket.

As an alternative to the loading patterns discussed above, fuel storage in the MPC-37 and MPC-89 is permitted to use the heat load charts shown in Figures 1.2.3a, 1.2.4a, 1.2.5a (MPC-37) and 1.2.6a (MPC-89) for undamaged fuel or Figures 1.2.3b, 1.2.3c, 1.2.4b, 1.2.4c, 1.2.5b, 1.2.5c (MPC-37) and Figure 1.2.4b (MPC-89) for damaged fuel and fuel debris.

The salutary consequences of all regionalized loading arrangements become evident from the computed peak cladding temperatures in this chapter, which show margin to the ISG-11 limit discussed earlier.

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

stresses due to restraint on basket periphery thermal growth is eliminated by providing adequate basket-to-canister shell gaps to allow for basket thermal growth during all operational modes.

The most important contributor to minimizing thermal stresses and maximizing heat transmission within the fuel basket is its material of construction (Metamic-HT) which has approximately ten times the thermal conductivity of the stainless steel material used in the stainless steel baskets in the HI-STORM 100 System [4.1.8]. The Metamic-HT plates in the HI-STORM FW MPCs are also considerably thicker than their counterparts in the stainless baskets, resulting in an additional enhancement in conduction heat transfer.

The MPCs uniform & regionalized fuel storage scenarios are defined in Figures 1.2.1a, 1.2.1b, 1.2.1c and 1.2.2 in Chapter 1 and design maximum decay heat loads for storage of zircaloy clad fuel are listed in Tables 1.2.3a, 1.2.3b, 1.2.3c, 1.2.4 and in Figures 1.2.3a thru 1.2.3c, 1.2.4a thru 1.2.4c, 1.2.5a thru 1.2.5c and Figures 1.2.6a thru 1.2.6b. The axial heat distribution in each fuel assembly is conservatively assumed to be non-uniformly distributed with peaking in the active fuel mid-height region (see axial burnup profiles in Figures 2.1.3 and 2.1.4). Table 4.1.1 summarizes the principal operating parameters of the HI-STORM FW system.

The fuel cladding temperature limits that the HI-STORM FW system is required to meet are discussed in Section 4.3 and given in Table 2.2.3. Additionally, when the MPCs are deployed for storing High Burnup Fuel (HBF) further restrictions during certain fuel loading operations (vacuum drying) are set forth herein to preclude fuel temperatures from exceeding the normal temperature limits. To ensure explicit compliance, a specific term "short-term operations" is defined in Chapter 2 to cover all fuel loading activities. ISG-11 fuel cladding temperature limits are applied for short-term operations.

The HI-STORM FW system (i.e., HI-STORM FW overpack, HI-TRAC VW transfer cask and MPC) is evaluated under normal storage (HI-STORM FW overpack), during off-normal and accident events and during short-term operations in a HI-TRAC VW. Results of HI-STORM FW thermal analysis during normal (long-term) storage are obtained and reported in Section 4.4. Results of HI-TRAC VW short-term operations (fuel loading, on-site transfer and vacuum drying) are reported in Section 4.5. Results of off-normal and accident events are reported in Section 4.6.

| Table 4.1.1<br><br>HI-STORM FW OPERATING CONDITION PARAMETERS | |
|---|---|
| **Condition** | **Value** |
| MPC Decay Heat, max. | Tables 1.2.3a, 1.2.3b, 1.2.3c and 1.2.4<br>Figures 1.2.3a thru 1.2.3c, Figures 1.2.4a thru 1.2.4c, Figures 1.2.5a thru 1.2.5c and Figures 1.2.6a thru 1.2.6b |
| MPC Operating Pressure | Note 1 |
| Normal Ambient Temperature | Table 2.2.2 |
| Helium Backfill Pressure | Table 4.4.8 |
| Note 1: The MPC operating pressure used in the thermal analysis is based on the minimum helium backfill pressure specified in Table 4.4.8 and MPC cavity average temperature. | |

Table 4.2.1

SUMMARY OF HI-STORM FW SYSTEM MATERIALS
THERMAL PROPERTY REFERENCES

| Material | Emissivity | Conductivity | Density | Heat Capacity |
|---|---|---|---|---|
| Helium | N/A | Handbook [4.2.2] | Ideal Gas Law | Handbook [4.2.2] |
| Air | N/A | Handbook [4.2.2] | Ideal Gas Law | Handbook [4.2.2] |
| Zircaloy | [4.2.3], [4.2.17], [4.2.18], [4.2.7] | NUREG [4.2.17] | Rust [4.2.4] | Rust [4.2.4] |
| $UO_2$ | Note 1 | NUREG [4.2.17] | Rust [4.2.4] | Rust [4.2.4] |
| Stainless Steel (machined forgings) Note 2 | Kern [4.2.5] | ASME [4.2.8] | Marks' [4.2.1] | Marks' [4.2.1] |
| Stainless Steel Plates Note 3 | ORNL [4.2.11], [4.2.12] | ASME [4.2.8] | Marks' [4.2.1] | Marks' [4.2.1] |
| Carbon Steel | Kern [4.2.5] | ASME [4.2.8] | Marks' [4.2.1] | Marks' [4.2.1] |
| Concrete | Note 1 | Marks' [4.2.1] | Appendix 1.D of HI-STORM 100 FSAR [4.1.8] | Handbook [4.2.2] |
| Lead | Note 1 | Handbook [4.2.2] | Handbook [4.2.2] | Handbook [4.2.2] |
| Water | Note 1 | ASME [4.2.10] | ASME [4.2.10] | ASME [4.2.10] |
| Metamic-HT | Test Data Table 1.2.8 | Test Data Table 1.2.8 | Test Data Table 1.2.8 | Test Data Table 1.2.8 |
| Aluminum Alloy 2219 | Note 4 | ASM [4.2.19] | ASM [4.2.19] | ASM [4.2.19] |

Note 1: Emissivity not reported as radiation heat dissipation from these surfaces is conservatively neglected.

Note 2: Used in the MPC lid.

Note 3: Used in the MPC shell and baseplate.

Note 4: Table 1.2.8 (oxidized), Ref. [4.2.21] (passivated).

Table 4.2.2

SUMMARY OF HI-STORM FW SYSTEM MATERIALS
THERMAL CONDUCTIVITY DATA

| Material | At 200°F (Btu/ft-hr-°F) | At 450°F (Btu/ft-hr-°F) | At 700°F (Btu/ft-hr-°F) | At 1000°F (Btu/ft-hr-°F) |
|---|---|---|---|---|
| Helium | 0.0976 | 0.1289 | 0.1575 | 0.1890 |
| Air* | 0.0173 | 0.0225 | 0.0272 | 0.0336 |
| Alloy X**** | 8.4 | 9.8 | 11.0 | 12.4 |
| Carbon Steel | 24.4 | 23.9 | 22.4 | 20.0 |
| Concrete** | 1.05 | 1.05 | 1.05 | 1.05 |
| Lead | 19.4 | 17.9 | 16.9 | N/A |
| Water | 0.392 | 0.368 | N/A | N/A |
| Metamic-HT | Table 1.2.8 | | | |
| Aluminum Alloy 2219 ** | 69.3 | 69.3 | 69.3 | 69.3 |
| Aluminum Alloy (Solid Shim Plate)*** | 86.7 | 86.7 | 86.7 | 86.7 |

* At lower temperatures, Air conductivity is between 0.0139 Btu/ft-hr-°F at 32°F and 0.0176 Btu/ft-hr-°F at 212°F.

** Conservatively assumed to be constant for the entire range of temperatures.

*** The optional solid shim aluminum plates discussed in Table 1.2.9 must have the tabulated minimum thermal conductivity.

**** Individual thermal conductivities of the alloys that comprise the Alloy X materials are reported in Appendix 1.A. Lowerbound Alloy X thermal conductivity is tabulated herein.

Table 4.2.4

SUMMARY OF MATERIALS SURFACE EMISSIVITY DATA*

| Material | Emissivity |
|---|---|
| Zircaloy | 0.80 |
| Painted surfaces | 0.85 |
| Stainless steel (machined forgings) | 0.36 |
| Stainless Steel Plates | 0.587** |
| Carbon Steel | 0.66 |
| Metamic-HT*** | Table 1.2.8 |
| Extruded Shims (Aluminum Alloy 2219) | Table 1.2.9 (oxidized)<br>0.1 (passivated) |
| Solid Shims (Aluminum Alloy)‡ | Table 1.2.9 |

* See Table 4.2.1 for cited references.

** Lower bound value from the cited references in Table 4.2.1.

*** Metamic-HT surfaces are oxidized to yield high emissivities. Emissivity of oxidized surfaces is reported in Table 1.2.8.

‡ Solid aluminum shim surfaces are oxidized to yield emissivities tabulated in Table 1.2.9.

# 4.4 THERMAL EVALUATION FOR NORMAL CONDITIONS OF STORAGE

The HI-STORM FW Storage System (i.e., HI-STORM FW overpack and MPC) and HI-TRAC VW transfer cask thermal evaluation is performed in accordance with the guidelines of NUREG-1536 [4.4.1] and ISG-11 [4.1.4]. To ensure a high level of confidence in the thermal evaluation, 3-dimensional models of the MPC, HI-STORM FW overpack and HI-TRAC VW transfer cask are constructed to evaluate fuel integrity under normal (long-term storage), off-normal and accident conditions and in the HI-TRAC VW transfer cask under short-term operation and hypothetical accidents. The principal features of the thermal models are described in this section for HI-STORM FW and Section 4.5 for HI-TRAC VW. Thermal analyses results for the long-term storage scenarios are obtained and reported in this section. The evaluation addresses the design basis thermal loadings defined in Section 1.2.3. Based on these evaluations the limiting thermal loading condition is defined in Subsection 4.4.4 and adopted for evaluation of on-site transfer in the HI-TRAC (Section 4.5) and off-normal and accident events defined in Section 4.6.

## 4.4.1 Overview of the Thermal Model

As illustrated in the drawings in Section 1.5, the basket is a matrix of interconnected square compartments designed to hold the fuel assemblies in a vertical position under long term storage conditions. The basket is a honeycomb structure of Metamic-HT plates that are slotted and arrayed in an orthogonal configuration to form an integral basket structure. The Metamic-HT neutron absorber plates contain 10% (min.) Boron Carbide in an aluminum matrix reinforced with nanoparticles of alumina to provide criticality control, while maximizing heat conduction capabilities (see Chapter 1, Section 1.2.1.4.1).

Thermal analysis of the HI-STORM FW System is performed for all heat load scenarios defined in Chapter 1 for regionalized storage (Figures 1.2.1a and 1.2.2) and uniform storage (Figures 1.2.1b and 1.2.1c). Each fuel assembly is *assumed to be generating heat at the maximum permissible rate (Tables 1.2.3a, 1.2.3b, 1.2.3c, 1.2.4, Figures 1.2.3a thru 1.2.3c, 1.2.4a thru 1.2.4c, 1.2.5a thru 1.2.5c and Figures 1.2.6a thru 1.2.6b)*. While the assumption of limiting heat generation in each storage cell imputes a certain symmetry to the cask thermal problem, it grossly overstates the total heat duty of the system in most cases because it is unlikely that any basket would be loaded with fuel emitting heat at their limiting values in *each* storage cell. Thus, the thermal model for the HI-STORM FW system is inherently conservative for real life applications. Other noteworthy features of the thermal analyses are:

i. While the rate of heat conduction through metals is a relatively weak function of temperature, radiation heat exchange increases rapidly as the fourth power of absolute temperature.

ii. Heat generation in the MPC is axially non-uniform due to non-uniform axial burnup profiles in the fuel assemblies.

| Storage Scenario | MPC | Fuel |
|---|---|---|
| PWR: 15x15I Short Fuel | Minimum Height MPC-37 for 15x15I fuel assembly array | 15x15I in Table 2.1.2 |
| PWR: Short Fuel | Minimum Height MPC-37 for all fuel assembly arrays except 15x15I | 14x14 Ft. Calhoun |
| PWR: Standard Fuel | Reference Height MPC-37 | W-17x17 |
| PWR: XL Fuel | Maximum Height MPC-37 | AP1000 |
| PWR: 16x16D | MPC-32ML | 16x16D |
| PWR: V10A/V10B | MPC-31C | VVER 1000 |
| BWR | MPC-89 | GE-10x10 |

The fuel region effective conductivity is defined as the calculated equivalent conductivity of the fuel storage cell due to the combined effect of conduction and radiation heat transfer in the manner of the approach used in the HI-STORM 100 system (Docket No. 72-1014). Because radiation is proportional to the fourth power of absolute temperature, the effective conductivity is a strong function of temperature. FLUENT computer code has been used to characterize fuel resistance at several representative storage cell temperatures and the effective thermal conductivity as a function of temperature obtained for all storage configurations defined above and tabulated in Table 4.4.1.

Heat Rejection from External Surfaces

The exposed surfaces of the HI-STORM FW dissipate heat by radiation and external natural convection heat transfer. Radiation is modeled using classical equations for radiation heat transfer (Rohsenow & Hartnett [4.2.2]). Jakob and Hawkins [4.2.9] recommend the following correlations for natural convection heat transfer to air from heated vertical and horizontal surfaces:

Turbulent range:

$$h = 0.19\,(\Delta T)^{1/3}\ (\text{Vertical}, GrPr > 10^9)$$

$$h = 0.18\,(\Delta T)^{1/3}\ (\text{Horizontal Cylinder}, GrPr > 10^9)$$

(in conventional U.S. units)

Laminar range:

$$h = 0.29\,\left(\frac{\Delta T}{L}\right)^{1/4}\ (\text{Vertical}, GrPr < 10^9)$$

$$h = 0.27\,\left(\frac{\Delta T}{D}\right)^{1/4}\ (\text{Horizontal Cylinder}, GrPr < 10^9)$$

(in conventional U.S. Units)

system's thermal performance.

f) The air flow in the HI-STORM FW/MPC annulus is simulated by the k-ω turbulence model with the transitional option enabled. The adequacy of this turbulence model is confirmed in the Holtec benchmarking report [4.1.6]. The annulus grid size is selected to ensure a converged solution.(See Section 4.4.1.6).

g) A limited number of fuel assemblies defined in Table 1.2.1 classified as damaged fuel are permitted to be stored in the MPC inside Damaged Fuel Containers (DFCs). A DFC can be stored in the outer peripheral locations of MPC-37, MPC-32ML, MPC-31C and MPC-89 as shown in Figures 2.1.1a, 2.1.1b, 2.1.1c and 2.1.2, respectively or in certain interior locations as shown in Figures 1.2.3b thru 1.2.3c, 1.2.4b thru 1.2.4c, 1.2.5b thru 1.2.5c and Figure 1.2.6b. DFC emplaced fuel assemblies have a higher resistance to helium flow because of the debris screens. DFC fuel storage under peripherally permitted scenarios does not affect temperature of hot fuel stored in the core of the basket because DFC storage is located away from hot fuel. For these scenarios the thermal modeling of the fuel basket under the assumption of all storage spaces populated with intact fuel is justified. Interior permitted DFC storage scenarios are addressed under item "m" below.

h) As shown in HI-STORM FW drawings in Section 1.5 the HI-STORM FW overpack is equipped with an optional heat shield to protect the inner shell and concrete from radiation heating by the emplaced MPC. The inner and outer shells and concrete are explicitly modeled. All the licensing basis thermal analyses explicitly include the heat shields. A sensitivity study is performed as described in paragraph 4.4.1.9 to evaluate the absence of heat shield on the overpack inner shell and overpack lid.

i) To maximize lateral resistance to heat dissipation in the fuel basket, 0.8 mm full length inter- panel gaps are conservatively assumed to exist at all intersections. This approach is identical to that used in the thermal analysis of the HI-STAR 180 Package in Docket 71-9325. The shims installed in the MPC peripheral spaces (See MPC-37, MPC-32ML, MPC-31C and MPC-89 drawings in Section 1.5) are explicitly modeled. For conservatism bounding as-built gaps (3 mm basket-to-shims and 3 mm shims-to-shell) are assumed to exist and incorporated in the thermal models.

j) The thermal models incorporate all modes of heat transfer (conduction, convection and radiation) in a conservative manner.

k) The Discrete Ordinates (DO) model, previously utilized in the HI-STAR 180 docket (Docket 71-9325), is deployed to compute radiation heat transfer.

l) Laminar flow conditions are applied in the MPC internal spaces to obtain a lowerbound rate of heat dissipation.

m) A limited number of fuel assemblies classified as damaged or fuel debris placed in Damaged Fuel Containers (DFCs) are permitted to be stored in certain interior locations of MPC-37 and MPC-89 under heat load charts defined in Figures 1.2.3b thru 1.2.3c, 1.2.4b thru 1.2.4c, 1.2.5b thru 1.2.5c and Figure 1.2.6b. These scenarios are evaluated herein.

The 3-D model described above is illustrated in the cross-section for the MPC-89, MPC-32ML, MPC-31C and MPC-37 in Figures 4.4.2a, 4.4.2b, 4.4.2c and 4.4.3, respectively. A closeup of the fuel cell spaces which explicitly include the channel-to-cell gap in the 3-D model applicable to BWR fueled basket (MPC-89) is shown in Figure 4.4.4. The principal 3-D modeling conservatisms are listed below:

1) The storage cell spaces are loaded with high flow resistance design basis fuel assemblies (See Table 2.1.4).
2) Each storage cell is generating heat at its limiting value under the regionalized storage scenarios defined in Chapter 2, Section 2.1.
3) Axial dissipation of heat by conduction in the fuel pellets is neglected.
4) Dissipation of heat from the fuel rods by radiation in the axial direction is neglected.
5) The fuel assembly channel length for BWR fuel is overstated.
6) The most severe environmental factors for long-term normal storage – ambient temperature of 80°F and 10CFR71 insolation levels – were coincidentally imposed on the system.
7) Reasonably bounding solar absorbtivity of HI-STORM FW overpack external surfaces is applied to the thermal models.
8) To understate MPC internal convection heat transfer, the helium pressure is understated.
9) No credit is taken for contact between fuel assemblies and the MPC basket wall or between the MPC basket and the basket supports.
10) Heat dissipation by fuel basket peripheral supports is neglected.
11) Conservatively specified fuel basket emissivity in Table 1.2.8 adopted in the thermal analysis.
12) Lowerbound stainless steel emissivity obtained from cited references (See Table 4.2.1) are applied to MPC shell.
13) The k-ω model used for simulating the HI-STORM FW annulus flow yields uniformly conservative results [4.1.6].
14) Fuel assembly length is conservatively modeled equal to the height of the fuel basket.

The effect of crud resistance on fuel cladding surfaces has been evaluated and found to be negligible [4.1.8]. The evaluation assumes a thick crud layer (130 μm) with a bounding low conductivity (conductivity of helium). The crud resistance increases the clad temperature by a

Thus the flow resistance defined in the manner above is significantly conservative for modeling the Ft. Calhoun 14x14 fuel placed in the limiting minimum height MPC-37 (See Table 4.4.2). The flow resistance for 15x15I short fuel is discussed in Section 4.4.1.7. In the following, explicit calculations for the case of MPC-37 are performed to quantify the conservatism introduced by using the “bounding” resistance data in the FLUENT analysis.

### 4.4.1.4 Evaluation of Flow Resistance in Enlarged Cell MPCs

The flow resistance factors used in the porous media model are bounding for all fuel types and MPC baskets. This was accomplished for the PWR fueled MPC-37 by placing the most resistive Westinghouse 17x17 fuel assembly in the smaller cell opening MPC-32 approved under the HI-STORM 100 Docket 72-1014, CoC Amendment No. 5 and computing the flow resistance factors. In the case of BWR fueled MPC-89 the most resistive GE-10x10 fuel assembly in the channeled configuration is explicitly modeled in the MPC-89 fuel storage spaces as shown in Figure 4.4.4. The channeled space occupied by the GE-10x10 fuel assembly is modeled as a porous region with effective flow resistance properties computed by deploying an independent 3D FLUENT model of the array of fuel rods and grid spacers.

In the PWR fuel resistance modeling case physical reasoning suggests that the flow resistance of a fuel assembly placed in the larger MPC-37 storage cell will be less than that computed using the (smaller) counterpart cells cavities in the MPC-32. However to provide numerical substantiation FLUENT calculations are performed for the case of W-17x17 fuel placed inside the MPC-32 cell opening of 8.79” and the enlarged MPC-37 cell opening of 8.94”. The FLUENT results for the cell pressure drops under the baseline (MPC-32) and enlarged cell opening (MPC-37) scenarios are shown plotted in Figure 4-4-7. The plot shows that, as expected, the larger cell cross section case (MPC-37) yields a smaller pressure loss. Therefore, the MPC-37 flow resistance is bounded by the MPC-32 flow resistance used in the FLUENT simulations in the SAR. This evaluation is significant because the MPC-37 basket is determined as the limiting MPC and therefore the licensing basis HI-STORM FW temperatures by use of higher-than-actual resistance are overstated.

However, as mentioned in Sub-section 4.4.1.2, a flow resistance of $1x10^{6}$ $m^{-2}$ through PWR fuel assemblies is used in the thermal analysis.

### 4.4.1.5 Screening Calculations to Ascertain Limiting Storage Scenario

To define the thermally most limiting HI-STORM FW storage scenario the following cases are evaluated under the limiting heat load patterns defined in Section 1.2.3[1]:

(i) MPC-89 under regionalized fuel storage Table 1.2.4
(ii) Minimum height MPC-37 under regionalized fuel storage Table 1.2.3a
(iii) Reference height MPC-37 under regionalized fuel storage Table 1.2.3a

1 Pattern A defined in Table 1.2.3a is the limiting fuel storage (See Subsection 4.4.4.1).

(iv) Maximum height MPC-37 under regionalized fuel storage Table 1.2.3a
(v) MPC-32ML under uniform fuel storage Table 1.2.3b
(vi) MPC-31C under uniform fuel storage Table 1.2.3c
(vii) MPC-89 under heat load Figures 1.2.6a, 1.2.6b
(viii) MPC-37 under heat load Figures 1.2.3a/b/c, 1.2.4a/b/c and 1.2.5a/b/c

To evaluate the above scenarios, 3D FLUENT screening models of the HI-STORM FW cask are constructed, Peak Cladding Temperatures (PCT) computed and tabulated in Table 4.4.2. The results of the calculations yield the following:

(a) Fuel storage in MPC-37 produces a higher peak cladding temperature than that in MPC-89
(b) Fuel storage in the minimum height MPC-37 is limiting (produces the highest peak cladding temperature).

To bound the HI-STORM FW storage temperatures the limiting scenario ascertained above is adopted for evaluation of all normal, off-normal and accident conditions.

### 4.4.1.6 Grid Sensitivity Studies

To achieve grid independent CFD results, a grid sensitivity study is performed on the HI-STORM FW thermal model. The grid refinement is performed in the entire domain i.e. for both fluid and solid regions in both axial and radial directions. Non-uniform meshes with grid cells clustered near the wall regions are generated to resolve the boundary flow near the walls.

A number of grids are generated to study the effect of mesh refinement on the fuel and component temperatures. All sensitivity analyses were carried out for the case of MPC-37 with minimum fuel length under the bounding heat load pattern A. Following table gives a brief summary of the different sets of grids evaluated and PCT results.

| Mesh No | Total Mesh Size | PCT ($^oC$) | Permissible Limit ($^oC$) | Clad Temperature Margin ($^oC$) |
|---|---|---|---|---|
| 1 (Licensing Basis Mesh) | 1,536,882 | 373 | 400 | 27 |
| 2 | 3,354,908 | 372 | 400 | 28 |
| 3 | 7,315,556 | 372 | 400 | 28 |
| Note: Because the flow field in the annulus between MPC shell and overpack inner shell is in the transitional turbulent regime, the value of $y^+$ at the wall-adjacent cell is maintained on the order of 1 to ensure the adequate level of mesh refinement is reached to resolve the viscosity affected region near the wall. | | | | |

As can be seen from the above table, the PCT is essentially the same for all the meshes. The solutions from the different grids used are in the asymptotic range. Therefore, it can be

Therefore the FLUENT models report the peak temperature *in the fuel storage cells.* Thus, as the fuel assembly models include the fuel pellets, the FLUENT calculated peak temperatures are actually peak pellet centerline temperatures which bound the peak cladding temperatures with a modest margin.

The following observations can be derived by inspecting the temperature field obtained from the thermal models:

- The fuel cladding temperatures are below the regulatory limit (ISG-11 [4.1.4]) under all uniform and regionalized storage scenarios defined in Chapter 1 (Figures 1.2.1a, 1.2.1b, 1.2.1c and 1.2.2) and thermal loading scenarios defined in Tables 1.2.3a, 1.2.3b, 1.2.3c,1.2.4, Figures 1.2.3a/b/c, 1.2.4a/b/c, 1.2.5a/b/c, 1.2.6a and 1.2.6b.

- The limiting fuel temperatures are reached under the Pattern A thermal loading condition defined in Table 1.2.3a in the MPC-37. Accordingly this scenario is adopted for thermal evaluation under on-site transfer (Section 4.5) and under off-normal and accident conditions (Section 4.6).

- The maximum temperature of the basket structural material is within its design limit.

- The maximum temperatures of the MPC pressure boundary materials are below their design limits.

- The maximum temperatures of concrete are within the guidance of the governing ACI Code (see Table 2.2.3).

- The calculated fuel temperature for the 15x15I short fuel assembly (Table 4.4.12) is bounded by the thermal evaluations for the minimum MPC-37 for short fuel (Table 4.4.3). The temperatures of other cask components are similar. It is reasonable to conclude that the temperatures and pressure for the minimum height MPC-37 (short fuel) bounds all scenarios.

The above observations lead us to conclude that the temperature field in the HI-STORM FW System with a loaded MPC containing heat emitting SNF complies with all regulatory temperature limits (Table 2.2.3). In other words, the thermal environment in the HI-STORM FW System is in compliance with Chapter 2 Design Criteria.

Also, all the licensing basis thermal evaluations documented in this chapter are performed for the most limiting thermal scenarios i.e. minimum MPC-37 with heat load pattern A.

#### 4.4.4.2 Minimum Temperatures

Table 4.4.1

EFFECTIVE FUEL PROPERTIES UNDER BOUNDING FUEL STORAGE CONFIGURATIONS[Note 1]

| | Conductivity (Btu/hr-ft-°F) | | | |
|---|---|---|---|---|
| | **PWR: Short Fuel** | | **PWR: Standard Fuel** | |
| Temperature (°F) | Planar | Axial | Planar | Axial |
| 200 | 0.265 | 0.802 | 0.26 | 0.755 |
| 450 | 0.441 | 0.891 | 0.419 | 0.84 |
| 700 | 0.7 | 1.002 | 0.649 | 0.945 |
| | 0.833@800°F | 1.16@1000°F | 0.767@800°F | 1.094@1000°F |
| | **PWR: XL Fuel** | | **BWR Fuel** | |
| | Planar | Axial | Planar | Axial |
| 200 | 0.269 | 0.794 | 0.321 | 1.077 |
| 450 | 0.426 | 0.882 | 0.491 | 1.189 |
| 700 | 0.647 | 0.993 | 0.727 | 1.332 |
| | 0.759@800°F | 1.148@1000°F | 0.847@800°F | 1.539@1000°F |

| **PWR: 15x15I Short Fuel** | | |
|---|---|---|
| Temperature (°F) | Planar | Axial |
| 200 | 0.249 | 0.76 |
| 450 | 0.407 | 0.845 |
| 700 | 0.631 | 0.952 |
| | 0.742@800°F | 1.101@1000°F |

| Thermal Inertia Properties | | |
|---|---|---|
| | Density ($lb/ft^3$) | Heat Capacity (Btu/lb-°F)[Note 2] |
| PWR: 15x15I Short Fuel | 196.4 | 0.056 |
| PWR: Short Fuel | 165.1 | 0.056 |
| PWR: Standard Fuel | 175.4 | 0.056 |
| PWR: XL Fuel | 186.6 | 0.056 |
| BWR Fuel | 255.5 | 0.056 |

Note 1: Bounding fuel storage configurations defined in 4.4.1.1(ii).
Note 2: The lowerbound heat capacity of principal fuel assembly construction materials tabulated in Table 4.2.5 ($UO_2$ heat capacity) is conservatively adopted.
Note 3: The fuel properties tabulated herein are used in screening calculations to define the limiting scenario for fuel storage (See Table 4.4.2).

Table 4.4.2

RESULTS OF SCREENING CALCULATIONS UNDER NORMAL STORAGE CONDITIONS

| Storage Scenario | Peak Cladding Temperature, °C (°F) |
|---|---|
| MPC-37 (Note 2)<br>- regionalized storage Table 1.2.3a<br>Minimum Height[1]<br>Reference Height<br>Maximum Height | <br><br>**353 (667)**<br>342 (648)<br>316 (601) |
| MPC-37 (Note 4)<br>- heat load Figure 1.2.3a<br>- heat load Figure 1.2.4a<br>- heat load Figure 1.2.5a<br>- heat load Figure 1.2.3b[Notes 5,6,7] | <br>371 (700)<br>368 (694)<br>367 (693)<br>364 (687) |
| MPC-32ML (Note 3) | 349 (660) |
| MPC-31C (Note 3) | 345 (653) |
| MPC-89 (Note 2)<br>- regionalized storage Table 1.2.4 | 333 (631) |
| MPC-89 (Note 4)<br>- heat load Figure 1.2.6a<br>- heat load Figure 1.2.6b[Note 5, 7] | <br>366 (691)<br>360 (680) |

Notes:

(1) The highest temperature highlighted above is reached under the case of minimum height MPC-37 designed to store the short height Ft. Calhoun 14x14 fuel. This scenario is adopted in Chapter 4 for the licensing basis evaluation of fuel storage in the HI-STORM FW system. See Note 4.

(2) All the screening calculations for MPC-37 and MPC-89 were performed using a reference coarse mesh [4.1.9] and flow resistance based on the calculations in Holtec report [4.4.2].

(3) Screening calculations for MPC-32ML and MPC-31C performed using a mesh with similar density as the licensing basis converged mesh adopted for MPC-37 in Section 4.4.1.6.

(4) Screening evaluation used the same mesh as licensing basis mesh adopted in Section 4.4.1.6. The computed temperatures are bounded by the licensing basis minimum height temperatures tabulated in Table 4.4.3.

(5) PCT of intact fuel assemblies in the loading patterns with fuel debris in the DFCs is bounded by that with damaged fuel in the DFCs as justified next. It is conservatively assumed that the damaged fuel assemblies inside DFCs have the same axial heat distribution as the intact fuel assemblies to maximize the PCT of intact fuel assemblies. Fuel debris consistent with it's physical condition is modeled as packed towards bottom of the DFCs. This yields less impact on the PCT of intact fuel assemblies.

(6) The computed temperature under short length Damaged Fuel Storage is bounded by undamaged fuel temperatures computed above in heat load Figure 1.2.3a. This reasonably supports the conclusion that Damaged Fuel Storage under standard and long fuel storage in Figures 1.2.4b/c, 1.2.5b/c is bounded by undamaged fuel heat load scenarios evaluated in Figure 1.2.4a and 1.2.5a above.

(7) Peak temperatures including damaged fuel in DFC tabulated herein.

1 Bounding scenario adopted in this Chapter for all thermal evaluations.

| MINIMUM MPC FREE VOLUMES | | |
|---|---|---|
| **Item** | **Lowerbound Height MPC-37 (ft$^3$)** | **MPC-89 (ft$^3$)** |
| Net Free Volume* | 211.89 | 210.12 |
| | **MPC-32ML (ft$^3$)** | **MPC-31C (ft$^3$)** |
| Net Free Volume* | 291.23 | 277.52 |
| **Net free volumes are obtained by subtracting basket, fuel, aluminum shims, spacers, basket supports and DFCs metal volume from the MPC cavity volume.* | | |

| Table 4.4.5<br>SUMMARY OF MPC INTERNAL PRESSURES UNDER LONG-TERM STORAGE* | | |
|---|---|---|
| **Condition** | **MPC-37*** (psig) Pattern A/Pattern B** | **MPC-89*** (psig)** |
| Initial maximum backfill** (at 70°F) | 45.5/46.0 | 47.5 |
| Normal:<br>intact rods<br>1% rods rupture | <br>96.6/97.9<br>97.7/99.0 | <br>98.4<br>99.0 |
| Off-Normal (10% rods rupture) | 107.5/108.9 | 104.0 |
| Accident (100% rods rupture) | 191.5/194.4 | 155.0 |

* Per NUREG-1536, pressure analyses with ruptured fuel rods (including BPRA rods for PWR fuel) is performed with release of 100% of the ruptured fuel rod fill gas and 30% of the significant radioactive gaseous fission products.
** Conservatively assumed at the Tech. Spec. maximum value (see Table 4.4.8).
*** Tabulated pressures bound storage under heat load Figures 1.2.3a/b/c, 1.2.4a/b/c, 1.2.5a/b/c, 1.2.6a and 1.2.6b.
(continued next page)

| Table 4.4.7<br>THEORETICAL LIMITS* OF MPC HELIUM BACKFILL PRESSURE** | | |
|---|---|---|
| **MPC** | **Minimum Backfill Pressure (psig)** | **Maximum Backfill Pressure (psig)** |
| MPC-37<br>Pattern A | 41.0 | 47.3 |
| MPC-37<br>Pattern B | 40.8 | 47.1 |
| MPC-37<br>Figures 1.2.3a<br>Figures 1.2.4a<br>Figure 1.2.5a | <br>43.9<br>43.6<br>44.1 | <br>50.6<br>50.3<br>50.8 |
| MPC-89<br>Table 1.2.4<br>Figure 1.2.6a | <br>41.9<br>41.7 | <br>48.4<br>48.2 |
| MPC-32ML | 39.7 | 50.6 |
| MPC-31C | 40.6 | 50.3 |

* The helium backfill pressures are set forth in the Technical Specifications with a margin (see Table 4.4.8).
** The pressures tabulated herein are at 70°F reference gas temperature.

Table 4.4.8
MPC HELIUM BACKFILL PRESSURE SPECIFICATIONS

| MPC | Item | Specification |
|---|---|---|
| MPC-37 Pattern A | Minimum Pressure | 42.0 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 45.5 psig @ 70°F Reference Temperature |
| MPC-37 Pattern B | Minimum Pressure | 41.0 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 46.0 psig @ 70°F Reference Temperature |
| MPC-89 Table 1.2.4 | Minimum Pressure | 42.5 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 47.5 psig @ 70°F Reference Temperature |
| MPC-32ML | Minimum Pressure | 41.5 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 45.5 psig @ 70°F Reference Temperature |
| MPC-31C | Minimum Pressure | 41.5 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 45.5 psig @ 70°F Reference Temperature |
| MPC-37 Figures 1.2.3a/b/c | Minimum Pressure | 45.5 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 49.0 psig @ 70°F Reference Temperature |
| MPC-37 Figures 1.2.4a/b/c | Minimum Pressure | 44.0 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 47.5 psig @ 70°F Reference Temperature |
| MPC-37 Figures 1.2.5a/b/c | Minimum Pressure | 44.5 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 48.0 psig @ 70°F Reference Temperature |
| MPC-89 Figure 1.2.6a/b | Minimum Pressure | 42.0 psig @ 70°F Reference Temperature |
| | Maximum Pressure | 47.0 psig @ 70°F Reference Temperature |

| Table 4.4.15<br><br>DESIGN OPERATING ABSOLUTE PRESSURES[Note 1] | |
|---|---|
| MPC-37<br>Loading Pattern A<br>Loading Pattern B | <br>7.1 atm<br>7 atm |
| MPC-32ML | 6.5 atm |
| MPC-31C | 6.3 atm |
| MPC-89 Table 1.2.4 | 7 atm |
| MPC-37 load Figure 1.2.3a | 7.0 atm |
| MPC-37 heat load Figure 1.2.4a | 6.9 atm |
| MPC-37 heat load Figure 1.2.5a | 6.8 atm |
| MPC-89 heat load Figure 1.2.6a | 6.8 atm |
| Note 1: Table 4.4.8 helium backfill specifications ensure MPC operating pressures meet or exceed design values tabulated herein. | |

from the MPC cavity. In this case, relatively cooler water will enter via MPC lid ports and heated water will exit from the vent port. The minimum water flow rate required to maintain the MPC cavity water temperature below boiling with an adequate subcooling margin is determined as follows:

$$M_W = \frac{Q}{C_{pW}\,(T_{max} - T_{in})}$$

where:

$M_W$ = minimum water flow rate (lb/hr)
$C_{pw}$ = water heat capacity (Btu/lb-°F)
$T_{max}$ = suitably limiting temperature below boiling (°F)
$T_{in}$ = water supply temperature to MPC

### 4.5.4 Analysis of Limiting Thermal States During Short-Term Operations

4.5.4.1 Vacuum Drying

The vacuum drying option is evaluated for the limiting scenarios defined in Section 4.4.1.5 to address Moderate Burnup Fuel and High Burnup Fuel under threshold heat load defined in Table 4.5.1 (MPC-37 and MPC-89) and Table 4.5.16 (MPC-32ML and MPC-31C). The principle objective of the analysis is to ensure compliance with ISG-11 temperature limits. For this purpose 3-D FLUENT thermal models of the MPC-37, MPC-32ML, MPC-31C and MPC-89 canisters are constructed as described in Section 4.5.2.2 and bounding steady state temperatures computed. The results are tabulated in Tables 4.5.6, 4.5.7, 4.5.17 and 4.5.18, 4.5.20 and 4.5.21. The results show that the cladding temperatures comply with the ISG-11 limits for moderate and high burnup fuel in Table 4.3.1 by robust margins. The analysis presented above supports MPC drying options as summarized in Table 4.5.19.

4.5.4.2 Forced Helium Dehydration

To reduce moisture to trace levels in the MPC using a Forced Helium Dehydration (FHD) system, a conventional, closed loop dehumidification system consisting of a condenser, a demoisturizer, a compressor, and a pre-heater is utilized to extract moisture from the MPC cavity through repeated displacement of its contained helium, accompanied by vigorous flow turbulation. Demoisturization to the 3 torr vapor pressure criteria required by NUREG 1536 is assured by verifying that the helium temperature exiting the demoisturizer is maintained at or below the psychrometric threshold of 21°F for a minimum of 30 minutes. Appendix 2.B of [4.1.8] provides a detailed discussion of the design criteria and operation of the FHD system.

The FHD system provides concurrent fuel cooling during the moisture removal process through forced convective heat transfer. The attendant forced convection-aided heat transfer occurring during operation of the FHD system ensures that the fuel cladding temperature will remain below the applicable peak cladding temperature limit in Table 2.2.3. Because the FHD operation induces a state of forced convection heat transfer in the MPC, (in contrast to the quiescent mode

Table 4.5.5

MPC CONFINEMENT BOUNDARY PRESSURE UNDER ON-SITE TRANSPORT

| Condition | Pressure (psig) |
|---|---|
| Initial backfill pressure (at 70°F)<br>(Tech. Spec. maximum in Table 4.4.8) | 45.5 |
| Maximum pressure | 100.7 |

Table 4.5.6

MAXIMUM TEMPERATURES OF MPC-37 DURING VACUUM DRYING CONDITIONS

| Component | Temperatures @DB Heat Load (Note 1)<br>°C (°F) | Temperatures @ Threshold Heat Load (Note 2)<br>°C (°F) |
|---|---|---|
| Fuel Cladding | 480 (896) | 384 (723) |
| MPC Basket | 464 (867) | 367 (693) |
| Basket Periphery | 357 (675) | 288 (550) |
| Aluminum Basket Shims | 278 (532) | 232 (450) |
| MPC Shell | 156 (313) | 142 (288) |
| MPC Lid (Note 3) | 107 (225) | 100 (212) |

Note 1: Addresses vacuum drying of Moderate Burnup Fuel under limiting heat load (Pattern A) defined in Section 1.2 under heat load Table 1.2.3a Limiting Pattern A. See Table 4.5.20 for evaluation of alternate heat load patterns defined in Section 1.2.3.
Note 2: Addresses vacuum drying of High Burnup Fuel under threshold heat load (Table 4.5.1). For conservatism heat load applied to FLUENT models is overstated.
Note 3: Maximum section temperature reported.

Table 4.5.7

MAXIMUM TEMPERATURES OF MPC-89 DURING VACUUM DRYING CONDITIONS

| **Component** | **Temperatures @DB Heat Load**[Note 1] **°C (°F)** | **Temperatures @ Threshold Heat Load**[Note 2] **°C (°F)** |
|---|---|---|
| Fuel Cladding | 464 (867) | 376 (709) |
| MPC Basket | 449 (840) | 359 (678) |
| Basket Periphery | 348 (658) | 286 (547) |
| Aluminum Basket Shims | 275 (527) | 232 (450) |
| MPC Shell | 158 (316) | 144 (291) |
| MPC Lid[Note 3] | 127 (261) | 110 (230) |

Note 1: Addresses vacuum drying of Moderate Burnup Fuel under Design Basis heat load defined in Section 1.2 under heat load Table 1.2.4. See Table 4.5.21 for evaluation of alternate heat load patterns defined in Section 1.2.3.
Note 2: Addresses vacuum drying of High Burnup Fuel under threshold heat load (Table 4.5.1). For conservatism heat load applied to FLUENT models is overstated.
Note 3: Maximum section temperature reported.

Table 4.5.8

EFFECTIVE CONDUCTIVITY OF DESIGN BASIS FUEL UNDER VACUUM DRYING OPERATIONS (Btu/hr-ft-ºF)

| Ft. Calhoun 14x14[Note 1] | | |
|---|---|---|
| Temperature (ºF) | Planar | Axial |
| 200 | 0.125 | 0.726 |
| 450 | 0.265 | 0.793 |
| 700 | 0.498 | 0.886 |
| | 0.623@800ºF | 1.024@1000ºF |
| Note 1: Ft. Calhoun 14x14 fuel is defined as the design basis fuel under the limiting condition of fuel storage in the minimum height MPC-37 (See Table 4.4.2). | | |
| 16x16D[Note 2] | | |
| Temperature (ºF) | Planar | Axial |
| 212 | 0.095 | 0.8 |
| 450 | 0.229 | 0.867 |
| 700 | 0.458 | 0.962 |
| 785 | 0.558 | 1.003 |
| VVER-1000[Note 3] | | |
| Temperature (ºF) | Planar | Axial |
| 212 | 0.085 | 0.86 |
| 450 | 0.154 | 0.927 |
| 700 | 0.206 | 1.025 |
| BWR Fuel | | |
| Temperature (ºF) | Planar | Axial |
| 200 | 0.112 | 1.004 |
| 450 | 0.236 | 1.095 |
| 700 | 0.441 | 1.221 |
| | 0.553@800ºF | 1.408@100ºF |
| Note 2: Design Basis MPC-32ML fuel<br>Note 3: Design Basis MPC-31C fuel | | |

Table 4.5.19
MPC DRYING OPERATIONS

| MPC Type | Fuel | Heat Load Limit (kW) | Method of Drying |
|---|---|---|---|
| MPC-31C | MBF | 43.4 (Note 1) | FHD/Vacuum Drying with Time Limit |
| | | 32.984 | FHD/Vacuum Drying without Time Limit |
| | HBF | 43.4 (Note 1) | FHD/Vacuum Drying with Time Limit |
| | | 17.36 | FHD/Vacuum Drying without Time Limit |
| MPC-32ML | MBF | 44.16 (Note 1) | FHD/Vacuum Drying without Time Limit |
| | HBF | 44.16 (Note 1) | FHD |
| | | 28.704 | FHD/Vacuum Drying without Time Limit |
| MPC-37 | MBF | 44.09 (Pattern A)<br>45.0 (Pattern B)<br>37.4/39.95/44.85 (Figures 1.2.3a, 1.2.4a, 1.2.5a)<br>34.4 (Figures 1.2.3b/c)<br>36.65 (Figures 1.2.4b/c)<br>40.95 (Figures 1.2.5b/c)<br>(Note 1) | FHD/Vacuum Drying without Time Limit |
| | HBF | 44.09 (Pattern A)<br>45.0 (Pattern B)<br>(Note 1) | FHD |
| | | 29.6 | FHD/Vacuum Drying without Time Limit |
| MPC-89 | MBF | 46.36 (Table 1.2.4)<br>46.2 (Figure 1.2.6a)<br>44.92 (Figure 1.2.6b)<br>(Note 1) | FHD/Vacuum Drying without Time Limit |
| | HBF | 46.36 (Note 1) | FHD |
| | | 30 | FHD/Vacuum Drying without Time Limit |

Note 1: Design Basis heat load.
Note 2:Cyclic drying under time limited vacuum drying operations is permitted in accordance with ISG-11, Rev. 3 requirements by limiting number of cycles to less than 10 and cladding temperature variations to less than 65°C (117°F). Suitable time limits for these cycles shall be evaluated based on site specific conditions and thermal methodology defined in Section 4.5.

| Table 4.5.20<br><br>MAXIMUM TEMPERATURES OF MPC-37 DURING VACUUM DRYING CONDITIONS UNDER SHORT FUEL HEAT LOAD FIGURE 1.2.3a (Note 3) | |
|---|---|
| **Component** | Temperature $^{o}$C ($^{o}$F)$^{Note\ 1}$ |
| Fuel Cladding | 465 (869) |
| MPC Basket | 412 (774) |
| Basket Periphery | 335 (635) |
| Aluminum Basket Shims | 272 (522) |
| MPC Shell | 165 (329) |
| MPC Lid$^{Note\ 2}$ | 100 (212) |
| Note 1: Addresses vacuum drying of Moderate Burnup Fuel<br>Note 2: Section temperature reported<br>Note 3: Bounding scenario of short fuel from Table 4.4.2 is evaluated. | |

| Table 4.5.21<br><br>MAXIMUM TEMPERATURES OF MPC-89 DURING VACUUM DRYING CONDITIONS UNDER HEAT LOAD FIGURE 1.2.6a | |
|---|---|
| **Component** | Temperature $^{o}$C ($^{o}$F)$^{Note\ 1}$ |
| Fuel Cladding | 469 (876) |
| MPC Basket | 449 (840) |
| Basket Periphery | 362 (684) |
| Aluminum Basket Shims | 305 (581) |
| MPC Shell | 181 (358) |
| MPC Lid$^{Note\ 2}$ | 119 (246) |
| Note 1: Addresses vacuum drying of Moderate Burnup Fuel<br>Note 2: Section temperature reported | |

## 4.8 REFERENCES

[4.1.1] Deleted

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[4.1.3] "The TN-24P PWR Spent-Fuel Storage Cask: Testing and Analyses," EPRI NP-5128, (April 1987).

[4.1.4] "Cladding Considerations for the Transportation and Storage of Spent Fuel," Interim Staff Guidance – 11, Revision 3, USNRC, Washington, DC.

[4.1.5] "Topical Report on the HI-STAR/HI-STORM Thermal Model and its Benchmarking with Full-Size Cask Test Data," Holtec Report HI-992252, Revision 1, Holtec International, Marlton, NJ, 08053.

[4.1.6] "Identifying the Appropriate Convection Correlation in FLUENT for Ventilation Air Flow in the HI-STORM System", Revision 1, Holtec Report HI-2043258, Holtec International, Marlton, NJ, 08053.

[4.1.7] "Performance Testing and Analyses of the VSC-17 Ventilated Concrete Cask", EPRI TR-100305, (May 1992).

[4.1.8] "Holtec International Final Safety Analysis Report for the HI-STORM 100 Cask System", Holtec Report No. 2002444, Revision 7, NRC Docket No. 72-1014.

[4.1.9] "Thermal Evaluation of HI-STORM FW", Holtec Report HI-2094400, Latest Revision.

[4.1.10] "Effective Thermal Properties of PWR Fuel in MPC-37", Holtec Report HI-2094356, Revision 5.

[4.1.11] "Safety Analysis Report on the HI-STAR 180 Package", Holtec Report HI-2073681, Latest Revision.

[4.1.12] "Effective Properties of PWR and BWR Fuel assemblies to Support Thermal Evaluations of HI-STORM FW", HI-2167474, Rev. 0.

[4.2.1] Baumeister, T., Avallone, E.A. and Baumeister III, T., "Marks' Standard Handbook for Mechanical Engineers," 8th Edition, McGraw Hill Book Company, (1978).

[4.2.2] Rohsenow, W.M. and Hartnett, J.P., "Handbook of Heat Transfer," McGraw Hill Book Company, New York, (1973).

# CHAPTER 5†: SHIELDING EVALUATION

## 5.0 INTRODUCTION

The shielding analysis of the HI-STORM FW system is presented in this chapter. As described in Chapter 1, the HI-STORM FW system is designed to accommodate both PWR and BWR MPCs within HI-STORM FW overpacks (see Table 1.0.1).

In addition to storing intact PWR and BWR fuel assemblies, the HI-STORM FW system is designed to store BWR and PWR damaged fuel assemblies and fuel debris. Damaged fuel assemblies and fuel debris are defined in Subsection 2.1. Both damaged fuel assemblies and fuel debris are required to be loaded into Damaged Fuel Containers (DFCs).

PWR fuel assemblies may contain burnable poison rod assemblies (BPRAs), with any number of full-length rods and thimble plug rodlets in the locations without a full-length rod, thimble plug devices (TPDs), control rod assemblies (CRAs) or axial power shaping rod assemblies (APSRs), neutron source assemblies (NSAs), or similarly named devices. These non-fuel hardware devices are an integral yet removable part of PWR fuel assemblies and therefore the HI-STORM FW system has been designed to store PWR fuel assemblies with or without these devices. Since each device occupies the same location within a fuel assembly, a single PWR fuel assembly will not contain multiple devices, with the exception of instrument tube tie rods (ITTRs), which may be stored in the assembly along with other types of non-fuel hardware.

As described in Chapter 1(see Tables 1.2.3 and 1.2.4), the loading of fuel in all HI-STORM FW MPCs will follow specific heat load limitations.

In order to offer the user more flexibility in fuel storage, the HI-STORM FW System offers several heat load patterns, each with three to six regions with different heat load limits. This is taken into consideration when calculating dose rates in this chapter. The regionalized storage patterns are guided by the considerations of minimizing occupational and site boundary dose to comply with ALARA principles.

Two different lids have been developed for the HI-STORM FW concrete overpack. The lid included in the initial application, referred to as "standard lid", and a revised design with overall improved shielding performance, referred to as "XL lid". Since by now essentially all installations utilize the "XL lid", all dose rates provided in this chapter are for that lid design,

† 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 and component nomenclature of the Bill-of-Materials (Section 1.5).

with the only exception being some tables in Section 5.4 which contain selected results for the "standard lid" from previous versions of this chapter for reference. All references to the "lid" are to be understood to refer to the "XL lid", unless otherwise noted.

The sections that follow will demonstrate that the design of the HI-STORM FW dry cask storage system fulfills the following acceptance criteria outlined in the Standard Review Plan, NUREG-1536 [5.2.1]:

Acceptance Criteria

1. The minimum distance from each spent fuel handling and storage facility to the controlled area boundary must be at least 100 meters. The "controlled area" is defined in 10CFR72.3 as the area immediately surrounding an ISFSI or monitored retrievable storage (MRS) facility, for which the licensee exercises authority regarding its use and within which ISFSI operations are performed.

2. The system designer must show that, during both normal operations and anticipated occurrences, the radiation shielding features of the proposed dry cask storage system are sufficient to meet the radiation dose requirements in Sections 72.104(a). Specifically, the vendor must demonstrate this capability for a typical array of casks in the most bounding site configuration. For example, the most bounding configuration might be located at the minimum distance (100 meters) to the controlled area boundary, without any shielding from other structures or topography.

3. Dose rates from the cask must be consistent with a well established "as low as reasonably achievable" (ALARA) program for activities in and around the storage site.

4. After a design-basis accident, an individual at the boundary or outside the controlled area shall not receive a dose greater than the limits specified in 10CFR72.106.

5. The proposed shielding features must ensure that the dry cask storage system meets the regulatory requirements for occupational and radiation dose limits for individual members of the public, as prescribed in 10CFR Part 20, Subparts C and D.

Consistent with the Standard Review Plan, NUREG-1536, this chapter contains the following information:

- A description of the shielding features of the HI-STORM FW system, including the HI-TRAC transfer cask.
- A description of the source terms.
- A general description of the shielding analysis methodology.
- A description of the analysis assumptions and results for the HI-STORM FW system, including the HI-TRAC transfer cask.

- Analyses are presented for each MPC showing that the radiation dose rates follow As-Low-As-Reasonably-Achievable (ALARA) practices.
- Analyses to show that the 10CFR72.106 controlled area boundary radiation dose limits are met during accident conditions of storage for non-effluent radiation from illustrative ISFSI configurations at a minimum distance of 100 meters.
- Since only dose rate values for representative cask arrays for normal conditions are presented in this chapter, compliance with the radiation and exposure objectives of 10CFR72.104 is not being evaluated herein but will be performed as part of the site specific evaluations.

Chapter 2 contains a detailed description of structures, systems, and components important to safety.

Chapter 7 contains a discussion on the release of radioactive materials from the HI-STORM FW system. Therefore, this chapter only calculates the dose from direct neutron and gamma radiation emanating from the HI-STORM FW system.

Chapter 11, Radiation Protection, contains the following information:

- A discussion of the estimated occupational exposures for the HI-STORM FW system, including the HI-TRAC transfer cask.
- A summary of the estimated radiation exposure to the public.

The safety analyses summarized in this chapter demonstrate that under accident conditions, acceptable margins to allowable limits exist under all design basis loading conditions. For normal and off-normal conditions, the analyses in this chapter simply provide a generic evaluation that demonstrates that the dose requirements as specified in 10CFR72.104 can be met under site specific conditions. 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 dose rates in this chapter 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 cannot be deemed any more to be insignificant. For accident conditions, the dose limit as specified in 10CFR72.106 is 5 rem. The only accident which impacts dose rates is the loss of water in the water jacket for the HI-TRAC VW. For the purposes of determining if the changes to the HI-TRAC VW are insignificant, an insignificant loss of margin with reference to the 5 rem acceptance criteria is defined as the estimated reduction that is no more than one order of magnitude less than the available margin reported in the FSAR. For normal and off-normal conditions, site specific dose evaluations are required to demonstrate compliance with 10CFR72.104. Incorporating any minor changes into those site specific evaluations is only warranted if it would be expected, on a site specific basis, that those changes could result in a situation where the limits are no longer met and where therefore other compensatory measures are required, such as a change in the loading plan or the concrete density. Incorporating changes into the analyses in this chapter for normal and off-normal conditions will only be performed under extenuating circumstances, e.g. major

changes to the shielding design or loading patterns, in order to provide an updated template for the site specific dose analyses.

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.

to the analyses in this Chapter 5, and the burnup and cooling times selected for the various analyses, are as follows:

- 10CFR72.104 specifies the dose limits from an ISFSI (and other operations) at a site boundary under normal and off-normal conditions. Compliance with §104 can therefore only be demonstrated on a site-specific basis, since it depends not only on the design of the cask system and the loaded fuel, but also on the ISFSI layout, the distance to the site boundary, and possibly other factors such as use of higher density concrete or the terrain around the ISFSI. The purpose of this chapter is therefore to present a general overview over the expected or maximum dose rates, next to the casks and at various distances, to aid the user in applying ALARA considerations and planning of the ISFSI.
- For the accident dose limit in 10CFR72.106 it is desirable to show compliance in this Chapter 5 on a generic basis, so that calculations on a site-by-site basis are not required. To that extend, a burnup and cooling time calculation that maximizes the dose rate under accident conditions needs to be selected.

It is recognized that for a given heat load, an infinite number of burnup and cooling time combination could be selected, which would result in slightly different dose rate distributions around the cask. For a high burnup with a corresponding longer cooling time, dose locations with a high neutron contribution would show higher dose values, due to the non-linear relationship between burnup and neutron source term. At other locations dose rates are more dominated by contribution from the gamma sources. In these cases, short cooling time and lower burnup combinations with heat load comparable to the higher burnup and corresponding longer cooling time combinations would result in higher dose rates. However, in those cases, there would always be a compensatory effect, since for each dose location, higher neutron dose rates would be partly offset by lower gamma dose rates and vice versa. This is further complicated by the regionalized loading patterns qualified from a thermal perspective. These contain cells with substantially different heat load limits, and hence substantially different ranges of burnup, enrichment and cooling time combinations. The approach to cover all those variations in a conservative way is outlined below.

The calculations are based on the loading patterns from Figure 1.2.5a and 1.2.6a, since those contain the assemblies with highest heat loads and hence highest source terms. A comparison of those dose rates with dose rates calculated earlier and retained in Section 5.4 show that the dose rates evaluated for patterns in Figure 1.2.5a and 1.2.6a bound those earlier dose rates (except for some dose locations with reduced dose rates due to the XL lid). The dose rates are therefore bounding for all patterns in Section 1.2. The accident dose rates in Table 5.1.9 are slightly lower than for the dose rates from the uniform pattern. However, the regionalized patterns better represent the dose rates from the actual loading and are therefore presented in this section. For each heat load limit, a large range of burnup, enrichment and cooling time values are selected that meet or exceed that heat load. Dose calculations are then performed for a large range of combinations of the burnup, enrichment and cooling times for the different regions, and for each principal dose location, the maximum dose rate together with the set of limiting burnup, enrichment and cooling times are determined. The range of burnups and cooling times conservatively exceeds that permitted for the fuel being loaded, and is selected as follows:

- Burnups from 5 GWd/mtU to 75 GWd/mtU for PWR fuel, in increments of 2.5 GWd/mtU, and to 70 GWd/mtU for BWR fuel, in increments of 5 GWd/mtU.
- Corresponding cooling times that result in a heat load value meeting or slightly exceeded in corresponding cell limit, between 1.2 and 35 years.

For enrichments, lower values result in higher source terms and dose rates. However, using very low enrichments (e.g. 1 wt%) with highly burned (e.g. 70 GWd/mtU) fuel would be unrealistically conservative since no such fuel exists. Hence the lower bound enrichment is selected as a function of the burnup, based on a review of actual fuel assemblies in the industry. The values are listed in Table 5.0.3 and cover the vast majority of fuel (>98%).

Based on this approach, the source terms used in the analyses are reasonably bounding for all realistically expected assemblies.

All dose rates in this chapter are developed using this approach, except for some dose rates in Section 5.4 that were retained from previous versions of the FSAR and that are based on a conservative uniform loading pattern, as discussed in that Section.

Table 5.0.1

Table Deleted

Table 5.0.2

Table Deleted

Table 5.0.3

INITIAL ENRICHMENTS USED IN THE SOURCE TERM CALCULATIONS

| **Burnup Range (MWD/MTU)** | **Initial Enrichment (wt.% $^{235}U$)** | |
|---|---|---|
| | **PWR Fuel** | **BWR Fuel** |
| 5,000-10,000 | 0.7 | 0.7 |
| 10,000-15,000 | 1.0 | 1.1 |
| 15,000-20,000 | 1.7 | 1.4 |
| 20,000-25,000 | 1.5 | 1.3 |
| 25,000-30,000 | 1.8 | 1.6 |
| 30,000-35,000 | 2.1 | 1.8 |
| 35,000-40,000 | 2.5 | 2.1 |
| 40,000-45,000 | 2.6 | 2.2 |
| 45,000-50,000 | 2.8 | 2.5 |
| 50,000-55,000 | 3.1 | 2.8 |
| 55,000-60,000 | 3.5 | 3.2 |
| 60,000-65,000 | 3.7 | 3.7 |
| 65,000-70,000 | 4.0 | 4.0 |
| 70,000-75,000 | 4.2 | n/a |

Notes:

- The burnup ranges do not overlap. Therefore, 20,000-25,000 MWD/MTU means 20,000-24,999.9 MWD/MTU, etc. This note does not apply to the maximum burnups of 70,000 and 75,000 MWD/MTU.

Tables 5.1.5 and 5.1.6 provide the design basis dose rates adjacent to the HI-STORM FW overpack during normal conditions for the MPC-37 and MPC-89. Tables 5.1.7 and 5.1.8 provide the design basis dose rates at one meter from the HI-STORM FW overpack containing the MPC-37 and MPC-89, respectively.

The dose to any real individual at or beyond the controlled area boundary is required to be below 25 mrem per year. The minimum distance to the controlled area boundary is 100 meters from the ISFSI. Table 5.1.3 presents the annual dose to an individual from a single HI-STORM FW cask and various storage cask arrays, assuming an 8760 hour annual occupancy at the dose point location. The minimum distance required for the corresponding dose is also listed. It is noted that these data are provided for illustrative purposes only. A detailed site-specific evaluation of dose at the controlled area boundary must be performed for each ISFSI in accordance with 10CFR72.212. The site-specific evaluation will consider dose from other portions of the facility and will consider the actual conditions of the fuel being stored (burnup and cooling time).

Figure 5.1.3 is an annual dose versus distance graph for the HI-STORM FW cask array configurations provided in Table 5.1.3. This curve, which is based on an 8760 hour occupancy, is provided for illustrative purposes only and will be re-evaluated on a site-specific basis.

Subsection 5.2.3 discusses the BPRAs, TPDs, CRAs and APSRs that are permitted for storage in the HI-STORM FW system. Subsection 5.4.4 discusses the increase in dose rate as a result of adding non-fuel hardware in the MPCs.

The analyses summarized in this section demonstrate that the HI-STORM FW system is in compliance with the radiation and exposure objectives of 10CFR72.106. Since only representative dose rate values for normal conditions are presented in this chapter, compliance with 10CFR72.104 is not being evaluated. This will be performed as part of the site specific evaluations.

### 5.1.2 Accident Conditions

The 10CFR72.106 radiation dose limits at the controlled area boundary for design basis accidents are:

> Any individual located on or beyond the nearest boundary of the controlled area may not receive from any design basis accident the more limiting of a total effective dose equivalent of 5 Rem, or the sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 50 Rem. The lens dose equivalent shall not exceed 15 Rem and the shallow dose equivalent to skin or to any extremity shall not exceed 50 Rem. The minimum distance from the spent fuel or high-level radioactive waste handling and storage facilities to the nearest boundary of the controlled area shall be at least 100 meters.

Structural evaluations, presented in Chapter 3, shows that a freestanding HI-STORM FW storage overpack containing a loaded MPC remains standing during events that could potentially lead to a tip-over event. Therefore, the tip-over accident is not considered as part of the shielding evaluation.

Design basis accidents which may affect the HI-STORM FW overpack can result in limited and localized damage to the outer shell and radial concrete shield. As the damage is localized and the vast majority of the shielding material remains intact, the effect on the dose at the site boundary is negligible. Therefore, the site boundary doses for the loaded HI-STORM FW overpack for accident conditions are equivalent to the normal condition doses, which meet the 10CFR72.106 radiation dose limits. However the adjacent and one meter dose rates may be increased, which should be considered in any post-accident activities near the affected cask.

The design basis accidents analyzed in Chapter 11 have one bounding consequence that affects the shielding materials of the HI-TRAC transfer cask. It is the potential for damage to the water jacket shell and the loss of the neutron shield (water). In the accident consequence analysis, it is conservatively assumed that the neutron shield (water) is completely lost and replaced by a void.

Throughout all design basis accident conditions the axial location of the fuel will remain fixed within the MPC because of the MPC's design features (see Chapter 1). Further, the structural evaluation of the HI-TRAC VW in Chapter 3 shows that the inner shell, lead, and outer shell remain intact throughout all design basis accident conditions. Localized damage of the HI-TRAC outer shell is possible; however, localized deformations will have only a negligible impact on the dose rate at the boundary of the controlled area.

The complete loss of the HI-TRAC neutron shield significantly affects the dose at mid-height (Dose Point #2) adjacent to the HI-TRAC. Loss of the neutron shield has a small effect on the dose at the other dose points. To illustrate the impact of the design basis accident, the dose rates at Dose Point #2 (see Figure 5.1.2) are provided in Table 5.1.4 (MPC-37) for the HI-TRAC VW at a distance of 1 meter and at a distance of 100 meters. The normal condition dose rates are provided for reference. The dose for a period of 30 days is shown in Table 5.1.9, where 30 days is used to illustrate the radiological impact for a design basis accident. Based on this dose rate and the short duration of use for the loaded HI-TRAC transfer cask, it is evident that the dose as a result of the design basis accident cannot exceed 5 rem at the controlled area boundary for the short duration of the accident.

Analyses summarized in this section demonstrate that the HI-STORM FW system, including the HI-TRAC VW transfer cask, is in compliance with the 10CFR72.106 limits.

Table 5.1.1

DOSE RATES FROM THE HI-TRAC VW FOR NORMAL CONDITIONS
MPC-37

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}$Co Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) | Totals with BPRAs (mrem/hr) |
|---|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | | |
| 1 | 1081 | 24 | 705 | 64 | 1875 | 1875 |
| 2 | 3580 | 2 | <1 | 3 | 3584 | 3584 |
| 3 | 30 | 9 | 373 | 10 | 421 | 611 |
| 4 | 118 | 2 | 509 | 358 | 986 | 1281 |
| 5 | 627 | 4 | 1874 | 1619 | 4124 | 4124 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | | |
| 1 | 840 | <1 | 59 | 1 | 901 | 901 |
| 2 | 1854 | 1 | 5 | 1 | 1861 | 1863 |
| 3 | 206 | 3 | 115 | 4 | 328 | 394 |
| 4 | 82 | 1 | 315 | 114 | 512 | 676 |
| 5 | 555 | 1 | 1214 | 485 | 2256 | 2256 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- Values are rounded to nearest integer.
- Dose rates are based on no water within the MPC, an empty annulus, and a water jacket full of water. For the majority of the duration that the HI-TRAC bottom lid is installed, the MPC cavity will be flooded with water. The water within the MPC greatly reduces the dose rate.
- Streaming may occur through the annulus. However, during handling/operations the annulus is filled with water and lead snakes are typically present to reduce the streaming effects. Further, operators are not present on top of the transfer cask.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.1.2

DOSE RATES FROM THE HI-TRAC VW FOR NORMAL CONDITIONS
MPC-89

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}$Co Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) |
|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | |
| 1 | 314 | 29 | 2423 | 64 | 2829 |
| 2 | 3916 | 121 | <1 | 226 | 4262 |
| 3 | 18 | 5 | 698 | 6 | 727 |
| 4 | 48 | 2 | 454 | 314 | 819 |
| 5 | 135 | 4 | 1812 | 1573 | 3524 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | |
| 1 | 566 | 16 | 242 | 32 | 856 |
| 2 | 1887 | 5 | 14 | 11 | 1917 |
| 3 | 144 | 8 | 327 | 11 | 490 |
| 4 | 37 | 1 | 354 | 70 | 461 |
| 5 | 158 | 1 | 1432 | 332 | 1922 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- Values are rounded to nearest integer.
- Dose rates are based on no water within the MPC, an empty annulus, and a water jacket full of water. For the majority of the duration that the HI-TRAC bottom lid is installed, the MPC cavity will be flooded with water. The water within the MPC greatly reduces the dose rate.
- Streaming may occur through the annulus. However, during handling/operations the annulus is filled with water and lead snakes are typically present to reduce the streaming effects. Further, operators are not present on top of the transfer cask.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer grids.

Table 5.1.3

DOSE RATES FOR ARRAYS OF HI-STORM FWs CONTAINING THE MPC-37

| Array Configuration | 1 cask | 2x2 | 2x3 | 2x4 | 2x5 |
|---|---|---|---|---|---|
| **HI-STORM FW Overpack** | | | | | |
| Annual Dose (mrem/year) | 8 | 21 | 11 | 14 | 18 |
| Distance to Controlled Area Boundary (meters) | 300 | 300 | 400 | 400 | 400 |

Notes:

- Values are rounded up to nearest integer.
- 8760 hour annual occupancy is assumed.
- Dose location is at the center of the long side of the array.
- The bounding regionalized loading source term, consistent with Table 5.1.7 for dose point location 2, is used.

Table 5.1.4

DOSE RATES FROM HI-TRAC VW WITH MPC-37
FOR ACCIDENT CONDITIONS

| Dose Point Location | Fuel Gammas (mrem/hr) | N, Gamma (mrem/hr) | Co-60 Gamma (mrem/hr) | Neutrons (mrem/hr) | Total (mrem/hr) |
|---|---|---|---|---|---|
| 1 meter from HI-TRAC VW | | | | | |
| 2 (Accident Condition) | 1651.6 | 2.8 | 13.3 | 2658.3 | 4330.5 |
| 2 (Normal Condition) | 1854.1 | 0.5 | 5.3 | 1.3 | 1863.3 |
| 100 meters from HI-TRAC VW | | | | | |
| 2 (Accident Condition) | 0.7 | <0.1 | 0.1 | 1.4 | 2.2 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- The “Fuel Gammas” category includes gammas from the spent fuel and $^{60}$Co from the spacer grids.

Table 5.1.5

DOSE RATES ADJACENT TO HI-STORM FW OVERPACK
FOR NORMAL CONDITIONS
MPC-37

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** | **Totals with BPRAs (mrem/hr)** |
|---|---|---|---|---|---|---|
| 1 | 370.9 | <0.1 | 8.3 | 0.1 | 379.3 | 379.3 |
| 2 | 240.1 | <0.1 | <0.1 | <0.1 | 240.2 | 240.2 |
| 3 (surface) | 15.5 | 0.4 | 16.6 | 5.3 | 37.8 | 46.6 |
| 3 (overpack edge) | 8.1 | 0.2 | 9.1 | 2.0 | 19.4 | 24.1 |
| 4 (center) | 0.7 | 3.6 | 1.9 | 3.1 | 9.3 | 10.7 |
| 4 (mid) | 12.4 | 1.5 | 8.4 | 5.4 | 27.8 | 32.5 |
| 4 (outer) | 0.8 | <0.1 | 0.5 | <0.1 | 1.2 | 1.5 |

Notes:

- Refer to Figure 5.1.1 for dose locations.
- Dose location 3 (surface) is at the surface of the outlet vent. Dose location 3 (overpack edge) is in front of the outlet vent, but located radially above the overpack outer diameter.
- Dose location 4 (center) is at the center of the top surface of the top lid. Dose location 4 (mid) is situated directly above the vertical section of the outlet vent. Dose location 4 (outer) is extended along the top plane of the top lid, located radially above the overpack outer diameter.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.1.6

DOSE RATES ADJACENT TO HI-STORM FW OVERPACK
FOR NORMAL CONDITIONS
MPC-89

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}Co$ Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) |
|---|---|---|---|---|---|
| 1 | 206.1 | 0.3 | 18.0 | 0.5 | 224.8 |
| 2 | 178.4 | 0.2 | 0.1 | 0.2 | 178.9 |
| 3 (surface) | 7.7 | 0.3 | 21.1 | 3.4 | 32.5 |
| 3 (overpack edge) | 3.3 | 0.1 | 10.5 | 1.2 | 15.0 |
| 4 (center) | 0.4 | 2.3 | 2.5 | 2.0 | 7.1 |
| 4 (mid) | 7.6 | 1.0 | 15.1 | 3.6 | 27.3 |
| 4 (outer) | 0.5 | <0.1 | 2.1 | 0.1 | 2.7 |

Notes:

- Refer to Figure 5.1.1 for dose locations.
- Dose location 3 (surface) is at the surface of the outlet vent. Dose location 3 (overpack edge) is in front of the outlet vent, but located radially above the overpack outer diameter.
- Dose location 4 (center) is at the center of the top surface of the top lid. Dose location 4 (mid) is situated directly above the vertical section of the outlet vent. Dose location 4 (outer) is extended along the top plane of the top lid, located radially above the overpack outer diameter.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}Co$ from the spacer grids.

Table 5.1.7

DOSE RATES AT ONE METER FROM HI-STORM FW OVERPACK
FOR NORMAL CONDITIONS
MPC-37

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** | **Totals with BPRAs (mrem/hr)** |
|---|---|---|---|---|---|---|
| 1 | 88.5 | <0.1 | 1.8 | <0.1 | 90.3 | 90.4 |
| 2 | 123.3 | <0.1 | 0.3 | <0.1 | 123.6 | 123.7 |
| 3 | 9.6 | <0.1 | 2.1 | <0.1 | 11.7 | 13.4 |
| 4 (center) | 2.8 | 1.0 | 3.3 | 2.1 | 9.2 | 11.0 |

Notes:

- Refer to Figure 5.1.1 for dose locations.
- The “Fuel Gammas” category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.1.8

DOSE RATES AT ONE METER FROM HI-STORM FW OVERPACK
FOR NORMAL CONDITIONS
MPC-89

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** |
|---|---|---|---|---|---|
| 1 | 59.3 | 0.1 | 4.8 | 0.1 | 64.2 |
| 2 | 92.9 | 0.1 | 0.7 | 0.1 | 93.7 |
| 3 | 4.5 | <0.1 | 3.5 | 0.1 | 8.1 |
| 4 (center) | 1.2 | 0.9 | 3.7 | 1.8 | 7.6 |

Notes:

- Refer to Figure 5.1.1 for dose locations.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer girds.

Table 5.1.9

DOSE FROM HI-TRAC VW WITH MPC-37
FOR ACCIDENT CONDITIONS
AT 100 METERS

| **Dose Point Location** | **Dose Rate (rem/hr)** | **Accident Duration (days)** | **Total Dose (rem)** | **Regulatory Limit (rem)** | **Time to Reach Regulatory Limit (days)** |
|---|---|---|---|---|---|
| 2 (Accident Condition) | 2.2E-3 | 30 | 1.57 | 5 | 96 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- Values are rounded to nearest integer where appropriate.
- Dose rates used to evaluated "Total Dose (rem)" are from Table 5.1.4
- Regulatory Limit is from 10CFR72.106.

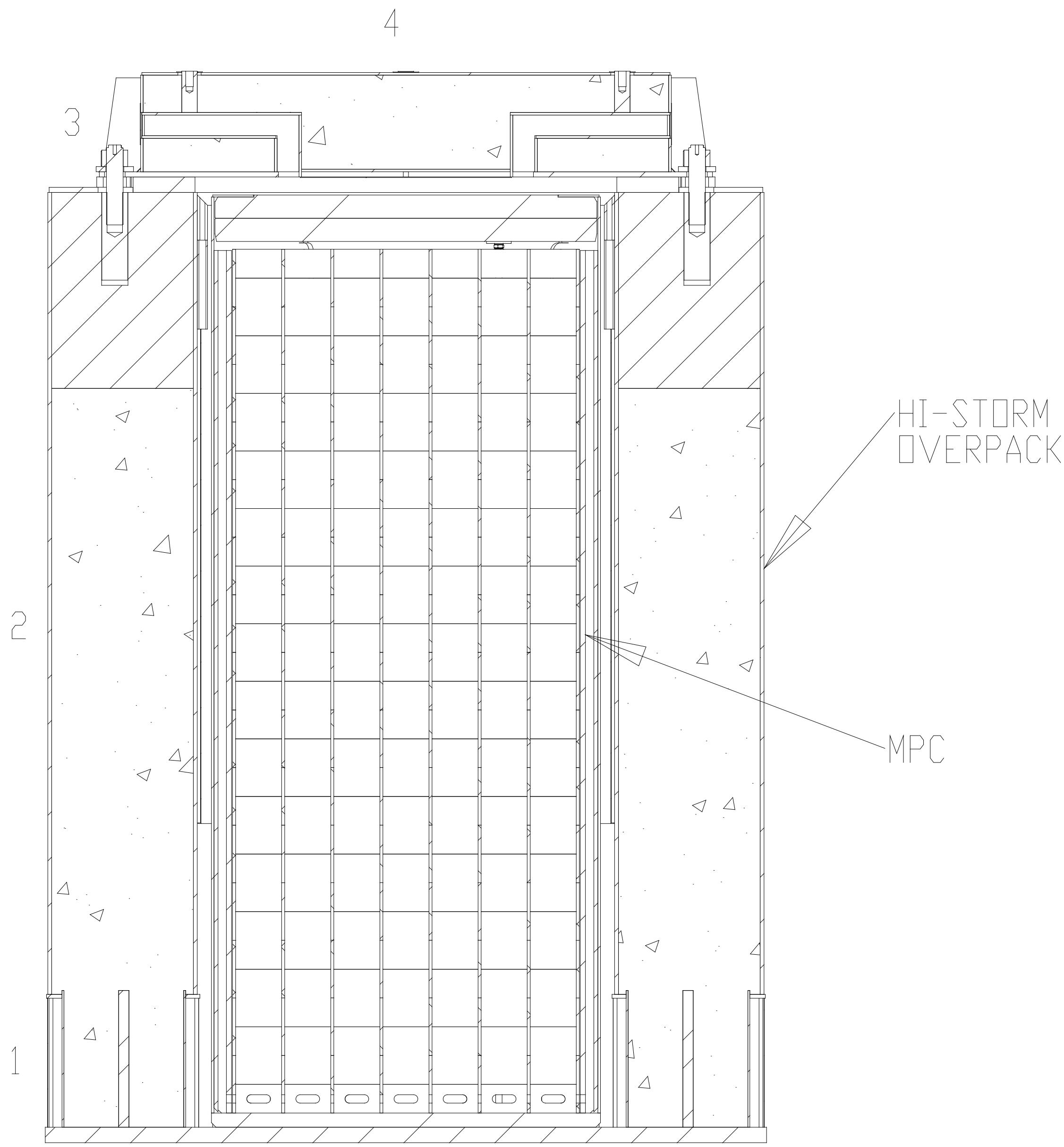


Figure 5.1.1

CROSS SECTION ELEVATION VIEW OF HI-STORM FW OVERPACK WITH DOSE POINT LOCATIONS
(Standard Lid is Shown)

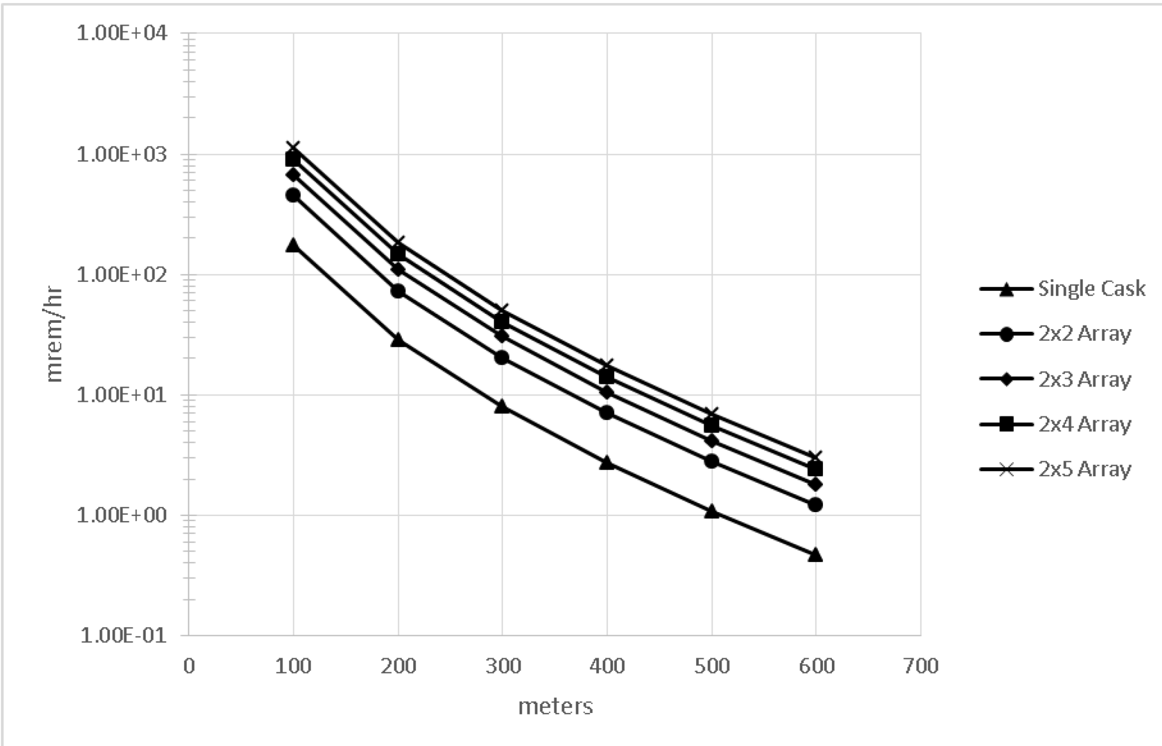


Figure 5.1.3

ANNUAL DOSE VERSUS DISTANCE FOR VARIOUS CONFIGURATIONS OF THE MPC-37 (8760 HOUR OCCUPANCY ASSUMED)

| Table 5.2.2<br><br>CALCULATED MPC-37 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS | | | |
|---|---|---|---|
| **Lower Energy** | **Upper Energy** | **45,000 MWD/MTU 4.5-Year Cooling** | |
| (MeV) | (MeV) | (MeV/s) | (Photons/s) |
| 0.45 | 0.7 | 2.11E+15 | 3.68E+15 |
| 0.7 | 1.0 | 7.67E+14 | 9.02E+14 |
| 1.0 | 1.5 | 1.74E+14 | 1.39E+14 |
| 1.5 | 2.0 | 1.45E+13 | 8.30E+12 |
| 2.0 | 2.5 | 1.01E+13 | 4.47E+12 |
| 2.5 | 3.0 | 4.05E+11 | 1.47E+11 |
| Total | | 3.08E+15 | 4.73E+15 |

| Table 5.2.3<br><br>CALCULATED MPC-37 PWR FUEL GAMMA SOURCE PER ASSEMBLY FOR BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS | | | |
|---|---|---|---|
| **Lower Energy** | **Upper Energy** | **65,000 MWD/MTU 8-Year Cooling** | |
| (MeV) | (MeV) | (MeV/s) | (Photons/s) |
| 0.45 | 0.7 | 2.05E+15 | 3.56E+15 |
| 0.7 | 1.0 | 4.16E+14 | 4.89E+14 |
| 1.0 | 1.5 | 1.30E+14 | 1.04E+14 |
| 1.5 | 2.0 | 8.66E+12 | 4.95E+12 |
| 2.0 | 2.5 | 6.46E+11 | 2.87E+11 |
| 2.5 | 3.0 | 4.49E+10 | 1.63E+10 |
| Total | | 2.60E+15 | 4.16E+15 |

| Table 5.2.4<br><br>CALCULATED MPC-89 BWR FUEL GAMMA SOURCE PER ASSEMBLY FOR A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS | | | |
|---|---|---|---|
| **Lower Energy** | **Upper Energy** | **45,000 MWD/MTU 5-Year Cooling** | |
| (MeV) | (MeV) | (MeV/s) | (Photons/s) |
| 0.45 | 0.7 | 7.52E+14 | 1.31E+15 |
| 0.7 | 1.0 | 2.40E+14 | 2.82E+14 |
| 1.0 | 1.5 | 5.53E+13 | 4.42E+13 |
| 1.5 | 2.0 | 4.15E+12 | 2.37E+12 |
| 2.0 | 2.5 | 2.02E+12 | 8.97E+11 |
| 2.5 | 3.0 | 9.74E+10 | 3.54E+10 |
| Total | | 1.05E+15 | 2.04E+15 |

| Table 5.2.5<br><br>CALCULATED MPC-89 BWR FUEL GAMMA SOURCE PER ASSEMBLY FOR BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS | | | |
|---|---|---|---|
| **Lower Energy** | **Upper Energy** | **65,000 MWD/MTU 10-Year Cooling** | |
| (MeV) | (MeV) | (MeV/s) | (Photons/s) |
| 0.45 | 0.7 | 6.98E+14 | 1.21E+15 |
| 0.7 | 1.0 | 8.37E+13 | 9.85E+13 |
| 1.0 | 1.5 | 3.50E+13 | 2.80E+13 |
| 1.5 | 2.0 | 2.52E+12 | 1.44E+12 |
| 2.0 | 2.5 | 4.49E+10 | 2.00E+10 |
| 2.5 | 3.0 | 3.90E+09 | 1.42E+09 |
| Total | | 8.19E+14 | 1.34E+15 |

Table 5.2.7

CALCULATED MPC-37 $^{60}Co$ SOURCE PER ASSEMBLY FOR DESIGN BASIS FUEL AT A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS

| Location | 45,000 MWD/MTU and 4.5-Year Cooling (curies) |
|---|---|
| Lower End Fitting | 86.02 |
| Gas Plenum Springs | 16.77 |
| Gas Plenum Spacer | 11.91 |
| Expansion Springs | NA |
| Incore Grid Spacers | 357.19 |
| Upper End Fitting | 57.22 |
| Handle | NA |

Table 5.2.8

CALCULATED MPC-37 $^{60}Co$ SOURCE PER ASSEMBLY FOR DESIGN BASIS FUEL AT BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS

| Location | 65,000 MWD/MTU and 8-Year Cooling (curies) |
|---|---|
| Lower End Fitting | 64.89 |
| Gas Plenum Springs | 12.65 |
| Gas Plenum Spacer | 8.99 |
| Expansion Springs | NA |
| Incore Grid Spacers | 269.46 |
| Upper End Fitting | 43.17 |
| Handle | NA |

Table 5.2.9

CALCULATED MPC-89 $^{60}Co$ SOURCE PER ASSEMBLY FOR DESIGN BASIS FUEL AT A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS

| **Location** | **45,000 MWD/MTU and 5-Year Cooling (curies)** |
|---|---|
| Lower End Fitting | 158.66 |
| Gas Plenum Springs | 48.48 |
| Gas Plenum Spacer | N/A |
| Expansion Springs | 8.81 |
| Grid Spacer Springs | 72.72 |
| Upper End Fitting | 44.07 |
| Handle | 5.51 |

Table 5.2.10

CALCULATED MPC-89 $^{60}Co$ SOURCE PER ASSEMBLY FOR DESIGN BASIS FUEL AT BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS

| **Location** | **65,000 MWD/MTU and 10-Year Cooling (curies)** |
|---|---|
| Lower End Fitting | 90.17 |
| Gas Plenum Springs | 27.55 |
| Gas Plenum Spacer | N/A |
| Expansion Springs | 5.01 |
| Grid Spacer Springs | 41.33 |
| Upper End Fitting | 25.05 |
| Handle | 3.13 |

Table 5.2.11

CALCULATED MPC-37 PWR NEUTRON SOURCE PER ASSEMBLY
FOR A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS

| Lower Energy (MeV) | Upper Energy (MeV) | 45,000 MWD/MTU 4.5-Year Cooling (Neutrons/s) |
|---|---|---|
| 1.0e-01 | 4.0e-01 | 3.05E+07 |
| 4.0e-01 | 9.0e-01 | 6.64E+07 |
| 9.0e-01 | 1.4 | 6.63E+07 |
| 1.4 | 1.85 | 5.30E+07 |
| 1.85 | 3.0 | 9.88E+07 |
| 3.0 | 6.43 | 8.97E+07 |
| 6.43 | 20.0 | 8.56E+06 |
| Totals | | 4.13E+08 |

Table 5.2.12

CALCULATED MPC-37 PWR NEUTRON SOURCE PER ASSEMBLY
FOR BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS

| Lower Energy (MeV) | Upper Energy (MeV) | 65,000 MWD/MTU 8-Year Cooling (Neutrons/s) |
|---|---|---|
| 1.0e-01 | 4.0e-01 | 6.80E+07 |
| 4.0e-01 | 9.0e-01 | 1.48E+08 |
| 9.0e-01 | 1.4 | 1.47E+08 |
| 1.4 | 1.85 | 1.17E+08 |
| 1.85 | 3.0 | 2.18E+08 |
| 3.0 | 6.43 | 1.98E+08 |
| 6.43 | 20.0 | 1.89E+07 |
| Totals | | 9.16E+08 |

Table 5.2.13

CALCULATED MPC-89 BWR NEUTRON SOURCE
PER ASSEMBLY
FOR DESIGN BASIS FUEL
FOR A SELECTED BURNUP AND COOLING TIME FOR NORMAL CONDITIONS

| **Lower Energy (MeV)** | **Upper Energy (MeV)** | **45,000 MWD/MTU 5-Year Cooling (Neutrons/s)** |
|---|---|---|
| 1.0e-01 | 4.0e-01 | 1.37E+07 |
| 4.0e-01 | 9.0e-01 | 2.99E+07 |
| 9.0e-01 | 1.4 | 2.99E+07 |
| 1.4 | 1.85 | 2.38E+07 |
| 1.85 | 3.0 | 4.44E+07 |
| 3.0 | 6.43 | 4.03E+07 |
| 6.43 | 20.0 | 3.86E+06 |
| Totals | | 1.86E+08 |

Table 5.2.14

CALCULATED MPC-89 BWR NEUTRON SOURCE
PER ASSEMBLY
FOR DESIGN BASIS FUEL
FOR BURNUP AND COOLING TIME FOR ACCIDENT CONDITIONS

| **Lower Energy (MeV)** | **Upper Energy (MeV)** | **65,000 MWD/MTU 10-Year Cooling (Neutrons/s)** |
|---|---|---|
| 1.0e-01 | 4.0e-01 | 2.40E+07 |
| 4.0e-01 | 9.0e-01 | 5.22E+07 |
| 9.0e-01 | 1.4 | 5.20E+07 |
| 1.4 | 1.85 | 4.15E+07 |
| 1.85 | 3.0 | 7.71E+07 |
| 3.0 | 6.43 | 7.00E+07 |
| 6.43 | 20.0 | 6.68E+06 |
| Totals | | 3.24E+08 |

# 5.3 MODEL SPECIFICATIONS

The shielding analysis of the HI-STORM FW system was performed with MCNP5 [5.1.1]. MCNP is a Monte Carlo transport code that offers a full three-dimensional combinatorial geometry modeling capability including such complex surfaces as cones and tori. This means that no gross approximations were required to represent the HI-STORM FW system, including the HI-TRAC transfer casks, in the shielding analysis. A sample input file for MCNP is provided in Appendix 5.A.

As discussed in Subsection 5.1.1, off-normal conditions do not have any implications for the shielding analysis. Therefore, the MCNP models and results developed for the normal conditions also represent the off-normal conditions. Subsection 5.1.2 discussed the accident conditions and stated that the only accident that would impact the shielding analysis would be a loss of the neutron shield (water) in the HI-TRAC. Therefore, the MCNP model of the normal HI-TRAC condition has the neutron shield in place while the accident condition replaces the neutron shield with void. Subsection 5.1.2 also mentioned that there is no credible accident scenario that would impact the HI-STORM shielding analysis. Therefore, models and results for the normal and accident conditions are identical for the HI-STORM overpack.

## 5.3.1 Description of the Radial and Axial Shielding Configuration

Chapter 1 provides the drawings that describe the HI-STORM FW system, including the HI-TRAC transfer cask. These drawings, using nominal dimensions, were used to create the MCNP models used in the radiation transport calculations. Modeling deviations from these drawings are discussed below. Figures 5.3.1 and 5.3.2, as well as Figures 5.3.12 and 5.3.13, show cross sectional views of the HI-STORM FW overpack, MPCs, and basket cells as they are modeled in MCNP. Figures 5.3.1 and 5.3.2 were created in VISED and are drawn to scale. The inlet and outlet vents were modeled explicitly, therefore, streaming through these components is accounted for in the calculations of the dose adjacent to the overpack and at 1 meter. Figures 5.3.3 and 5.3.4 show a cross sectional view of the HI-TRAC VW with the MPC-37 and MPC-89, respectively, as it was modeled in MCNP. These figures were created in VISED and are drawn to scale.

Figure 5.3.5 shows a cross sectional view of the HI-STORM FW overpack with the as-modeled thickness of the various materials.

Figure 5.3.6 shows the axial representation of the HI-STORM FW overpack with the XL lid.

Figure 5.3.7 shows axial cross-sectional views of the HI-TRAC VW transfer casks with the as-modeled dimensions and materials specified. Figures 5.3.8 and 5.3.9 shows fully labeled radial cross-sectional view of the HI-TRAC VW transfer casks and each of the MPCs.

Table 5.3.2 (continued)

COMPOSITION OF THE MATERIALS IN THE HI-STORM FW SYSTEM

| Component | Density (g/cm$^3$) | Elements | Mass Fraction (%) |
|---|---|---|---|
| BWR Fuel Region Mixture [1] | 4.239 (5.0 wt% U-235) | $^{235}U$ | 3.617 |
| | | $^{238}U$ | 68.722 |
| | | O | 9.724 |
| | | Zr | 17.618 |
| | | N | 0.009 |
| | | Cr | 0.018 |
| | | Fe | 0.022 |
| | | Sn | 0.269 |
| BWR Fuel Region Mixture [2] | 4.781 (5.0 wt% U-235) | $^{235}U$ | 3.207 |
| | | $^{238}U$ | 60.935 |
| | | O | 8.623 |
| | | Zr | 26.752 |
| | | N | 0.014 |
| | | Cr | 0.027 |
| | | Fe | 0.034 |
| | | Sn | 0.409 |
| PWR Fuel Region Mixture | 3.769 (5.0 wt% U-235) | $^{235}U$ | 3.709 |
| | | $^{238}U$ | 70.474 |
| | | O | 9.972 |
| | | Zr | 15.565 |
| | | Cr | 0.016 |
| | | Fe | 0.033 |
| | | Sn | 0.230 |

Table 5.3.2 (continued)

COMPOSITION OF THE MATERIALS IN THE HI-STORM FW SYSTEM

| Component | Density (g/cm³) | Elements | Mass Fraction (%) |
|---|---|---|---|
| Water w/ 2000 ppm | 0.958 | B-10 | 0.036 |
| | | B-11 | 0.164 |
| | | H | 11.17 |
| | | O | 88.63 |
| Concrete | 2.4 | H | 1.0 |
| | | O | 53.2 |
| | | Si | 33.7 |
| | | Al | 3.4 |
| | | Na | 2.9 |
| | | Ca | 4.4 |
| | | Fe | 1.4 |

[1] BWR fuel region mixture for dose rates based on the XL Lid Design.
[2] BWR fuel region mixture for dose rates based on the Standard Lid Design.

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.1
HI-STORM FW OVERPACK WITH MPC-37 CROSS SECTIONAL VIEW AS MODELED IN MCNP[†]

[†] This figure is drawn to scale using VISED.

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.2

HI-STORM FW OVERPACK WITH MPC-89 CROSS SECTIONAL VIEW AS MODELED IN MCNP†

† This figure is drawn to scale using VISED.

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.3

HI-TRAC VW OVERPACK WITH MPC-37 CROSS SECTIONAL VIEW AS MODELED IN MCNP†

† This figure is drawn to scale using VISED.

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.4

HI-TRAC VW OVERPACK WITH MPC-89 CROSS SECTIONAL VIEW AS MODELED IN MCNP†

† This figure is drawn to scale using VISED.

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.5
CROSS SECTION OF HI-STORM FW OVERPACK

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.6
HI-STORM FW OVERPACK WITH XL LID CROSS SECTIONAL ELEVATION VIEW

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.7
HI-TRAC VW TRANSFER CASK WITH POOL LID CROSS SECTIONAL ELEVATION VIEW (AS MODELED)

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.8

HI-TRAC VW TRANSFER CASK CROSS SECTIONAL VIEW WITH MPC-37 (AS MODELED)

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.9

HI-TRAC VW TRANSFER CASK CROSS SECTIONAL VIEW WITH MPC-89 (AS MODELED)

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.10

AXIAL LOCATION OF PWR DESIGN BASIS FUEL IN THE HI-STORM FW OVERPACK
(Standard Lid is Shown)

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.11

AXIAL LOCATION OF BWR DESIGN BASIS FUEL IN THE HI-STORM FW OVERPACK
(Standard Lid is Shown)

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.12

CROSS SECTIONAL VIEW OF AN MPC-37 BASKET CELL AS MODELED IN MCNP

**WITHHELD IN ACCORDANCE WITH 10 CFR 2.390**

Figure 5.3.13

CROSS SECTIONAL VIEW OF AN MPC-89 BASKET CELL AS MODELED IN MCNP

Tables 5.1.5 and 5.1.6 provide the design basis dose rates adjacent to the HI-STORM overpack during normal conditions for the MPC types in Table 1.0.1. Tables 5.1.7 and 5.1.8 provides the design basis dose rates at one meter from the overpack. A detailed discussion of the normal, off-normal, and accident condition dose rates is provided in Subsections 5.1.1 and 5.1.2.

Table 5.4.2 shows the corresponding dose rates adjacent to and one meter away from the HI-TRAC for the fully flooded MPC-37 condition with an empty water-jacket (condition in which the HI-TRAC is removed from the spent fuel pool). Table 5.4.3 shows the dose rates adjacent to and one meter away from the HI-TRAC for the fully flooded MPC-37 condition with the water jacket filled with water (condition in which welding operations are performed). For the conditions involving a fully flooded MPC-37, the internal water level was 5 inches below the MPC lid. These dose rates represent the various conditions of the HI-TRAC during operations. Comparing these results to Table 5.1.1 (dry MPC-37 and HI-TRAC water jacket filled with water) indicates that the dose rates in the upper and lower portions of the HI-TRAC are significantly reduced with water in the MPC.

Table 5.4.4 shows the corresponding dose rates adjacent to and one meter away from the HI-TRAC for the fully flooded MPC-89 condition with an empty water-jacket. Table 5.4.5 shows the dose rates adjacent to and one meter away from the HI-TRAC for the fully flooded MPC-89 condition with the water jacket filled with water. These results demonstrate that the dose rates on contact at the top and bottom of the HI-TRAC VW are somewhat higher in the MPC-37 case than in the MPC-89 case. The difference in dose rates between MPC-37 and MPC-89 is within approximately 30%. Therefore, the MPC-37 is sufficiently representative for the exposure calculations in Chapter 11 of the SAR.

Previous revisions of this FSAR with a smaller set of loading patterns used a conservative uniform loading conditions for dose evaluations, and analyses for the concrete overpack were performed with the standard lid. For reference purposes, those results are retained in this subsection of the chapter, in Tables 5.4.9 through 5.4.14. Tables 5.4.9 and 5.4.10 show the burnup, enrichment and cooling time combinations that were used. Tables 5.4.11 and 5.4.12 provide the dose rates adjacent to the HI-STORM overpack with the standard lid design during normal conditions for the MPC-37 and MPC-89, respectively. And Tables 5.4.13 and 5.4.14 provide the dose rates at one meter from the HI-STORM overpack with the standard lid design during normal conditions for the MPC-37 and MPC-89, respectively. The dose rates adjacent to and one meter from the HI-TRAC VW for normal conditions (i.e., dry MPC and full water jacket) and uniform loading source terms for the MPC-37 and MPC-89 are listed in Tables 5.4.15 and 5.4.16, respectively. The dose rates for MPC-89 at one meter and 100 meters from the HI-TRAC VW for accident conditions (i.e., dry MPC and empty water jacket) for the uniform and regionalized loading source terms are listed in Tables 5.4.17 and 5.4.18, respectively.

Since MCNP is a statistical code, there is an uncertainty associated with the calculated values. In

The annual dose, assuming 100% occupancy (8760 hours), at 300 meters from a single HI-STORM FW cask is presented in Table 5.4.6.

The annual dose, assuming 8760 hour occupancy, at distance from an array of casks was calculated in three steps.

1. The annual dose from the radiation leaving the side of the HI-STORM FW overpack was calculated at the distance desired. Dose value = A.

2. The annual dose from the radiation leaving the top of the HI-STORM FW overpack was calculated at the distance desired. Dose value = B.

3. The annual dose from the radiation leaving the side of a HI-STORM FW overpack, when it is behind another cask, was calculated at the distance desired. The casks have an assumed 15-foot pitch. Dose value = C.

The doses calculated in the steps above are listed in Table 5.4.7. Using these values, the annual dose (at the center of the long side) from an arbitrary 2 by Z array of HI-STORM FW overpacks can easily be calculated. The following formula describes the method.

Z = number of casks along long side

Dose = ZA + 2ZB + ZC

The results for various typical arrays of HI-STORM overpacks can be found in Section 5.1. While the off-site dose analyses were performed for typical arrays of casks containing design basis fuel, compliance with the requirements of 10CFR72.104(a) can only be demonstrated on a site-specific basis, as stated earlier. Therefore, a site-specific evaluation of dose at the controlled area boundary must be performed for each ISFSI in accordance with 10CFR72.212. The site-specific evaluation will consider the site-specific characteristics (such as exposure duration and the number of casks deployed), dose from other portions of the facility and the specifics of the fuel being stored (burnup and cooling time).

### 5.4.4 Non-Fuel Hardware

As discussed in Subsection 5.2.3, non-fuel hardware in the form of BPRAs, TPDs, CRAs, and APSRs are permitted for storage, integral with a PWR fuel assembly, in the HI-STORM FW system. Since each device occupies the same location within an assembly, only one device will be present in a given assembly. ITTRs, which are installed after core discharge and do not contain radioactive material, may also be stored in the assembly. BPRAs, TPDs and ITTRs are

rates due to the presence of CRAs is on the order of 10-15% (based on bounding configuration 1 in [5.2.17]). The dose rate out the top of the overpack is essentially 0. The latter is due to the fact that CRAs and APSRs do not achieve significant activation in the upper portion of the devices due to the manner in which they are utilized during normal reactor operations. In contrast, the dose rate out the bottom of the overpack is substantial due to these devices. However, these dose rates occur in an area (below the pool lid and transfer doors) which is not normally occupied.

While the evaluations described above are based on conservative assumptions, the conclusions can vary slightly depending on the number of CRAs and their operating conditions.

### 5.4.5 Effect of Uncertainties

The design basis calculations presented in this chapter are based on a range of conservative assumptions, but do not explicitly account for uncertainties in the methodologies, codes and input parameters, that is, it is assumed that the effect of uncertainties is small compared to the numerous conservatisms in the analyses. To show that this assumption is valid, calculations have previously been performed as "best estimate" calculations and with estimated uncertainties added [5.4.9]. In all scenarios considered (e.g., evaluation of conservatisms in modeling assumptions, uncertainties associated with MCNP as well as the depletion analysis (including input parameters), etc.), the total dose rates long with uncertainties are comparable to, or lower than, the corresponding values from the design basis calculations. This provides further confirmation that the design basis calculations are reasonable and conservative.

### 5.4.6 Dose Rate Evaluation for Fuel Assemblies with Irradiated Stainless Steel Replacement Rods

A dose rate evaluation for the HI-STORM FW containing the MPC-37 and the MPC-89 is performed to determine the impact of storing fuel assemblies with irradiated stainless steel replacement rods. The stainless steel rods are irradiated in the same neutron flux and for the same time period as the design basis PWR and BWR UO2 fuel rods. The dose rates at several locations, adjacent to and at 1 meter, from the HI-STORM containing the MPC-37 are presented in Table 5.1.5 and Table 5.1.7, respectively. The dose rates for the HI-STORM containing the MPC-89 are presented in Tables 5.1.6 and Table 5.1.8. The dose rates at the same locations are calculated assuming all 37 design basis PWR assemblies contain 4 irradiated stainless steel replacement rods and all 89 design basis BWR assemblies contain 2 irradiated stainless steel replacement rods. The dose rates with the 4 irradiated stainless steel replacement rods in the design basis PWR assembly are approximately 10% higher at the sides and top of the HI-STORM containing the MPC-37. The dose rates with the 2 irradiated stainless steel replacement rods in the design basis BWR assembly are approximately 21% higher at the sides and top of the HI-STORM containing the MPC-89. Therefore, fuel assemblies containing irradiated stainless

steel replacement rods are acceptable for storage and, if present in a fuel assembly, need to be considered in the site specific dose calculations.

Table 5.4.2

DOSE RATES FOR THE HI-TRAC VW FOR THE FULLY FLOODED MPC CONDITION WITH AN EMPTY NEUTRON SHIELD

MPC-37 DESIGN BASIS ZIRCALOY CLAD FUEL

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}$Co Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) | Totals with BPRAs (mrem/hr) |
|---|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | | |
| 1 | 813.0 | 0.0 | 378.3 | 5.8 | 1197.1 | 1197.1 |
| 2 | 2569.8 | 1.2 | <0.1 | 233.6 | 2804.6 | 2804.6 |
| 3 | 6.1 | <0.1 | 137.0 | 5.0 | 148.1 | 220.4 |
| 4 | 21.7 | <0.1 | 212.7 | 0.3 | 234.7 | 362.0 |
| 5 (bottom lid) | 332.8 | 0.4 | 1640.7 | 127.1 | 2101.1 | 2101.1 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | | |
| 1 | 532.8 | 0.2 | 32.1 | 36.8 | 601.9 | 602.1 |
| 2 | 1191.6 | 0.4 | 2.8 | 78.6 | 1273.4 | 1274.9 |
| 3 | 133.2 | 0.1 | 50.2 | 13.9 | 197.4 | 230.7 |
| 4 | 11.4 | <0.1 | 135.8 | 0.3 | 147.5 | 218.6 |
| 5 | 295.8 | 0.1 | 1065.2 | 31.0 | 1392.2 | 1392.2 |

Notes:

- Refer to Figure 5.1.2 for dose point locations.
- Values are rounded to nearest integer.
- MPC internal water level is 5 inches below the MPC lid.
- The “Fuel Gammas” category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.4.3

DOSE RATES FOR THE HI-TRAC VW FOR THE FULLY FLOODED MPC CONDITION WITH A FULL NEUTRON SHIELD

MPC-37 DESIGN BASIS ZIRCALOY CLAD FUEL

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}Co$ Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) | Totals with BPRAs (mrem/hr) |
|---|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | | |
| 1 | 509.8 | 0.1 | 232.0 | 0.4 | 742.3 | 742.3 |
| 2 | 1683.2 | 0.1 | <0.1 | 0.4 | 1683.7 | 1683.7 |
| 3 | 2.4 | <0.1 | 73.9 | <0.1 | 76.4 | 115.2 |
| 4 | 21.7 | <0.1 | 212.6 | 0.3 | 234.6 | 361.9 |
| 5 (bottom lid) | 332.0 | 0.4 | 1640.5 | 126.7 | 2099.7 | 2099.7 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | | |
| 1 | 340.7 | <0.1 | 17.0 | 0.1 | 357.8 | 357.9 |
| 2 | 762.5 | <0.1 | 1.4 | 0.1 | 764.1 | 764.7 |
| 3 | 79.8 | <0.1 | 27.1 | 0.1 | 107.1 | 125.8 |
| 4 | 11.4 | <0.1 | 135.8 | 0.1 | 147.3 | 218.5 |
| 5 | 295.4 | 0.1 | 1065.2 | 30.1 | 1390.8 | 1390.8 |

Notes:

- Refer to Figure 5.1.2 for dose point locations.
- Values are rounded to nearest integer.
- MPC internal water level is 5 inches below the MPC lid.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}Co$ from the spacer grids, and $^{60}Co$ from the BPRAs in the active fuel region.

Table 5.4.4

DOSE RATES FOR THE HI-TRAC VW FOR THE FULLY FLOODED MPC CONDITION WITH AN EMPTY NEUTRON SHIELD
MPC-89 DESIGN BASIS ZIRCALOY CLAD FUEL

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}Co$ Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) |
|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | |
| 1 | 239.0 | 0.3 | 1524.2 | 48.5 | 1812.0 |
| 2 | 3527.2 | 2.4 | <0.1 | 417.3 | 3946.9 |
| 3 | 1.9 | <0.1 | 393.6 | 3.0 | 398.5 |
| 4 | 4.2 | <0.1 | 216.7 | 0.0 | 220.9 |
| 5 (bottom lid) | 55.9 | <0.1 | 1483.4 | 11.8 | 1551.2 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | |
| 1 | 529.1 | 0.3 | 110.6 | 51.4 | 691.4 |
| 2 | 1597.1 | 0.7 | 9.1 | 133.0 | 1740.0 |
| 3 | 103.8 | 0.2 | 163.7 | 25.0 | 292.6 |
| 4 | 2.3 | <0.1 | 155.2 | 0.1 | 157.7 |
| 5 | 49.0 | <0.1 | 1031.0 | 3.7 | 1083.7 |

Notes:

- Refer to Figure 5.1.2 for dose point locations.
- Values are rounded to nearest integer.
- MPC internal water level is 5 inches below the MPC lid.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}Co$ from the spacer grids.

Table 5.4.5

DOSE RATES FOR THE HI-TRAC VW FOR THE FULLY FLOODED MPC CONDITION WITH A FULL NEUTRON SHIELD
MPC-89 DESIGN BASIS ZIRCALOY CLAD FUEL

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}$Co Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) |
|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | |
| 1 | 144.8 | 0.3 | 943.3 | 1.5 | 1090.0 |
| 2 | 2233.0 | 0.6 | <0.1 | 3.1 | 2236.7 |
| 3 | 0.6 | <0.1 | 215.6 | <0.1 | 216.2 |
| 4 | 4.2 | <0.1 | 216.7 | <0.1 | 220.9 |
| 5 (bottom lid) | 56.0 | 0.1 | 1483.6 | 12.4 | 1552.1 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | |
| 1 | 341.5 | 0.1 | 64.6 | 0.5 | 406.7 |
| 2 | 1011.2 | 0.2 | 4.6 | 1.1 | 1017.1 |
| 3 | 67.3 | 0.2 | 89.9 | 0.8 | 158.3 |
| 4 | 2.3 | <0.1 | 155.2 | <0.1 | 157.6 |
| 5 | 49.0 | <0.1 | 1030.9 | 3.4 | 1083.4 |

Notes:

- Refer to Figure 5.1.2 for dose point locations.
- Values are rounded to nearest integer.
- MPC internal water level is 5 inches below the MPC lid.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer grids.

| Table 5.4.6<br><br>ANNUAL DOSE AT 300 METERS FROM A SINGLE HI-STORM FW OVERPACK WITH THE XL LID DESIGN CONTAINING AN MPC-37 WITH DESIGN BASIS ZIRCALOY CLAD FUEL | |
|---|---|
| **Dose Component** | **45,000 MWD/MTU 4.5-Year Cooling (mrem/yr)** |
| Fuel gammas | 16.35 |
| $^{60}$Co Gammas | 1.11 |
| Neutrons | 0.25 |
| Total | 17.7 |

Notes:

- Gammas generated by neutron capture are included with fuel gammas.
- The Co-60 gammas include BPRAs.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.4.7

DOSE VALUES USED IN CALCULATING ANNUAL DOSE FROM VARIOUS HI-STORM FW ISFSI CONFIGURATIONS WITH THE XL LID DESIGN 45,000 MWD/MTU AND 4.5-YEAR COOLING ZIRCALOY CLAD FUEL

| **Distance** | **A Side of Overpack (mrem/yr)** | **B Top of Overpack (mrem/yr)** | **C Side of Shielded Overpack (mrem/yr)** |
|---|---|---|---|
| 100 meters | 396.8 | 44.1 | 79.4 |
| 200 meters | 60.9 | 6.8 | 12.2 |
| 300 meters | 15.9 | 1.8 | 3.2 |
| 400 meters | 5.2 | 0.6 | 1.0 |
| 500 meters | 1.9 | 0.2 | 0.4 |
| 600 meters | 0.8 | 0.1 | 0.2 |

Notes:

- 8760 hour annual occupancy is assumed.

Table 5.4.8

DOSE RATES DUE TO BPRAs AND TPDs FROM THE HI-TRAC VW FOR NORMAL CONDITIONS

| **Dose Point Location** | **BPRAs (mrem/hr)** | **TPDs (mrem/hr)** |
|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | |
| 1 | 159.09 | 0.0 |
| 2 | 509.04 | 0.0 |
| 3 | 192.78 | 165.31 |
| 4 | 304.15 | 275.53 |
| 5 | 137.27 | 0.0 |
| **ONE METER FROM THE HI-TRAC VW** | | |
| 1 | 122.06 | 0.40 |
| 2 | 240.70 | 3.10 |
| 3 | 128.50 | 86.95 |
| 4 | 174.25 | 153.49 |
| 5 | 63.13 | 0.0 |

Notes:
- Refer to Figure 5.1.2 for dose locations.
- Dose rates are based on no water within the MPC, an empty annulus, and a water jacket full of water. For the majority of the duration that the HI-TRAC bottom lid is installed, the MPC cavity will be flooded with water. The water within the MPC greatly reduces the dose rate
- Includes the BPRAs from both the active and non-active region.

Table 5.4.9

DESIGN BASIS FUEL BURNUP, COOLING TIME AND ENRICHMENT FOR NORMAL CONDITIONS

| Design Basis Burnup and Cooling Times Uniform Loading | |
|---|---|
| **MPC-37** | **MPC-89** |
| 45,000 MWD/MTU<br>4.5 Year Cooling<br>3.6 wt% U-235 Enrichment | 45,000 MWD/MTU<br>5 Year Cooling<br>3.2 wt% U-235 Enrichment |

Table 5.4.10

DESIGN BASIS FUEL BURNUP, COOLING TIME AND ENRICHMENT FOR ACCIDENT CONDITIONS

| Design Basis Burnup and Cooling Times Uniform Loading | |
|---|---|
| **MPC-37** | **MPC-89** |
| 65,000 MWD/MTU<br>8 Year Cooling<br>4.8 wt% U-235 Enrichment | 65,000 MWD/MTU<br>8 Year Cooling<br>4.8 wt% U-235 Enrichment |

Table 5.4.11

DOSE RATES ADJACENT TO HI-STORM FW OVERPACK WITH THE STANDARD LID DESIGN
FOR NORMAL CONDITIONS
MPC-37
BURNUP AND COOLING TIME
45,000 MWD/MTU AND 4.5-YEAR COOLING

| Dose Point Location | Fuel Gammas (mrem/hr) | (n,γ) Gammas (mrem/hr) | $^{60}$Co Gammas (mrem/hr) | Neutrons (mrem/hr) | Totals (mrem/hr) | Totals with BPRAs (mrem/hr) |
|---|---|---|---|---|---|---|
| 1 | 273 | 2 | 14 | 4 | 292 | 292 |
| 2 | 135 | 1 | <1 | 1 | 141 | 141 |
| 3 (surface) | 11 | 1 | 25 | 2 | 39 | 53 |
| 3 (overpack edge) | 13 | <1 | 63 | 1 | 78 | 113 |
| 4 (center) | <1 | 1 | <1 | <1 | <4 | <4 |
| 4 (mid) | 1 | 1 | 4 | 1 | 7 | 10 |
| 4 (outer) | 10 | <1 | 30 | <1 | 42 | 59 |

Notes:
- Refer to Figure 5.1.1 for dose locations.
- Values are rounded to nearest integer where appropriate.
- Dose location 3 (surface) is at the surface of the outlet vent. Dose location 3 (overpack edge) is in front of the outlet vent, but located radially above the overpack outer diameter.
- Dose location 4 (center) is at the center of the top surface of the top lid. Dose location 4 (mid) is situated directly above the vertical section of the outlet vent. Dose location 4 (outer) is extended along the top plane of the top lid, located radially above the overpack outer diameter.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.4.12

DOSE RATES ADJACENT TO HI-STORM FW OVERPACK WITH THE STANDARD LID DESIGN
FOR NORMAL CONDITIONS
MPC-89
BURNUP AND COOLING TIME
45,000 MWD/MTU AND 5-YEAR COOLING

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** |
|---|---|---|---|---|---|
| 1 | 172 | 2 | 31 | 3 | 208 |
| 2 | 92 | 2 | <1 | 1 | 96 |
| 3 (surface) | 3 | <1 | 29 | 2 | 35 |
| 3 (overpack edge) | 5 | <1 | 69 | <1 | 76 |
| 4 (center) | 0.1 | 0.4 | 0.4 | 0.1 | 1 |
| 4 (mid) | 0.2 | 0.5 | 4.3 | 0.5 | 6 |
| 4 (outer) | 2 | <1 | 33 | <1 | 37 |

Notes:
- Refer to Figure 5.1.1 for dose locations.
- Values are rounded to nearest integer where appropriate.
- Dose location 3 (surface) is at the surface of the outlet vent. Dose location 3 (overpack edge) is in front of the outlet vent, but located radially above the overpack outer diameter.
- Dose location 4 (center) is at the center of the top surface of the top lid. Dose location 4 (mid) is situated directly above the vertical section of the outlet vent. Dose location 4 (outer) is extended along the top plane of the top lid, located radially above the overpack outer diameter.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer grids.

Table 5.4.13

DOSE RATES AT ONE METER FROM HI-STORM FW OVERPACK WITH THE STANDARD LID DESIGN
FOR NORMAL CONDITIONS
MPC-37
BURNUP AND COOLING TIME
45,000 MWD/MTU AND 4.5-YEAR COOLING

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** | **Totals with BPRAs (mrem/hr)** |
|---|---|---|---|---|---|---|
| 1 | 57 | 1 | 4 | 1 | 62 | 62 |
| 2 | 75 | 1 | 1 | 1 | 77 | 78 |
| 3 | 6 | <1 | 5 | <1 | 13 | 15 |
| 4 (center) | 0.6 | 0.3 | 1.0 | 0.2 | 2.1 | 2.7 |

Notes:
- Refer to Figure 5.1.1 for dose locations.
- Values are rounded to nearest integer where appropriate.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.4.14

DOSE RATES AT ONE METER FROM HI-STORM FW OVERPACK WITH THE STANDARD LID DESIGN
FOR NORMAL CONDITIONS
MPC-89
BURNUP AND COOLING TIME
45,000 MWD/MTU AND 5-YEAR COOLING

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** |
|---|---|---|---|---|---|
| 1 | 38 | <1 | 7 | <1 | 47 |
| 2 | 47 | <1 | <1 | <1 | 50 |
| 3 | 3 | <1 | 5 | <1 | 10 |
| 4 (center) | 0.2 | 0.2 | 1 | 0.1 | 2 |

Notes:
- Refer to Figure 5.1.1 for dose locations.
- Values are rounded to nearest integer where appropriate.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer girds.

Table 5.4.15

DOSE RATES FROM THE HI-TRAC VW FOR NORMAL CONDITIONS
MPC-37 DESIGN BASIS FUEL
45,000 MWD/MTU AND 4.5-YEAR COOLING

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** | **Totals with BPRAs (mrem/hr)** |
|---|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | | |
| 1 | 975 | 25 | 808 | 67 | 1874 | 1874 |
| 2 | 2939 | 75 | <1 | 154 | 3169 | 3169 |
| 3 | 20 | 5 | 339 | 6 | 371 | 561 |
| 4 | 98 | 1 | 530 | 225 | 854 | 1147 |
| 5 | 940 | 3 | 2074 | 1022 | 4038 | 4038 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | | |
| 1 | 695 | 12 | 99 | 30 | 835 | 835 |
| 2 | 1382 | 22 | 10 | 58 | 1472 | 1474 |
| 3 | 268 | 6 | 142 | 9 | 425 | 501 |
| 4 | 80 | <1 | 295 | 73 | 449 | 613 |
| 5 | 470 | 1 | 1129 | 297 | 1897 | 1897 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- Values are rounded to nearest integer.
- Dose rates are based on no water within the MPC, an empty annulus, and a water jacket full of water. For the majority of the duration that the HI-TRAC bottom lid is installed, the MPC cavity will be flooded with water. The water within the MPC greatly reduces the dose rate.
- Streaming may occur through the annulus. However, during handling/operations the annulus is filled with water and lead snakes are typically present to reduce the streaming effects. Further, operators are not present on top of the transfer cask.
- The "Fuel Gammas" category includes gammas from the spent fuel, $^{60}$Co from the spacer grids, and $^{60}$Co from the BPRAs in the active fuel region.

Table 5.4.16

DOSE RATES FROM THE HI-TRAC VW FOR NORMAL CONDITIONS
MPC-89 DESIGN BASIS FUEL
45,000 MWD/MTU AND 5-YEAR COOLING

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **(n,γ) Gammas (mrem/hr)** | **$^{60}$Co Gammas (mrem/hr)** | **Neutrons (mrem/hr)** | **Totals (mrem/hr)** |
|---|---|---|---|---|---|
| **ADJACENT TO THE HI-TRAC VW** | | | | | |
| 1 | 244 | 18 | 2247 | 40 | 2549 |
| 2 | 2466 | 107 | <1 | 219 | 2793 |
| 3 | 3 | 3 | 581 | 4 | 591 |
| 4 | 25 | <1 | 505 | 138 | 669 |
| 5 | 132 | 2 | 2135 | 720 | 2989 |
| **ONE METER FROM THE HI-TRAC VW** | | | | | |
| 1 | 411 | 13 | 291 | 29 | 744 |
| 2 | 1142 | 30 | 21 | 74 | 1267 |
| 3 | 119 | 5 | 280 | 8 | 412 |
| 4 | 16 | <1 | 300 | 43 | 360 |
| 5 | 79 | <1 | 1202 | 202 | 1484 |

Notes:

- Refer to Figure 5.1.2 for dose locations.
- Values are rounded to nearest integer.
- Dose rates are based on no water within the MPC, an empty annulus, and a water jacket full of water. For the majority of the duration that the HI-TRAC bottom lid is installed, the MPC cavity will be flooded with water. The water within the MPC greatly reduces the dose rate.
- Streaming may occur through the annulus. However, during handling/operations the annulus is filled with water and lead snakes are typically present to reduce the streaming effects. Further, operators are not present on top of the transfer cask.
- The "Fuel Gammas" category includes gammas from the spent fuel and $^{60}$Co from the spacer grids.

Table 5.4.17

DOSE RATES FROM HI-TRAC VW WITH MPC-89
FOR ACCIDENT CONDITIONS
AT UNIFORM LOADING BURNUP AND COOLING TIMES

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **N, Gamma (mrem/hr)** | **Co-60 Gamma (mrem/hr)** | **Neutrons (mrem/hr)** | **Total (mrem/hr)** |
|---|---|---|---|---|---|
| **1 meter from HI-TRAC VW** | | | | | |
| 65000 MWD/MTU and 8 Year Cooling | | | | | |
| 2 (Accident Condition) | 1601.8 | 3.5 | 26.9 | 3209.5 | 4841.7 |
| 2 (Normal Condition) | 903.6 | 57.9 | 17.6 | 153.9 | 1133.1 |
| **100 meters from HI-TRAC VW** | | | | | |
| 65000 MWD/MTU and 8 Year Cooling | | | | | |
| 2 (Accident Condition) | 0.7 | < 0.1 | 0.2 | 1.6 | 2.5 |

Table 5.4.18

DOSE RATES FROM HI-TRAC VW WITH MPC-89
FOR ACCIDENT CONDITIONS
AT REGIONALIZED LOADING BURNUP AND COOLING TIMES

| **Dose Point Location** | **Fuel Gammas (mrem/hr)** | **N, Gamma (mrem/hr)** | **Co-60 Gamma (mrem/hr)** | **Neutrons (mrem/hr)** | **Total (mrem/hr)** |
|---|---|---|---|---|---|
| **1 meter from HI-TRAC VW** | | | | | |
| 2 (Accident Condition) | 1330.7 | 3.7 | 33.1 | 3346.8 | 4714.3 |
| 2 (Normal Condition) | 1886.8 | 5.0 | 13.9 | 10.8 | 1916.5 |
| **100 meters from HI-TRAC VW** | | | | | |
| 2 (Accident Condition) | 0.4 | <0.1 | 0.1 | 0.8 | 1.4 |

Table 7.1.2

COMPARISON OF HOLTEC MPC DESIGN WITH ISG-18 GUIDANCE

| DESIGN/QUALIFICATION GUIDANCE | HOLTEC MPC DESIGN |
|---|---|
| The canister is constructed from Alloy X type material. | The MPC enclosure vessel is constructed entirely from Alloy X material. Alloy X is defined as Type 304, 304LN, 316, 316LN or duplex stainless steel material. |
| The canister closure welds meet the guidance of ISG-15 (or approved alternative), Section X.5.2.3. | The MPC lid-to-shell closure weld meets ISG-15, Section X.5.2.3 for austenitic stainless steels. UT examination is permitted and NB-5332 acceptance criteria are required. An optional multi-layer PT examination is also permitted. The multi-layer PT is performed at each approximately 3/8" of weld depth, which corresponds to the critical flaw size. |
| The canister maintains its confinement integrity during normal conditions, anticipated occurrences, and credible accidents and natural phenomena as required in 10CFR72. | The MPC is shown by analysis to maintain confinement integrity for all normal, off-normal, and accident conditions, including natural phenomena. The MPC is designed to ensure that the Confinement Boundary will not leak during any credible accident event and under the non-mechanistic tip-over scenario. |
| Records documenting the fabrication and closure welding of canisters shall comply with the provisions 10CFR72.174 and ISG-15. Record storage shall comply with ANSI N45.2.9. | Records documenting the fabrication and closure welding of MPCs meet the requirements of ISG-15 via controls required by the FSAR and HI-STORM FW CoC. Compliance with 10CFR72.174 and ANSI N.45.2.9 is achieved via Holtec QA program and implementing procedures. |
| Activities related to inspection, evaluation, documentation of fabrication, and closure welding of canisters shall be performed in accordance with an NRC-approved quality assurance program. | The NRC has approved Holtec's Quality Assurance program under 10CFR71. That same QA program has been adopted for activities governed by 10CFR72 as permitted by 10 CFR 72.140(d) |

shielding materials are treated in Section 8.8. The neutron absorbing materials are discussed in Section 8.9.

Chapter 1 provides a general description of the HI-STORM FW System including information on materials of construction. All materials of construction are identified in the drawing package provided in Section 1.5 and the ITS categories of the sub-components are identified in Table 2.0.1 through 2.0.8.

## 8.2.1 Structural Materials

### 8.2.1.1 Cask Components and Their Constituent Materials

The major structural materials that are used in the HI-STORM FW System are Alloy X, Metamic-HT, carbon steel, and aluminum. They are further discussed below in light of the ISG-15 requirements.

MPC

All structural components in an MPC Enclosure Vessel are made of Alloy X (stainless steel). Appendix 1.A provides discussions on Alloy X materials. The fuel basket is made of Metamic-HT neutron absorber described in Chapter 1, Section 1.2.1.4. The confinement boundary is made of stainless steel material for its superior strength, ductility, and resistance to corrosion and brittle fracture for long term storage. The basket shims used to support the basket are made of a creep resistant aluminum alloy. The two-piece MPC lid is either made entirely of Alloy X or the bottom portion of the lid is made of carbon steel with stainless steel veneer. The principal materials used in the fabrication of the MPC are listed in Section 1.2.

HI-STORM

The main structural function of the overpack is provided by carbon steel and the main shielding function is provided by plain concrete. Chapter 1 presents discussions on these materials. The materials used in the fabrication of the overpack are listed in Section 1.2.

HI-TRAC

As discussed in Chapter 1, the HI-TRAC VW transfer cask is principally made of carbon steel and lead. The HI-TRAC VW is equipped with a water jacket. The materials used in the fabrication of the transfer cask are listed in Section 1.2.

### 8.2.1.2 Synopsis of Structural Materials

i. Alloy X

The MPC enclosure vessel design allows use of any one of the five Alloy X materials: Types 304, 304LN, 316, 316LN and duplex steel (UNS S31803). Qualification of structures made of

### 8.4.3 Low Temperature Ductility of Ferritic Steels*

The risk of brittle fracture in the HI-STORM FW components is eliminated by utilizing materials that maintain high fracture toughness under extremely cold conditions.

The MPC canister is constructed from a series of stainless steels termed Alloy X. Austenitic stainless steel materials do not undergo a ductile-to-brittle transition (DBT) in the operating temperature range of the HI-STORM FW System. Therefore, brittle fracture is not a concern for the MPC components fabricated using austenitic stainless steel. Such an assertion cannot be made *a' priori* for the MPC confinement boundary components fabricated using duplex stainless steel grade of Alloy X, or for the HI-STORM FW storage overpack and HI-TRAC VW transfer cask that contain ferritic steel parts.

The use of duplex stainless steel grade of Alloy X material is limited to the MPC confinement boundary components and shall be restricted to the maximum temperatures specified in Table 1.A.6 as the material may suffer from precipitation of brittle micro-constituents above 600°F.

The duplex stainless steel material undergoes DBT below the temperature of -40°F/-40°C [8.4.2] (which is equal to the Lowest Service Temperature (LST) of MPC). In addition, Holtec Position Paper DS-213 [8.5.2] demonstrates that crack propagation in MPC lid-to-shell weld is not credible for austenitic and duplex stainless steel grades of Alloy X. Therefore, brittle fracture is not a concern for MPC confinement boundary components fabricated using duplex stainless steel grade of Alloy X as well.

In general, the impact testing requirement for the HI-STORM FW overpack and the HI-TRAC VW transfer cask is a function of two parameters: the LST† and the normal stress level. The significance of these two parameters, as they relate to impact testing of the overpack and the transfer cask, is discussed below.

In normal storage mode, the LST of the HI-STORM FW storage overpack structural members may reach -40°F in the limiting condition wherein the spent nuclear fuel (SNF) in the contained MPCs emits no (or negligible) heat and the ambient temperature is at -40°F (design minimum per Chapter 2: Principal Design Criteria). However, during the HI-STORM FW overpack transport operations, the applicable lowest service temperature is per 0°F (per the Technical Specifications). Therefore, two distinct LSTs are applicable to load bearing metal parts within the HI-STORM FW System; namely,

LST = 0°F for the HI-STORM FW overpack during transport operations and for the HI-TRAC VW transfer cask during all normal operating conditions.

LST = -40°F for the HI-STORM FW overpack during storage operations.

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* This subsection has been copied from the HI-STORM 100 FSAR (Section 3.1) without any substantive change.
† LST (Lowest Service Temperature) is defined as the daily average for the host ISFSI site when the outdoors portions of the "short-term operations" are carried out.

# 8.16 REFERENCES


[8.1.1] ISG-15, "Materials Evaluation," U.S. Nuclear Regulatory Commission, Washington, DC, Revision 0, January 2001.

[8.1.2] ISG-11, "Cladding Considerations for the Transportation and Storage of Spent Fuel," U.S. Regulatory Commission, Washington, DC, November 2003.

[8.3.1] ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, New York, NY, (2007).

[8.3.2] ACI 318-2005, "Building Code Requirements for Structural Concrete," American Concrete Institute, Ann Arbor, MI.

[8.3.3] NUREG-1536, "Standard Review Plan for Dry Cask Storage Systems," U.S. Nuclear Regulatory Commission, Washington, DC, January 1997.

[8.4.1] ASME Boiler & Pressure Vessel Code, Section III, Part D, 2007 Edition.

[8.4.2] "Practical Guidelines for the Fabrication of Duplex Stainless Steels," International Molybdenum Association (IMOA), London, UK – ISBN : 978-1-907470-00-4, Second Edition, 2009.

[8.5.1] Holtec Position Paper DS-329, "Stress Limits, Weld Categories, and Service Conditions", (Holtec Proprietary).

[8.5.2] Holtec Position Paper DS-213, "Acceptable Flaw Size in MPC Lid-to-Shell Welds" (Holtec Proprietary)

[8.7.1] Holtec Standard Procedure HSP-318, "Procedure for Blasting and Painting HI-TRAC Overpacks and Associated Components." (Holtec Proprietary)

[8.7.2] Holtec Standard Procedure HSP-319, "Procedure for Surface Preparation and Painting of HI-STORM 100 and 100S Overpacks." (Holtec Proprietary)

[8.8.1] A.M. Neville, "Properties of Concrete," Fourth Edition, Addison Wesley Longman, 1996.

[8.9.1] Turner, S.E., "Reactivity Effects of Streaming Between Discrete Boron Carbide Particles in Neutron Absorber Panels for Storage or Transport of Spent Nuclear Fuel," Nuclear Science and Engineering, Vol. 151, Nov. 2005, pp. 344-347.

[8.9.2] "HI-STORM 100 Final Safety Analysis Report", Holtec Report HI-2002444, latest revision, Docket No. 72-1014.

# 11.3 ESTIMATED ON-SITE CUMULATIVE DOSE ASSESSMENT

This section provides the estimates of the cumulative exposure to personnel performing loading, unloading and transfer operations using the HI-STORM FW system. This section uses the shielding analysis provided in Chapter 5, the operations procedures provided in Chapter 9 and the experience from the loading of many MPCs to develop a realistic estimate of the occupational dose.

The dose rates from the HI-STORM FW overpack, MPC lid, HI-TRAC VW, and HI-STAR 100 overpack are calculated to determine the dose to personnel during the fuel loading and unloading operations. No assessment is made with respect to background radiation since background radiation can vary significantly by site.

The estimated occupational dose is governed by three principal parameters, namely:

i. The dose rate emanating from the MPC.
ii. Average duration of human activity in the radiation elevated space.
iii. Relative proximity of humans to the radiation source.

The dose rate accreted by the MPC depends on its contents. Regionalized storage has been made mandatory in the HI-STORM FW MPC-37 to reduce its net radiation output. The duration of required human activity and the required human proximity, on the other hand, are dependent on the training level of the personnel, and user friendliness of ancillary equipment and the quality of fit-up of parts that need to be assembled in the radiation field.

To provide a uniform basis for the dose estimates presented in this chapter, the reference MPC contents data, available HI-TRAC VW weight, etc., are set down in Table 11.3.1.

Using Table 11.3.1 data, the dose data for fuel loading (wet to dry storage) is provided in Table 11.3.2. The dose for the reverse operation (dry to wet storage) is summarized in Table 11.3.3.

For each step in Table 11.3.2, the task description, average number of personnel in direct radiation field, exposure duration in direct radiation field and average dose rate are identified. The relative locations refer to all HI-STORM FW overpacks. The dose rate location points around the transfer cask and overpack were selected based on actual experience in loading HI-STORM 100 Overpacks. Cask operators typically work with workers entering and exiting the immediate cask area. To account for this, an average number of workers and average dose rates are used. The tasks involved in each step presented in Table 11.3.2 are not provided in any specific order.