# CHAPTER 4[1] THERMAL EVALUATION

## 4.0 OVERVIEW

The HI-STORM System is designed for long-term storage of spent nuclear fuel (SNF) in a vertical orientation. An array of HI-STORM Systems laid out in a rectilinear pattern will be stored on a concrete ISFSI pad in an open environment. In this section, compliance of the HI-STORM thermal performance to 10CFR72 requirements for outdoor storage at an ISFSI is established. The analysis considers passive rejection of decay heat from the stored SNF assemblies to the environment under normal, off-normal, and accident conditions of storage. Effects of incident solar radiation (insolation) and partial radiation blockage due to the presence of neighboring casks at an ISFSI site are included in the analyses. Finally, the thermal margins of safety for long-term storage of both moderate burnup (up to 45,000 MWD/MTU) and high burnup spent nuclear fuel (greater than 45,000 MWD/MTU) in the HI-STORM 100 system are quantified. Safe thermal performance during on-site loading, unloading and transfer operations utilizing the HI-TRAC transfer cask is also demonstrated.

The HI-STORM thermal evaluation follows the guidelines of NUREG-1536 [4.4.1] and ISG-11 [4.1.4] to demonstrate thermal compliance of the HI-STORM system. . These guidelines provide specific limits on the permissible maximum cladding temperature in the stored commercial spent fuel (CSF)[2] and other confinement boundary components, and on the maximum permissible pressure in the confinement space under certain operating scenarios. Specifically, the requirements are:

1. The fuel cladding temperature for long-term storage shall be limited to 752°F (400°C).

2. The fuel cladding temperature for short-term operations shall be limited to 752°F (400°C) for high burnup fuel and 1058°F (570°C) for moderate burnup fuel.

3. The fuel cladding temperature should be maintained below 1058°F (570°C) for accident and off-normal event conditions.

4. The maximum internal pressure of the MPC should remain within its design pressures for normal, off-normal, and accident conditions.

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1 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 (Table 1.0.1) . This chapter has been substantially re-written in support of LAR #3 to improve clarity and to incorporate the 3-D thermal model. Because of extensive editing a clean chapter is issued with this amendment.

2 Defined as nuclear fuel that is used to produce energy in a commercial nuclear reactor (See Table 1.0.1).

4. The cask materials should be maintained within their minimum and maximum temperature criteria for normal, off-normal, and accident conditions.

5. For fuel assemblies proposed for storage, the cask system should ensure a very low probability of cladding breach during long-term storage.

6. The HI-STORM System should be passively cooled.

7. The thermal performance of the cask shall be in compliance with the design criteria specified in FSAR Chapters 1 and 2 for normal, off-normal, and accident conditions.

As demonstrated in this chapter, the HI-STORM System is designed to comply with all of the criteria listed above. Sections 4.1 through 4.3 describe thermal analyses and input data that are common to all conditions. All thermal analyses to evaluate normal conditions of storage in a HI-STORM storage module are described in Section 4.4. All thermal analyses to evaluate normal handling and on-site transfer in a HI-TRAC transfer cask are described in Section 4.5. All thermal analyses to evaluate off-normal and accident conditions are described in Section 4.6. This FSAR chapter is in full compliance with ISG-11 and with NUREG-1536 guidelines, subject to the exceptions and clarifications discussed in Chapter 1, Table 1.0.3.

The HI-STORM thermal evaluations for CSF are grouped in two categories of fuel assemblies. The two groups are classified as Low Heat Emitting (LHE) fuel assemblies and Design Basis (DB) fuel assemblies. The LHE group of fuel assemblies are characterized by low burnup, long cooling time, and short active fuel lengths. Consequently, their heat loads are dwarfed by the DB group of fuel assemblies. All Dresden-1 (6x6 and 8x8 and a thoria rod canister constituted as part of an 8x8 fuel assembly), Quad+, Humboldt Bay (7x7 and 6x6), Indian Point, Haddam Neck and all stainless-steel clad fuel assemblies are classified as LHE fuel. The low heat emitting characteristics of these fuel assemblies render them non-governing for thermal evaluation. The HI-STORM System temperatures for MPCs loaded with LHE fuel are bounded by design basis evaluations reported in this chapter.

The HI-STORM System is evaluated for two fuel storage scenarios. In one scenario, designated as uniform loading, every basket cell is assumed to be occupied with fuel producing heat at the maximum rate. As discussed in Chapter 2, this storage specification is extremely conservative, and virtually impossible to realize in actual practice. A less unrealistic, yet conservative idealization of storage scenario, designated as regionalized loading, involves defining two discrete regions within the basket. The two regions are designated as Region 1 (inner region) and Region 2 (outer region). Regionalized storage is designed to recognize storage of fuel assemblies having wide disparity in heat emission rates. For further discussion of regionalized storage, Section 2.1 of Chapter 2 should be consulted.

The HI-STORM System is designed for one reference storage condition defined in Table 4.0.1. This condition establishes the required helium backfill pressures computed later in this chapter (See Subsection 4.4.5.1). Having defined the helium backfill pressures an array of analyses are performed to evaluate the range of storage configurations specified in Chapter 2 and results reported in Section 4.4.

Table 4.0.1

REFERENCE HI-STORM OPERATING CONDITIONS

| **Condition** | **Value** |
|---|---|
| MPC Decay Heat | Table 2.1.26 |
| MPC Operating Pressure | 7 atm (absolute) |
| Normal Ambient Temperature | Table 2.2.2 |

## 4.1 DISCUSSION

The HI-STORM FSAR seeks to establish complete compliance with the provisions of ISG-11 [4.1.4]. For this purpose the HI-STORM normal storage fuel cladding temperatures are required to meet the 752°F (400°C) temperature limit for all CSF (See Section 4.3). Additionally, when the MPCs are deployed for storing High Burnup Fuel (HBF) further restrictions during certain fuel loading activities (vacuum drying) are set forth 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 (see Table 4.3.1).

Potential thermally challenging states for the spent fuel arise if the fuel drying process utilizes the pressure reduction process (i.e., vacuum drying). The short-term evolutions that may be thermally limiting and warrant analysis are:

i. Vacuum Drying
ii. Loaded MPC in HI-TRAC in the Vertical Orientation

The threshold MPC heat generation rate at which the HI-STORM peak cladding temperature reaches a steady state equilibrium value approaching the normal storage peak clad temperature limit is computed in this chapter. Likewise, the MPC heat generation rates that produce the steady state equilibrium temperature approaching the normal storage peak clad temperature limit for the MPC in HI-TRAC are computed in this chapter. These computed heat generation rates directly bear upon the compliance of the system with ISG-11 [4.1.4] and are, accordingly, adopted in the system Technical Specifications for high burnup fuel (HBF).

The aboveground HI-STORM system consists of a sealed MPC situated inside a vertically-oriented, ventilated storage overpack. Air inlet and outlet ducts that allow for air cooling of the stored MPC are located at the bottom and top, respectively, of the cylindrical overpack. The SNF assemblies reside inside the MPC, which is sealed with a welded lid to form the confinement boundary. The MPC contains a stainless-steel honeycomb fuel basket structure with square-shaped compartments of appropriate dimensions to allow insertion of the fuel assemblies prior to welding of the MPC lid and closure ring. Each fuel basket panel, with the exception of exterior panels on the MPC-68 and MPC-32, is equipped with a thermal neutron absorber panel sandwiched between an Alloy X steel sheathing plate and the fuel basket panel, along the entire length of the active fuel region. The MPC is backfilled with helium up to the design-basis initial fill level (Table 1.2.2). This provides a stable, inert environment for long-term storage of the SNF. Heat is rejected from the SNF in the HI-STORM System to the environment by passive heat transport mechanisms only.

The helium backfill gas plays an important role in the MPC's thermal performance. The helium fills all the spaces between solid components and provides an improved conduction medium (compared to air) for dissipating decay heat in the MPC. Within the MPC the pressurized helium environment sustains a closed loop thermosiphon action, removing SNF heat by an upward flow of helium through the storage cells. This MPC internal convection heat dissipation mechanism is illustrated in

Figure 4.1.1. On the outside of the MPC a ducted overpack construction with a vertical annulus facilitates an upward flow of air by buoyancy forces. The annulus ventilation flow cools the hot MPC surfaces and safely transports heat to the outside environment. The annulus ventilation cooling mechanism is illustrated in Figure 4.1.2. To ensure that the helium gas is retained and is not diluted by lower conductivity air, the MPC confinement boundary is designed and fabricated in accordance with the ASME B&PV Code Section III, Subsection NB as an all-seal-welded pressure vessel with redundant closures. It is demonstrated in Section 11.1.3 that the failure of one field-welded pressure boundary seal will not result in a breach of the pressure boundary. The helium gas is therefore assumed to be retained in an undiluted state, and may be credited in the thermal analyses.

An important thermal design criterion imposed on the HI-STORM System is to limit the maximum fuel cladding temperature to within design basis limits (Table 4.3.1) for long-term storage of design basis SNF assemblies. An equally important requirement is to minimize temperature gradients in the MPC so as to minimize thermal stresses. In order to meet these design objectives, the MPC baskets are designed to possess certain distinctive characteristics, which are summarized in the following.

The MPC design minimizes resistance to heat transfer within the basket and basket periphery regions. This is ensured by an uninterrupted panel-to-panel connectivity realized in the all-welded honeycomb basket structure. The MPC design incorporates top and bottom plenums with interconnected downcomer paths. The top plenum is formed by the gap between the bottom of the MPC lid and the top of the honeycomb fuel basket, and by elongated semicircular holes in each basket cell wall. The bottom plenum is formed by large elongated semicircular holes at the base of all cell walls. The MPC basket is designed to eliminate structural discontinuities (i.e., gaps) which introduce added thermal resistances to heat flow. Consequently, temperature gradients are minimized in the design, which results in lower thermal stresses within the basket. Low thermal stresses are also ensured by an MPC design that permits unrestrained axial and radial growth of the basket. The possibility of 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 MPCs design maximum decay heat loads for storage of zircaloy clad fuel are listed in Table 4.0.1. Storage of stainless steel clad fuel is permitted for a low decay heat limit set forth in Chapter 2 (Tables 2.1.17 through 2.1.24). Storage of zircaloy clad fuel with stainless steel clad fuel in an MPC is permitted. In this scenario, the zircaloy clad fuel must meet the lower decay heat limits for stainless steel clad fuel. 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 Table 2.1.11).

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

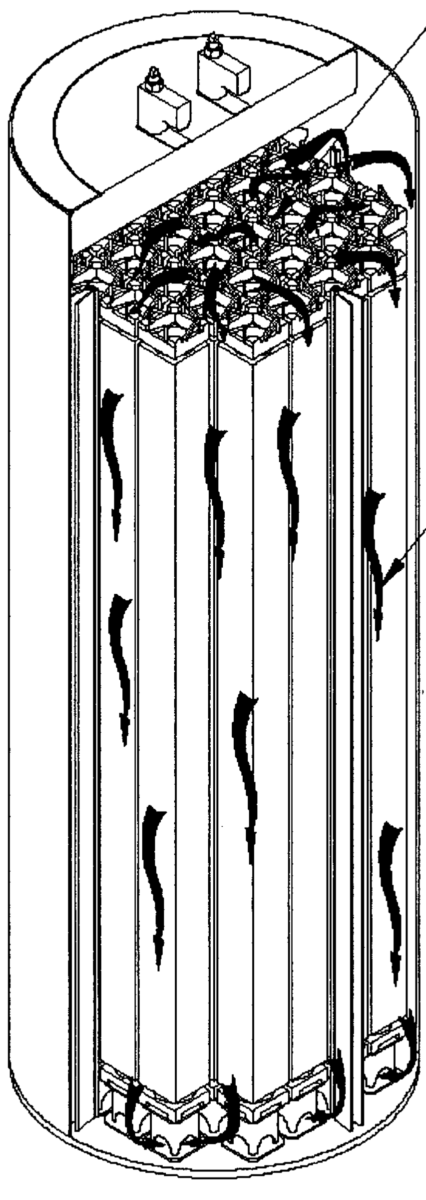


FIGURE 4.1.1: MPC INTERNAL HELIUM CIRCULATION

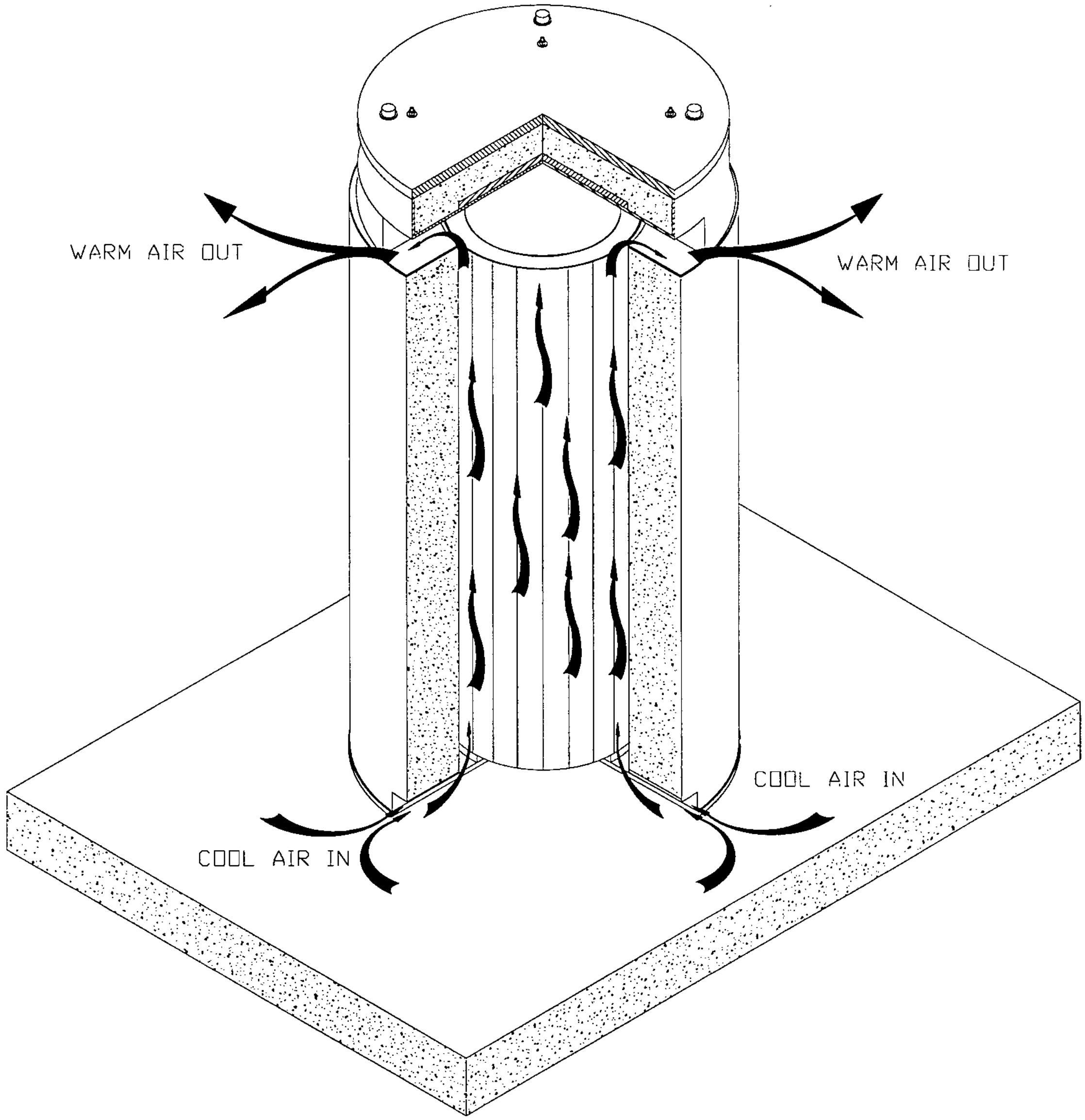


FIGURE 4.1.2: VENTILATION COOLING OF A HI-STORM SYSTEM

## 4.2 SUMMARY OF THERMAL PROPERTIES OF MATERIALS

Materials present in the MPCs include stainless steels (Alloy X), neutron absorber (Boral or METAMIC) and helium. Materials present in the HI-STORM storage overpack include carbon steels and concrete. Materials present in the HI-TRAC transfer cask include carbon steel, lead, Holtite-A neutron shield, paints (See Appendix 1.C) and demineralized water. In Table 4.2.1, a summary of references used to obtain cask material properties for performing all thermal analyses is presented.

Individual thermal conductivities of the alloys that comprise the Alloy X materials and the bounding Alloy X thermal conductivity are reported in Appendix 1.A of this report. Tables 4.2.2 and 4.2.3 provide numerical thermal conductivity data of materials at several representative temperatures. The currently approved neutron absorber materials, (Boral™ and Metamic™) are both made of aluminum powder and boron carbide powder. Although their manufacturing processes differ, from a thermal standpoint, their ability to conduct heat is virtually identical. Therefore, the values of conductivity of the original neutron absorber (Boral) continue to be used in the thermal calculations.

For the HI-STORM overpack, the thermal conductivity of concrete and the emissivity/absorptivity of painted surfaces are particularly important. Recognizing the considerable variations in reported values for these properties, the values that are conservative with respect to both authoritative references and values used in analyses on previously licensed cask dockets have been selected. Specific discussions of the conservatism of the selected values are included in the following paragraphs.

As specified in Table 4.2.1, the concrete thermal conductivity is taken from Marks' Standard Handbook for Mechanical Engineers, which is conservative compared to a variety of recognized concrete codes and references. Neville, in his book "Properties of Concrete" ($4^{th}$ Edition, 1996), gives concrete conductivity values as high as 2.1 Btu/(hr×ft×°F). For concrete with siliceous aggregates, the type to be used in HI-STORM overpacks, Neville reports conductivities of at least 1.2 Btu/(hr×ft×°F). Data from Loudon and Stacey, extracted from Neville, reports conductivities of 0.980 to 1.310 Btu/(hr×ft×°F) for normal weight concrete protected from the weather. ACI-207.1R provides thermal conductivity values for seventeen structures (mostly dams) at temperatures from 50-150°F. Every thermal conductivity value reported in ACI-207.1R is greater than the value used in the HI-STORM thermal analyses. Additionally, the NRC has previously approved analyses that use higher conductivity values than those applied in the HI-STORM thermal analysis. For example, thermal calculations for the NRC approved Vectra NUHOMS cask system (June 1996, Rev. 4A) used thermal conductivities as high as 1.17 Btu/(hr×ft×°F) at 100°F. Based on these considerations, the concrete thermal conductivity value chosen for HI-STORM thermal analyses is considered to be conservative.

Holtite-A is a composite material consisting of approximately 37 wt% epoxy polymer, 1 wt% $B_4C$ and 62 wt% aluminum trihydrate. While polymers are generally characterized by a low conductivity (0.05 to 0.2 Btu/ft-hr-°F), the addition of fillers in substantial amounts can raise the mixture conductivity by up to a factor of ten. The thermal conductivity of epoxy filled resins with alumina is reported in the technical literature[1] as approximately 0.5 Btu/ft-hr-°F and higher. A conservatively postulated conductivity of 0.3 Btu/ft-hr-°F is used in the thermal models for the neutron shield region[2] (in the HI-TRAC transfer cask). As the thermal inertia of the neutron shield is not credited in the analyses, the density and heat capacity properties are not reported herein.

Surface emissivity data for key materials of construction are provided in Table 4.2.4. The emissivity properties of painted external surfaces are generally excellent. Kern [4.2.5] reports an emissivity range of 0.8 to 0.98 for a wide variety of paints. In the HI-STORM thermal analysis, an emissivity of 0.85[3] is applied to painted surfaces. A conservative solar absorptivity coefficient of 1.0 is applied to all exposed overpack surfaces.

In Table 4.2.5, the heat capacity and density of the MPC, overpack and CSF materials are presented. These properties are used in performing transient (i.e., hypothetical fire accident condition) analyses. The temperature-dependent values of the viscosities of helium and air are provided in Table 4.2.6.

The heat transfer coefficient for exposed surfaces is calculated by accounting for both natural convection and thermal radiation heat transfer. The natural convection coefficient depends upon the product of Grashof (Gr) and Prandtl (Pr) numbers. Following the approach developed by Jakob and Hawkins [4.2.9], the product Gr×Pr is expressed as $L^3\Delta TZ$, where L is height of the overpack, $\Delta T$ is overpack surface temperature differential and Z is a parameter based on air properties, which are known functions of temperature, evaluated at the average film temperature. The temperature-dependent values of Z are provided in Table 4.2.7.

1 "Principles of Polymer Systems", F. Rodriguez, Hemisphere Publishing Company (Chapter 10).
2 The thermal conductivity value used in the thermal models for the neutron shield region is confirmed to be bounded by the Holtite-A test data [4.2.13] with a margin.
3 This is conservative with respect to prior cask industry practice, which has historically utilized higher emissivities [4.2.16].

Table 4.2.1

SUMMARY OF HI-STORM 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 [4.2.6] | Rust [4.2.4] | Rust [4.2.4] |
| $UO_2$ | Note 1 | NUREG [4.2.6] | Rust [4.2.4] | Rust [4.2.4] |
| Stainless Steel (machined forgings)[4] | Kern [4.2.5] | ASME [4.2.8] | Marks' [4.2.1] | Marks' [4.2.1] |
| Stainless Steel Plates[5] | 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] |
| Boral | Note 1 | Test Data (Note 2) | Test Data (Note 2) | Test Data (Note 2) |
| Holtite-A | Note 1 | [4.2.13] | Not Used | Not Used |
| Concrete | Note 1 | Marks' [4.2.1] | Appendix 1.D | 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 | Note 1 | Test Data [4.2.14], [4.2.15] | Test Data [4.2.14], [4.2.15] | Test Data [4.2.14], [4.2.15] |

Note 1: Emissivity not reported as radiation heat dissipation from these surfaces is conservatively neglected.
Note 2: AAR Structures Boral thermophysical test data.

4 Used in the top lid of the MPC.
5 Used in the basket panels, neutron absorber sheathing, MPC shell, and MPC baseplate.

Table 4.2.2

SUMMARY OF HI-STORM 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 |

* 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.

Table 4.2.3

SUMMARY OF FUEL ELEMENT COMPONENTS
THERMAL CONDUCTIVITY DATA

| Zircaloy Cladding | | Fuel ($UO_2$) | |
|---|---|---|---|
| Temperature (°F) | Conductivity (Btu/ft-hr-°F) | Temperature (°F) | Conductivity (Btu/ft-hr-°F) |
| 392 | 8.28* | 100 | 3.48 |
| 572 | 8.76 | 448 | 3.48 |
| 752 | 9.60 | 570 | 3.24 |
| 932 | 10.44 | 793 | 2.28* |

* Lowest values of conductivity used in the thermal analyses for conservatism.

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 |

* See Table 4.2.1 for cited references.

** Lowerbound value from the cited references in Table 4.2.1.

Table 4.2.5

DENSITY AND HEAT CAPACITY PROPERTIES SUMMARY*

| Material | Density ($lbm/ft^3$) | Heat Capacity (Btu/lbm-°F) |
|---|---|---|
| Helium | (Ideal Gas Law) | 1.24 |
| Zircaloy | 409 | 0.0728 |
| Fuel ($UO_2$) | 684 | 0.056 |
| Carbon steel | 489 | 0.1 |
| Stainless steel | 501 | 0.12 |
| Boral | 154.7 | 0.13 |
| Concrete | 140** | 0.156 |
| Lead | 710 | 0.031 |
| Water | 62.4 | 0.999 |
| METAMIC | 163.4** | 0.22** |

* See Table 4.2.1 for cited references.

** Lowerbound values reported for conservatism.

Table 4.2.6

GASES VISCOSITY* VARIATION WITH TEMPERATURE

| **Temperature (°F)** | **Helium Viscosity (Micropoise)** | **Temperature (°F)** | **Air Viscosity (Micropoise)** |
|---|---|---|---|
| 167.4 | 220.5 | 32.0 | 172.0 |
| 200.3 | 228.2 | 70.5 | 182.4 |
| 297.4 | 250.6 | 260.3 | 229.4 |
| 346.9 | 261.8 | 338.4 | 246.3 |
| 463.0 | 288.7 | 567.1 | 293.0 |
| 537.8 | 299.8 | 701.6 | 316.7 |
| 737.6 | 338.8 | 1078.2 | 377.6 |
| 921.2 | 373.0 | - | - |
| 1126.4 | 409.3 | - | - |
| * Obtained from Rohsenow and Hartnett [4.2.2]. | | | |

Table 4.2.7

VARIATION OF NATURAL CONVECTION PROPERTIES
PARAMETER "Z" FOR AIR WITH TEMPERATURE

| **Temperature (°F)** | **Z ($ft^{-3}$°$F^{-1}$)*** |
|---|---|
| 40 | $2.1 \times 10^6$ |
| 140 | $9.0 \times 10^5$ |
| 240 | $4.6 \times 10^5$ |
| 340 | $2.6 \times 10^5$ |
| 440 | $1.5 \times 10^5$ |
| * Obtained from Jakob and Hawkins [4.2.9] | |

## 4.3 SPECIFICATIONS FOR COMPONENTS

HI-STORM System materials and components designated as "Important to Safety" (i.e., required to be maintained within their safe operating temperature ranges to ensure their intended function) which warrant special attention are summarized in Table 4.3.1. The neutron shielding ability of Holtite-A neutron shield material used in the HI-TRAC transfer cask is ensured by demonstrating that the material exposure temperatures are maintained below the maximum allowable limit. Long-term integrity of SNF is ensured by the HI-STORM System thermal evaluation which demonstrates that fuel cladding temperatures are maintained below design basis limits. Neutron absorber materials used in MPC baskets for criticality control (made from $B_4C$ and aluminum) are stable in excess of 1000°F[1]. Accordingly 1000°F is conservatively adopted as the short-term temperature limit for neutron absorber materials. The overpack concrete, the primary function of which is shielding, will maintain its structural, thermal and shielding properties provided that American Concrete Institute (ACI) guidance on temperature limits (see Appendix 1.D) is followed.

Compliance to 10CFR72 requires, in part, identification and evaluation of short-term off-normal and severe hypothetical accident conditions. The inherent mechanical characteristics of cask materials and components ensure that no significant functional degradation is possible due to exposure to short-term temperature excursions outside the normal long-term temperature limits. For evaluation of HI-STORM System thermal performance, material temperature limits for long-term normal, short-term operations, and off-normal and accident conditions are provided in Table 4.3.1. In Table 4.3.1, ISG-11 [4.1.4] temperature limits are adopted for Commercial Spent Fuel (CSF). These limits are applicable to all fuel types, burnup levels and cladding materials approved by the NRC for power generation.

### 4.3.1 Evaluation of Moderate Burnup Fuel

It is recognized that hydrides present in irradiated fuel rods (predominantly circumferentially oriented) dissolve at cladding temperatures above 400°C [4.3.1]. Upon cooling below a threshold temperature ($T_p$), the hydrides precipitate and reorient to an undesirable (radial) direction if cladding stresses at the hydride precipitation temperature $T_p$ are excessive. For moderate burnup fuel, $T_p$ is conservatively estimated as 350°C [4.3.1]. In a recent study, PNNL has evaluated a number of bounding fuel rods for reorientation under hydride precipitation temperatures for MBF [4.3.1]. The study concludes that hydride reorientation is not credible during short-term operations involving low to moderate burnup fuel (up to 45 GWD/MTU). Accordingly, the higher ISG-11 temperature limit is justified for moderate burnup fuel and is adopted in the HI-STORM FSAR for short-term operations for MBF fueled MPCs (see Table 4.3.1).

1 $B_4C$ is a refractory material that is unaffected by high temperature (on the order of 1000°F) and aluminum is solid at temperatures in excess of 1000°F.

Table 4.3.1

HI-STORM SYSTEM MATERIAL TEMPERATURE LIMITS[2]

| Material | Normal Long-Term Temperature Limits [°F] | Short-Term Temperature Limits [°F] |
|---|---|---|
| CSF cladding (zirconium alloys and stainless steel) | 752 | Short-Term Operations<br>752 (HBF)<br>1058 (MBF)<br>Off-Normal and Accident<br>1058 |
| Neutron Absorber | 800 | 1000 |
| Holtite-A[3] | N/A (Not Used) | 350 (Short Term Operations) |
| Concrete[4] | 300 | 350 |
| Water | N/A | 307[5] (Short Term Operations)<br>N/A (Off-Normal and Accident) |

2 This table specifies temperature limits for non-ASME Code materials. Temperature limits of ASME Code materials (structural steels) are specified in Table 2.2.3.

3 See Chapter 1, Appendix 1.B.

4 These values are applicable for concrete in the overpack body, overpack lid and overpack pedestal. As stated in Chapter 1 (Appendix 1.D), these limits are compared to the through-thickness section average temperature.

5 Saturation temperature at HI-TRAC water jacket design pressure specified in Table 2.2.1.

## 4.4 THERMAL EVALUATION FOR NORMAL CONDITIONS OF STORAGE

The HI-STORM System (i.e., HI-STORM overpack, HI-TRAC transfer cask and MPC) 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 overpack and HI-TRAC transfer cask are constructed to evaluate fuel integrity under normal (long-term storage), off-normal and accident conditions and in the HI-TRAC transfer cask under short-term operation and hypothetical accidents. The thermal models incorporate an array of conservatisms to ensure robustly bounding thermal solutions. The principal features of these models are described in this section for HI-STORM and Section 4.5 for HI-TRAC. Thermal analysis results for the long-term storage scenarios are obtained and reported in this section.

### 4.4.1 Overview of the Thermal Model

The MPC basket design consists of four distinct geometries to hold 24 or 32 PWR, or 68 BWR fuel assemblies. 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 stainless steel (Alloy X) plates with full-length edge-welded intersections to form an integral basket configuration. All individual cell walls, except outer periphery cell walls in the MPC-68 and MPC-32, are provided with neutron absorber plates sandwiched between the box wall and a stainless steel sheathing plate over the full length of the active fuel region. The neutron absorber plates used in all MPCs are made of an aluminum-based, boron carbide-containing material to provide criticality control, while maximizing heat conduction capabilities.

Thermal analysis of the HI-STORM System is performed for an array of limiting heat load scenarios defined in Chapter 2 for uniform and regionalized fuel loading (wherein each fuel assembly in a region is assumed to be generating heat at the maximum permissible rate). 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 casks because it is unlikely that any basket would be loaded with fuel emitting heat at their limiting values (see for example a fuel loading scenario discussed in Section 2.1). The principal attributes of the thermal model are described in the following:

i. While the rate of heat conduction through metals is a relatively weak function of temperature, radiation heat exchange is a highly nonlinear function of surface temperatures.

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

iii. Inasmuch as the transfer of heat occurs from inside the basket region to the outside, the temperature field in the MPC is spatially distributed with the maximum values reached in the central core region.

4.4.1.1 Description of the 3-D Thermal Model

i. Introduction

The interior of the MPC is a 3-D array of square shaped cells inside an irregularly shaped basket outline confined inside the cylindrical space of the MPC cavity. To ensure an adequate representation of these features, a 3-D geometric model of the MPC is constructed using the FLUENT CFD code pre-processor [4.1.2]. Other than representing the composite cell walls (made up of Alloy X panels, neutron absorber panels and Alloy X sheathing) by a homogeneous panel with equivalent orthotropic (thru-thickness and parallel plates direction) thermal conductivities, the 3-D model requires no idealizations of the fuel basket structure. Further, since it is impractical to model every fuel rod in every stored fuel assembly explicitly, the cross section bounded by the inside of the storage cell (inside of the fuel channel in the case of BWR MPCs), which surrounds the assemblage of fuel rods and the interstitial helium gas (also called the "rodded region"), is replaced with an "equivalent" square homogeneous section characterized by an effective thermal conductivity. Homogenization of the storage cell cross-section is illustrated in Figure 4.4.1. As the effective conductivity of the rodded region includes radiation heat transfer the conductivities will be a strong function of temperature because radiation heat transfer (a major component of the heat transport between the fuel rods and the surrounding basket cell metal) rises as the fourth power of absolute temperature. Therefore, in effect, the effective conductivity of the equivalent square section (depending on the coincident temperature) will be different throughout the basket. For thermal-hydraulic simulation, each fuel assembly in its storage cell is represented by an equivalent porous medium. For BWR fuel, the presence of the fuel channel divides the storage cell space into two distinct axial flow regions, namely, the in-channel (rodded) region and the square prismatic annulus region (in the case of PWR fuel this modeling complication does not exist).

ii. Details of the 3-D Model

The 3-D model implemented to analyze the HI-STORM system has the following key attributes:

a. As mentioned above, the composite walls in the fuel basket consisting of the Alloy X structural panels, the aluminum-based neutron absorber, and the Alloy X sheathing, are represented by an orthotropic homogeneous panel of equivalent thermal conductivity in the three principal directions. The in-plane and thru-thickness thermal conductivities of the composite wall are computed using a standard procedure for such shapes with certain conservatisms, as described below.

   During fabrication, a uniform normal pressure is applied to each "Box Wall - Neutron Absorber - Sheathing" sandwich in the assembly fixture during welding of the sheathing periphery on the box wall. This ensures adequate surface-to-surface contact between the neutron absorber and the adjacent Alloy X surfaces. The mean coefficient of linear expansion of the neutron absorber is higher than the thermal expansion coefficients of the basket and sheathing materials. Consequently, basket heat-up from the stored SNF will further ensure a tight fit of the neutron absorber plate in the sheathing-to-box pocket. Nevertheless the possible presence of small microscopic gaps due to less than perfect surface-to-surface contact requires consideration of an interfacial contact resistance between the neutron absorber and box-sheathing surfaces. In the thermal analysis a 2 mil neutron absorber to pocket gap has been used. This is conservative as the sandwich is engineered to ensure an essentially no-gap fitup and assembly of the neutron-absorber panels. Furthermore, no credit is taken for radiative heat exchange across the neutron absorber to sheathing or neutron absorber to box wall gaps.

The heat conduction properties of the composite "Box Wall - Neutron Absorber - Sheathing" sandwich panels in the two principal basket cross sectional directions (i.e., thru-thickness and parallel plates direction) are unequal. In the thru-thickness direction, heat is transported across layers of sheathing, helium-gap, neutron absorber and box wall resistances that are essentially in series. Heat conduction in the parallel plates direction, in contrast, is through an array of essentially parallel resistances comprised of these several layers listed above. In this manner the composite walls of the fuel basket storage cells are replaced with a solid wall of equivalent through thickness and parallel plates direction conductivities. Table 4.4.1 provides the values of the conductivities as a function of temperature for the different MPC types.

b. In the case of a BWR CSF, the fuel bundle and the small surrounding spaces inside the fuel "channel" are replaced by an equivalent porous media having the flow impedance properties computed using a conservatively articulated 3-D CFD model [4.4.2]. The space between the BWR fuel channel and the storage cell is represented as an open flow annulus. The fuel channel is also explicitly modeled. The porous medium within the channel space is also referred to as the "rodded region". The fuel assembly is assumed to be positioned coaxially with respect to its storage cell. The 3-D model of an MPC-68 storage cell occupied with channeled BWR fuel is shown in Figure 4.4.4.

In the case of the PWR CSF, the porous medium extends to the entire cross-section of the storage cell. As described in [4.4.2], the CFD model for both the BWR and PWR case is prepared for the Design Basis fuel in comprehensive detail, which includes grid straps, BWR water rods and PWR guide and instrument tubes (assumed to be plugged for conservatism).

c. Every MPC fuel storage cell is assumed to be occupied by design basis PWR or BWR fuel assemblies specified in Chapter 2 (Table 2.1.5). The in-plane thermal conductivity of the design basis fuel assemblies are obtained using ANSYS [4.1.1] finite element models of an array of fuel rods enclosed by a square box. Radiation heat transfer from solid surfaces (cladding and box walls) are enabled in these models. Using these models the effective conduction-radiation conductivities are obtained and reported in Table 4.4.2. For heat transfer in the axial direction an area weighted mean of cladding and helium conductivities are computed (see Table 4.4.2). Axial conduction heat transfer in the fuel pellets and radiation heat dissipation in the axial direction are conservatively ignored. Thus, the thermal conductivity of the rodded region, like the porous media simulation for helium flow, is represented by a 3-D continuum having effective planar and axial conductivities.

d. The internals of the MPC, including the basket cross section, bottom mouse holes, top plenum, and circumferentially irregular downcomer are modeled explicitly. For simplicity, the mouse holes are modeled as rectangular openings with understated flow area.

e. The inlet and outlet vents in the HI-STORM overpack are modeled explicitly to incorporate any effects of non-axisymmetry of inlet air passages on the system's thermal performance.

f. The air flow in the HI-STORM/MPC annulus is simulated by a k-ω turbulence model with the transitional option enabled.

The 3-D model described above is illustrated in the cross section for the MPC-68 in Figure 4.4.3. A closeup of the fuel cell spaces which explicitly include the channel-to-cell gap in the 3-D model is shown in Figure 4.4.4. The principal 3-D modeling conservatisms are listed below:

1) The storage cell spaces are loaded with design basis fuel having the highest axial flow resistance (See Table 2.1.5 ).
2) Each storage cell is generating heat at its limiting value under uniform or regionalized storage scenarios as defined in Chapter 2, Section 2.1.
3) Axial dissipation of heat by the fuel pellets is neglected.
4) Axial dissipation of heat by radiation in the fuel bundle 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) The absorbtivity of the external surfaces of the HI-STORM is conservatively assumed to be unity.
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) Fuel basket and MPC shell emissivities are understated (see Table 4.2.4).
12) The k-ω model used for simulating the HI-STORM annulus flow yields uniformly conservative results [4.1.6].

The effect of crud resistance on fuel cladding surfaces has been evaluated and found to be negligible. 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 very small amount (~0.1°F). Accordingly this effect is neglected in the thermal evaluations.

4.4.1.2 Fuel Assembly 3-Zone Flow Resistance Model

The HI-STORM System is evaluated for storage of bounding PWR (W-17x17) and BWR (GE-10x10) fuel assemblies. During fuel storage helium enters the MPC fuel cells from the bottom plenum and flows upwards through the open spaces in the fuel storage cells and exits in the top plenum. Because of the low flow velocities the helium flow in the fuel storage cells and MPC spaces is in the deep laminar regime (Re < 100). The bottom and top plenums are essentially open spaces engineered in the fuel basket ends to facilitate helium circulation. In the case of BWR fuel storage, a channel enveloping the fuel bundle divides the flow in two parallel paths. One flow path is through the in-channel or rodded region of the storage cell and the other flow path is in the square annulus area outside the channel. In the global thermal modeling of the HI-STORM System the following approach is adopted:

(i) In BWR fueled MPCs an explicit channel-to-cell gap is modeled.
(ii) The fuel assembly enclosed in a square envelope (fuel channel for BWR fuel or fuel storage cell for PWR fuel) is replaced by porous media with equivalent flow resistance.

The above modeling approach is illustrated in Figure 4.4.4.

In the FLUENT program, porous media flow resistance is modeled as follows:

$$\Delta P = D\mu VL \qquad \text{(Eq. 1)}$$

where $\Delta P$ is the hydraulic pressure loss, D is the flow resistance coefficient, $\mu$ is the fluid viscosity, V is the superficial fluid velocity and L is the porous media length. In the HI-STORM thermal models the fuel storage cell length between the bottom and top plenums[1] is replaced by porous media. As discussed below the porous media length is partitioned in three zones with discrete flow resistances.

To characterize the flow resistance of fuel assemblies inside square envelopes (fuel channel for BWR fuel or fuel storage cell for PWR fuel) 3D models of W-17x17 and GE-10x10 fuel assemblies are constructed using the FLUENT CFD program. These models are embedded with several pessimistic assumptions to overstate flow resistance. These are:

(a) Water rods (BWR fuel) and guide tubes (PWR fuel) are assumed to be completely blocked
(b) Fuel rods assumed to be full length
(c) Channel length (BWR fuel) overstated
(d) Bounding grid thickness used
(e) Bottom fittings resistance overstated
(f) Bottom nozzle lateral flow holes (BWR fuel) assumed to be blocked

Using the 3D fuel assembly models flow solutions under an impressed pressure differential between the two extremities of the fuel storage cell are computed at reference conditions (7 atmosphere

1 These are the mousehole openings at the ends of the fuel basket to facilitate helium circulation. The mouseholes are explicitly included in the 3D thermal models with an understated flow area.

absolute pressure and 450°F temperature). The results of the 3D flow solutions are post-processed as described next and equivalent porous media flow resistances obtained.

Because of the narrow flow passages in the bare rods and gridded regions of the fuel assembly the flow resistance of the fueled length to axial helium flow is greater than the flow resistance from the fuel assembly ends (bottom nozzle, top fitting, handle etc.). This physical fact is duly recognized by defining three distinct axial zones as follows:

Zone 1: Length below the active fuel region
Zone 2: Active fuel region
Zone 3: Length above the active fuel region

In the 3-Zone flow resistance modeling, the flow resistance of each zone is characterized by post-processing the 3D fuel flow model solutions. For this purpose two approaches to flow resistance characterization are adopted. The first approach is the pressure drop method. This method is suitable when a zone is characterized by irregular geometries and the objective is to obtain a lumped resistance to duplicate the pressure drop. The second method is the shear stress method, which is suitable for flow zones characterized by regular geometries. For the 3-Zone flow resistance modeling the pressure drop method is adopted for the inactive regions (Zone 1 and Zone 3). The flow resistance coefficients are computed by post-processing the fuel assemblies 3D model flow solutions as follows:

Step 1: Obtain the helium volumetric flow Q under the impressed pressure differential.
Step 2: Compute helium superficial velocity, V = Q/A where A is the square envelope cross-sectional area.
Step 3: Obtain the individual Zone 1 and Zone 3 lengths ($L_1$ and $L_3$) and pressure drops ($\Delta P_1$ and $\Delta P_3$) from the FLUENT solutions.
Step 4: Compute Zone 1 and Zone 3 resistance coefficients $D_1$ and $D_3$ using Eq. 1, V, $L_1$, $L_3$, $\Delta P_1$ and $\Delta P_3$ from above steps.

The shear stress method is suitable for the active fuel region (Zone 2) as this region is characterized by an ordered array of entities (rods and grids). This method uses area averaged wall shear stresses post-processed from the active region (Zone 2) of the fuel assembly. Using hydraulic flow principles the wall shear stresses are mapped to flow resistance coefficients. To account for geometric discontinuities the active fuel region is sliced in a suitable number of constant geometry (bare rods and grids) sub-regions. Based on the fuel bundle layout, a total of 17 slices are identified for GE-10x10 fuel and 20 slices for W-17x17 fuel. In each sub-region an area averaged shear stress over all wetted surfaces (fuel rods, non-fuel rods, square envelope and grids) is post-processed and flow resistance coefficients of each slice are computed. The flow resistance of Zone 2 is obtained by computing the length-weighted average of the slice resistance coefficients.

4.4.2 [deleted]

4.4.3 Test Model

The HI-STORM thermal analysis is performed on the FLUENT [4.1.2] Computational Fluid Dynamics (CFD) program. To ensure a high degree of confidence in the HI-STORM thermal evaluations, the FLUENT code is benchmarked using data from tests conducted with casks loaded with irradiated SNF ([4.1.3],[4.1.7]). The benchmark work is archived in QA validated Holtec reports ([4.1.5],[4.1.6]).These evaluations show that the FLUENT solutions are conservative in all cases. In view of these considerations, additional experimental verification of the thermal design is not necessary.

4.4.4 Maximum and Minimum Temperatures

4.4.4.1 Maximum Temperatures

The 3-D model from the previous subsection is used to determine temperature distributions under long-term normal storage conditions for an array of cases covering PWR and BWR fuel storage in uniform and regionalized loading configurations. For this purpose one bounding MPC design in each of the two fuel classes – MPC-68 for BWR and MPC-32 for PWR – are analyzed and results obtained and summarized in this subsection. For a bounding evaluation the MPCs are assumed to be emplaced in a limiting overpack (HI-STORM 100S Version B).

The HI-STORM 100S Version B is the limiting overpack by virtue of the inlet and outlet vents design. Compared to two other overpack designs (i.e., HI-STORM 100 and HI-STORM 100S), the HI-STORM 100S Version B has smaller inlet and outlet vents. Thus Version B vent airflow resistances are bounding. Also, the HI-STORM 100S Version B is the shortest of the overpacks. This reduces the chimney height which minimizes the driving head for air flow. Because the HI-STORM 100S Version B will have the least cooling air flow, it will yield bounding results.

A cross-reference of HI-STORM thermal analyses is provided in Table 4.4.5. Under regionalized loading, an array of runs covering a range of regionalized storage configurations specified in Chapter 2 (X=0.5 to X=3) are analyzed. The results are graphed in Figures 4.4.6 and 4.4.7 for PWR and BWR fuel storage respectively. Based on this array of runs the fuel storage condition corresponding to X = 0.5 is determined to be limiting for both PWR and BWR MPCs. Accordingly HI-STORM MPC and overpack temperatures are reported for this storage condition in Tables 4.4.6 and 4.4.7.

It should be noted that the 3-D FLUENT cask model incorporates the effective conductivity of the fuel assembly submodell. 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 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 storage scenarios (uniform and regionalized) in all MPCs.
- The maximum temperature of the basket structural materials are within their design limits.
- The maximum temperature of the neutron absorbers are below their design limits.
- The maximum temperatures of the MPC pressure boundary materials are below their design limits.
- The maximum temperatures of concrete is within the guidance of the governing ACI Code (see Table 4.3.1).

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

4.4.4.2 Minimum Temperatures

In Table 2.2.2 of this report, the minimum ambient temperature condition for the HI-STORM storage overpack and MPC is specified to be -40°F. If, conservatively, a zero decay heat load with no solar input is applied to the stored fuel assemblies, then every component of the system at steady state would be at a temperature of -40°F. Low service temperature (-40°F) evaluation of the HI-STORM is provided in Chapter 3. All HI-STORM storage overpack and MPC materials of construction will satisfactorily perform their intended function in the storage mode at this minimum temperature condition.

4.4.4.3 Effects of Elevation

The reduced ambient pressure at site elevations significantly above the sea level will act to reduce the ventilation air mass flow, resulting in a net elevation of the peak cladding temperature. However, the ambient temperature (i.e., temperature of the feed air entering the overpack) also drops with the increase in elevation. Because the peak cladding temperature also depends on the feed air temperature (the effect is one-for-one within a small range, i.e., 1°F drop in the feed air temperature results in ~1°F drop in the peak cladding temperature), the adverse ambient pressure effect of increased elevation is partially offset by the ambient air temperature decrease. The table below illustrates the variation of air pressure and corresponding ambient temperature as a function of elevation.

| Elevation (ft) | Pressure (psia) | Ambient Temperature Reduction versus Sea Level |
|---|---|---|
| Sea Level (0) | 14.70 | 0°F |
| 2000 | 13.66 | 7.1°F |
| 4000 | 12.69 | 14.3°F |

A survey of the elevation of nuclear plants in the U.S. shows that nuclear plants are situated near about sea level or elevated slightly (~1000 ft). The effect of the elevation on peak fuel cladding temperatures is evaluated by performing calculations for a HI-STORM 100 System situated at an elevation of 1500 feet. At this elevation the ambient temperature would decrease by approximately 5°F (See Table above). The peak cladding temperatures are calculated for a bounding configuration (non-uniform storage at X = 0.5), and conservatively assuming no reduction in ambient temperature using the 3D model described in Subsection 4.4.1.1 and compared to the sea level conditions. The results are given in the following table.

| MPC Design | PCT at Sea Level | PCT at 1500 feet |
|---|---|---|
| MPC-68 BWR | 711.4°F | 723.8°F |
| MPC-32 PWR | 697.1°F | 718.2°F |

These results show that the PCT, including the effects of site elevation, continues to be well below the regulatory cladding temperature limit of 752°F. In light of the above evaluation, it is not necessary to place any ISFSI elevation constraints for HI-STORM deployment at elevations up to 1500 feet. If, however, an ISFSI is sited at an elevation greater than 1500 feet, the effect of altitude on the PCT shall be quantified as part of the 10 CFR 72.212 evaluation for the site using the site ambient conditions.

### 4.4.5 Maximum Internal Pressure

#### 4.4.5.1 MPC Helium Backfill Pressure

The quantity of helium emplaced in the MPC cavity shall be sufficient to produce an operating pressure of 7 atmospheres (absolute) during normal storage at reference conditions (See Table 4.0.1). Thermal analyses performed on the different MPC designs indicate that this operating pressure requires a certain minimum helium backfill pressure ($P_b$) specified at a reference temperature (70°F). The minimum backfill pressure for each MPC type is provided in Table 4.4.11. A theoretical upper limit on the helium backfill pressure also exists and is defined by the design pressure of the MPC vessel (Table 2.2.1). The upper limit of $P_b$ is also reported in Table 4.4.11. To bound the minimum and maximum backfill pressures listed in Table 4.4.11 with a margin, a helium backfill specification is set forth in Table 4.4.12.

Two methods are available for ensuring that the appropriate quantity of helium has been placed in an MPC:

i. By pressure measurement
ii. By measurement of helium backfill volume (in standard cubic feet)

The direct pressure measurement approach is more convenient if the FHD method of MPC drying is used. In this case, a certain quantity of helium is already in the MPC. Because the helium is mixed inside the MPC during the FHD operation, the temperature of the helium gas at the MPC's exit, along with the pressure provides a reliable means to compute the inventory of helium using pressure and temperature gages. A shortfall or excess of helium is adjusted by a calculated raising or lowering of the MPC pressure such that the reference MPC backfill pressure is within the $P_b$ specifications.

When vacuum drying is used as the method for MPC drying, then it is more convenient to fill the MPC by introducing a known quantity of helium (in standard cubic feet) by measuring the quantity of helium introduced using a calibrated mass flow meter or other measuring apparatus. The required quantity of helium is computed by the product of net free volume and helium specific volume at the reference temperature (70°F) and a target pressure that lies in the mid-range of the $P_b$ specifications.

The net free volume of the MPC is obtained by subtracting B from A, where

A = MPC cavity volume in the absence of contents (fuel and non-fuel hardware) computed from nominal design dimensions

B = Total volume of the contents (fuel including DFCs, if used) based on nominal design dimensions

Using commercially available mass flow totalizers or other appropriate measuring devices, an MPC cavity is filled with the computed quantity of helium.

4.4.5.2 MPC Pressure Calculations

The MPC is initially filled with dry helium after fuel loading and drying prior to installing the MPC closure ring. During normal storage, the gas temperature within the MPC rises to its maximum operating basis temperature. The gas pressure inside the MPC will also increase with rising temperature. The pressure rise is determined using the ideal gas law.

Table 4.4.8 presents a summary of the minimum MPC free volumes determined for each MPC type (MPC-24, MPC-68, MPC-32, and MPC-24E). The MPC maximum gas pressure is computed for a postulated release of fission product gases from fuel rods into this free space. For these scenarios, the amounts of each of the release gas constituents in the MPC cavity are summed and the resulting total pressures determined from the ideal gas law. Based on fission gases release fractions (NUREG 1536 criteria [4.4.1]), rods' net free volume and initial fill gas pressure, maximum gas pressures with 1% (normal), 10% (off-normal) and 100% (accident condition) rod rupture are given in Table 4.4.9. The maximum computed gas pressures reported in Table 4.4.9 are all below the MPC internal design pressures for normal, off-normal and accident conditions specified in Table 2.2.1.

Evaluation of Non-Fuel Hardware

The inclusion of PWR non-fuel hardware (BPRA control elements and thimble plugs) to the PWR baskets influences the MPC internal pressure through two distinct effects. The presence of non-fuel hardware increases the effective basket conductivity, thus enhancing heat dissipation and lowering fuel temperatures as well as the temperature of the gas filling the space between fuel rods. The gas volume displaced by the mass of non-fuel hardware lowers the cavity free volume. These two effects, namely, temperature lowering and free volume reduction, have opposing influence on the MPC cavity pressure. The first effect lowers gas pressure while the second effect raises it. In the HI-STORM thermal analysis, the computed temperature field (with non-fuel hardware excluded) has been determined to provide a conservatively bounding temperature field for the PWR baskets (MPC-24, MPC-24E, and MPC-32). The MPC cavity free space is computed based on volume displacement by the heaviest fuel (bounding weight) with non-fuel hardware included. This approach ensures conservative bounding pressures.

During in-core irradiation of BPRAs, neutron capture by the B-10 isotope in the neutron absorbing material produces helium. Two different forms of the neutron absorbing material are used in BPRAs: Borosilicate glass and $B_4C$ in a refractory solid matrix ($Al_2O_3$). Borosilicate glass (primarily a constituent of Westinghouse BPRAs) is used in the shape of hollow pyrex glass tubes sealed within steel rods and supported on the inside by a thin-walled steel liner. To accommodate helium diffusion from the glass rod into the rod internal space, a relatively high void volume (~40%) is engineered in this type of rod design. The rod internal pressure is thus designed to remain below reactor operation conditions (2,300 psia and approximately 600°F coolant temperature). The $B_4C$- $Al_2O_3$ neutron absorber material is principally used in B&W and CE fuel BPRA designs. The relatively low temperature of the poison material in BPRA rods (relative to fuel pellets) favor the entrapment of helium atoms in the solid matrix.

Several BPRA designs are used in PWR fuel that differ in the number, diameter, and length of poison rods. The older Westinghouse fuel (W-14x14 and W-15x15) has used 6, 12, 16, and 20 rods per assembly BPRAs and the later (W-17x17) fuel uses up to 24 rods per BPRA. The BPRA rods in the older fuel are much larger than the later fuel and, therefore, the B-10 isotope inventory in the 20-rod BPRAs bounds the newer W-17x17 fuel. Based on bounding BPRA rods internal pressure, a large hypothetical quantity of helium (7.2 g-moles/BPRA) is assumed to be available for release into the MPC cavity from each fuel assembly in the PWR baskets. The MPC cavity pressures (including helium from BPRAs) are summarized in Table 4.4.9.

### 4.4.6 Engineered Clearances to Eliminate Thermal Interferences

Thermal stress in a structural component is the resultant sum of two factors, namely: (i) restraint of free end expansion and (ii) non-uniform temperature distribution. To minimize thermal stresses in load bearing members, the HI-STORM System is engineered with adequate gaps to permit free thermal expansion of the fuel basket and MPC in axial and radial directions. In this subsection, differential thermal expansion calculations are performed to demonstrate that engineered gaps in the HI-STORM System are adequate to accommodate thermal expansion of the fuel basket and MPC.

The HI-STORM System is engineered with gaps for the fuel basket and MPC to expand thermally without restraint of free end expansion. Differential thermal expansion of the following gaps are evaluated:

a. Fuel Basket-to-MPC Radial Gap
b. Fuel Basket to MPC Axial Gap
c. MPC-to-Overpack Radial Gap
d. MPC-to-Overpack Axial Gap

To demonstrate that the fuel basket and MPC are free to expand without restraint, it is required to show that differential thermal expansion from fuel heatup is less than the as-built gaps that exist in the HI-STORM System. For this purpose a suitably bounding temperature profile (T(r)) for the fuel basket is established in Figure 4.4.5 wherein the center temperature (TC) is set at the limit (752°F) for fuel cladding (conservatively bounding assumption) and the basket periphery (TP) conservatively postulated at an upperbound of 610°F (see Table 4.4.6 for the maximum fuel and basket periphery temperatures). To maximize the fuel basket differential thermal expansion, the basket periphery-to-MPC shell temperature difference is conservatively maximized (ΔT = 175°F). From the bounding temperature profile T(r) and ΔT, the mean fuel basket temperature (T1) and MPC shell temperature (T2) are computed as follows:

$$T1 = \frac{\int_0^1 rT(r)dr}{\int_0^1 rdr} = 676°F$$

$$T2 = TP - \Delta T = 425°F$$

The differential radial growth of the fuel basket (Y1) from an initial reference temperature (To = 70°F) is computed as:

$$Y1 = R \times \left[A1 \times (T1 - To) - A2 \times (T2 - To)\right]$$

where:

R = Basket radius (conservatively assumed to be the MPC radius)

A1, A2 = Coefficients of thermal expansion for fuel basket and MPC shell at T1 and T2 respectively for Alloy X (Chapter 1 and Table 3.3.1)

For computing the relative axial growth of the fuel basket in the MPC, bounding temperatures for the fuel basket (TC) and MPC shell temperature T2 utilized above are adopted. The differential expansion is computed by a formula similar to the one for radial growth after replacing R with basket height (H), which is conservatively assumed to be that of the MPC cavity.

For computing the radial and axial MPC-to-overpack differential expansions, the MPC shell is postulated at its design temperature (Chapter 2, Table 2.2.3) and thermal expansion of the overpack is ignored. Even with the conservative computation of the differential expansions in the manner of the foregoing, it is evident from the data compiled in Table 4.4.10 that the differential expansions are a fraction of their respective gaps.

### 4.4.7 Evaluation of System Performance for Normal Conditions of Storage

The HI-STORM System thermal analysis is based on a detailed and complete heat transfer model that conservatively accounts for all modes of heat transfer in various portions of the MPC and overpack. The thermal model incorporates conservative features that render the results for long-term storage to be extremely conservative.

Temperature distribution results obtained from this highly conservative thermal model show that the maximum fuel cladding temperature limits are met with adequate margins. Expected margins during normal storage will be much greater due to the conservative assumptions incorporated in the analysis. The long-term impact of decay heat induced temperature levels on the HI-STORM System structural and neutron shielding materials is considered to be negligible. The maximum local MPC basket temperature level is below the recommended limits for structural materials in terms of susceptibility to stress, corrosion and creep-induced degradation. Furthermore, stresses induced due to imposed temperature gradients are within Code limits (See Structural Evaluation Chapter 3). Therefore, it is concluded that the HI-STORM System thermal design is in compliance with 10CFR72 requirements.

Table 4.4.1

EFFECTIVE CONDUCTIVITY OF THE COMPOSITE FUEL BASKET WALLS
(Btu/hr-ft-°F)

| | MPC-32 | | MPC-24/MPC-24E* | | MPC-68 | |
|---|---|---|---|---|---|---|
| Temperature (°F) | Thru-Thickness Direction | Parallel Plates Direction | Thru-Thickness Direction | Parallel Plates Direction | Thru-Thickness Direction | Parallel Plates Direction |
| 200 | 6.000 | 14.65 | 5.676<br>4.800** | 13.85<br>11.17** | 5.544 | 12.06 |
| 450 | 7.260 | 16.12 | 6.864<br>5.808** | 15.32<br>12.54** | 6.708 | 13.45 |
| 700 | 8.316 | 17.20 | 7.884<br>6.672** | 16.44<br>13.62** | 7.680 | 14.52 |

* Lowerbound values reported.
** Effective conductivities of basket peripheral panels.

Table 4.4.2

LIMITING EFFECTIVE CONDUCTIVITIES OF THE RODDED REGION
(Btu/hr-ft-°F)

| | PWR Fuel | | BWR FUEL | |
|---|---|---|---|---|
| Temperature (°F) | Planar | Axial | Planar | Axial |
| 200 | 0.257 | 0.753 | 0.282 | 0.897 |
| 450 | 0.406 | 0.833 | 0.425 | 0.988 |
| 700 | 0.604 | 0.934 | 0.606 | 1.104 |

Table 4.4.3

[deleted]

Table 4.4.4

[deleted]

Table 4.4.5

MATRIX OF HI-STORM SYSTEM THERMAL EVALUATIONS

| Scenario | Description | Ultimate Heat Sink | Analysis Type | Principal Input Parameters | Results in FSAR Subsection |
|---|---|---|---|---|---|
| 1 | Long Term Normal | Ambient | SS | $N_T$, $Q_D$, ST, SC, $I_O$ | 4.4.4 |
| 2 | Off-Normal Environment | Ambient | SS(B) | $O_T$, $Q_D$, ST, SC, $I_O$ | 4.6.1 |
| 3 | Extreme Environment | Ambient | SS(B) | $E_T$, $Q_D$, ST, SC, $I_O$ | 4.6.2 |
| 4 | Partial Ducts Blockage | Ambient | SS(B) | $N_T$, $Q_D$, ST, SC, $I_{1/2}$ | 4.6.1 |
| 5 | All Inlets Ducts Blocked | Overpack | TA | $N_T$, $Q_D$, ST, SC, $I_C$ | 4.6.2 |
| 6 | Fire Accident | Overpack | TA | $Q_D$, F | 4.6.2 |
| 7 | Burial Under Debris | Overpack | AH | $Q_D$ | 4.6.2 |

<u>Legend:</u>

$N_T$ - Maximum Annual Average (Normal) Temperature (80°F)
$O_T$ - Off-Normal Temperature (100°F)
$E_T$ - Extreme Hot Temperature (125°F)
$Q_D$ - Design Basis Maximum Heat Load
SS - Steady State
SS(B) - Bounding Steady State
TA - Transient Analysis
AH - Adiabatic Heating

$I_O$ - All Inlet Ducts Open
$I_{1/2}$ - Half of Inlet Ducts Open
$I_C$ - All Inlet Ducts Closed
ST - Insolation Heating (Top)
SC - Insolation Heating (Curved)
F - Fire Heating (1475°F)

Table 4.4.6

MAXIMUM MPC TEMPERATURES FOR LONG-TERM NORMAL STORAGE CONDITION[2]

| Component | Temperature, °F | |
|---|---|---|
| | **MPC-32** | MPC-68 |
| Fuel Cladding | **711** | 697 |
| MPC Basket | **708** | 692 |
| Basket Periphery | **604** | 566 |
| MPC Shell | **469** | 452 |

Table 4.4.7

BOUNDING HI-STORM OVERPACK TEMPERATURES FOR LONG-TERM NORMAL STORAGE[3]

| Component | Local Section Temperature[4], °F |
|---|---|
| Inner shell | 322 |
| Outer shell | 174 |
| Lid bottom plate | 302 |
| Lid top plate | 190 |
| Overpack Body Concrete | 248 |
| Overpack Lid Concrete | 246 |
| Area Averaged Air outlet[5] | 235 |

2 The temperatures reported in this table for the bounding fuel storage configuration (regionalized storage at X = 0.5) are below the design temperatures specified in Chapter 2, Table 2.2.3. Results of the bounding canister (MPC-32) are highlighted in bold.

3 The temperatures reported in this table (all for MPC-32 at X = 0.5) are below the design temperatures specified in Chapter 2, Table 2.2.3.

4 Section temperature is defined as the through-thickness average temperature.

5 Reported herein for the option of temperature measurement surveillance of outlet ducts air temperature as set forth in the Technical Specifications.

Table 4.4.8

SUMMARY OF MPC FREE VOLUME CALCULATIONS

| Item | Volume (MPC-24) [$ft^3$] | Volume (MPC-24E) [$ft^3$] | Volume (MPC-32) [$ft^3$] | Volume (MPC-68) [$ft^3$] |
|---|---|---|---|---|
| Cavity Volume | 367.9 | 367.9 | 367.9 | 367.3 |
| Basket Metal Volume | 44.3 | 51.4 | 24.9 | 34.8 |
| Bounding Fuel Assemblies Volume | 78.8 | 78.8 | 105.0 | 93.0 |
| Basket Supports and Fuel Spacers Volume | 6.1 | 6.1 | 9.0 | 11.3 |
| Net Free Volume* | 238.7 (6,759 liters) | 231.6 (6,558 liters) | 229 (6,484 liters) | 228.2 (6,462 liters) |
| * Net free volumes are obtained by subtracting basket, fuel, supports and spacers metal volume from cavity volume. The free volumes used for MPC internal pressure calculations are conservatively understated. | | | | |

Table 4.4.9

SUMMARY OF MPC INTERNAL PRESSURES UNDER LONG-TERM STORAGE*

| Condition | MPC-24*** (psig) | MPC-24E*** (psig) | MPC-32 (psig) | MPC-68 (psig) |
|---|---|---|---|---|
| Initial backfill** (at 70°F) | 48.5 | 48.5 | 48.5 | 48.5 |
| Normal:<br>intact rods<br>1% rods rupture | <br>99.0<br>100.0 | <br>99.0<br>99.7 | <br>99.0<br>99.7 | <br>96.8<br>97.2 |
| Off-Normal (10% rods rupture) | 106.0 | 106.2 | 108.7 | 101.2 |
| Accident (100% rods rupture) | 169.3 | 171.5 | 196.4 | 141.1 |

* 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 4.4.12).

*** Pressure calculations use the bounding MPC-32 temperature field.

Table 4.4.10

SUMMARY OF HI-STORM DIFFERENTIAL THERMAL EXPANSIONS

| Gap Description | Cold Gap U (in) | Differential Expansion V (in) | Is Free Expansion Criterion Satisfied (i.e., U > V) |
|---|---|---|---|
| Fuel Basket-to-MPC Radial Gap | 0.1875 | 0.095 | Yes |
| Fuel Basket-to-MPC Axial Gap | 1.25 | 0.487 | Yes |
| MPC-to-Overpack Radial Gap | 0.5 | 0.139 | Yes |
| MPC-to-Overpack Minimum Axial Gap | 1.0 | 0.771 | Yes |

Table 4.4.11

THEORETICAL LIMITS* OF MPC HELIUM BACKFILL PRESSURE**

| MPC | Minimum Backfill Pressure (psig) | Maximum Backfill Pressure (psig) |
|---|---|---|
| MPC-32/24/24E | 44.1 | 49.1 |
| MPC-68 | 45.2 | 50.3 |
| * The helium backfill pressures are set forth in the Technical Specifications with a margin (See Table 4.4.12).<br>** The pressures tabulated herein are at a reference gas temperature of 70°F. | | |

Table 4.4.12

MPC HELIUM BACKFILL PRESSURE SPECIFICATIONS

| Item | Specification |
|---|---|
| Minimum Pressure | 45.5 psig @ 70°F Reference Temperature |
| Maximum Pressure | 48.5 psig @ 70°F Reference Temperature |

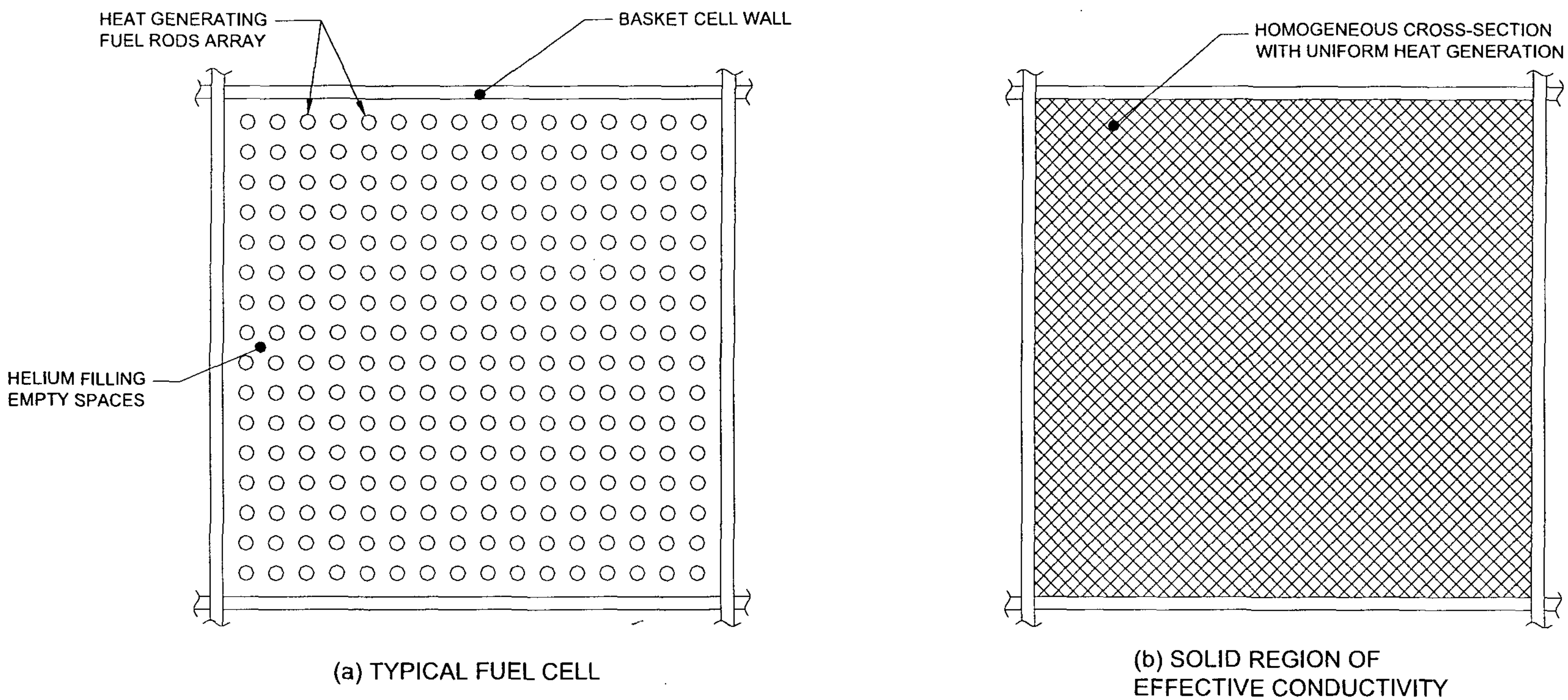


FIGURE 4.4.1: HOMOGENIZATION OF THE STORAGE CELL CROSS-SECTION

FIGURE 4.4.2

[Intentionally Deleted]

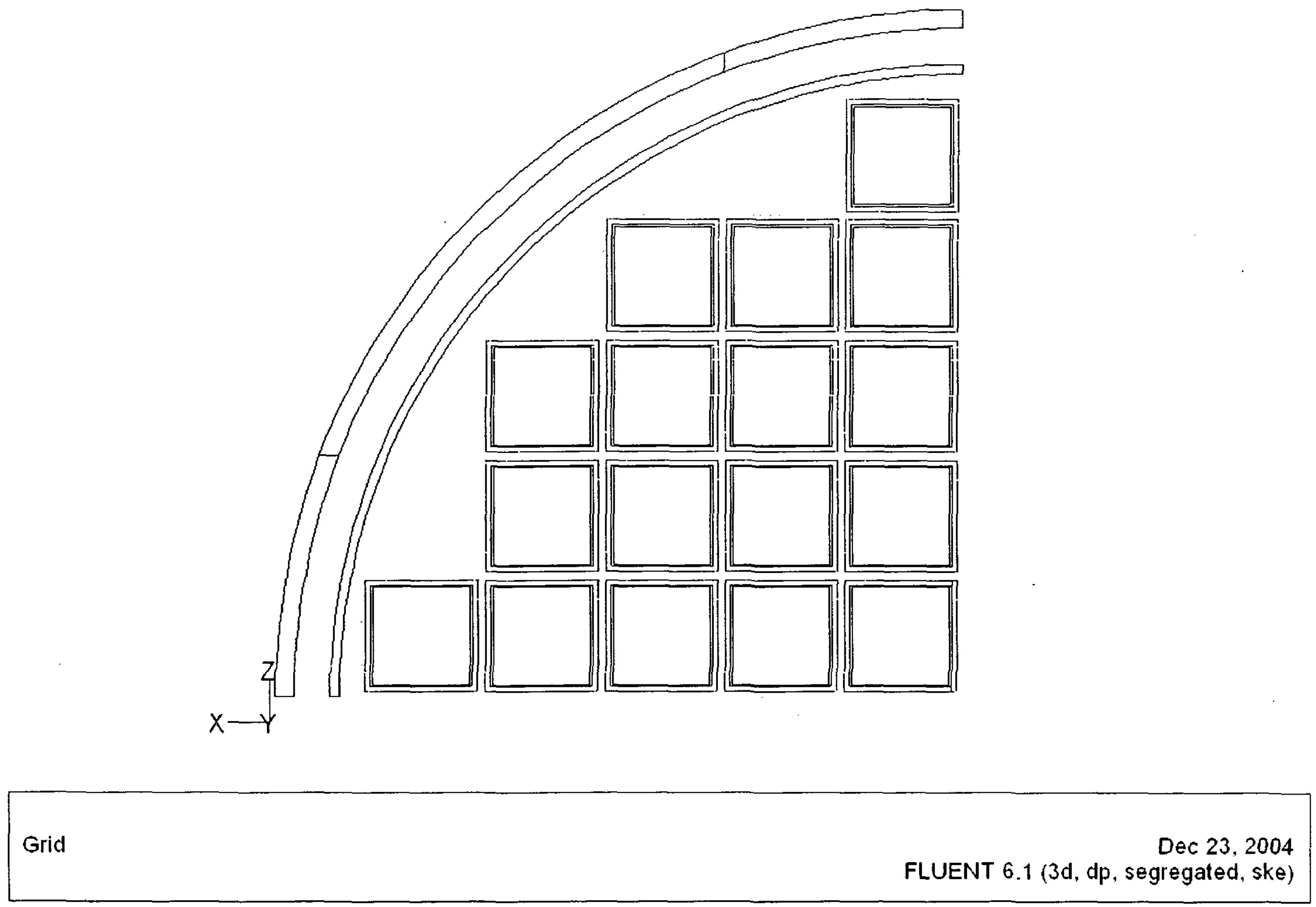


FIGURE 4.4.3: PLANAR VIEW OF HI-STORM MPC-68 QUARTER SYMMETRIC 3-D MODEL

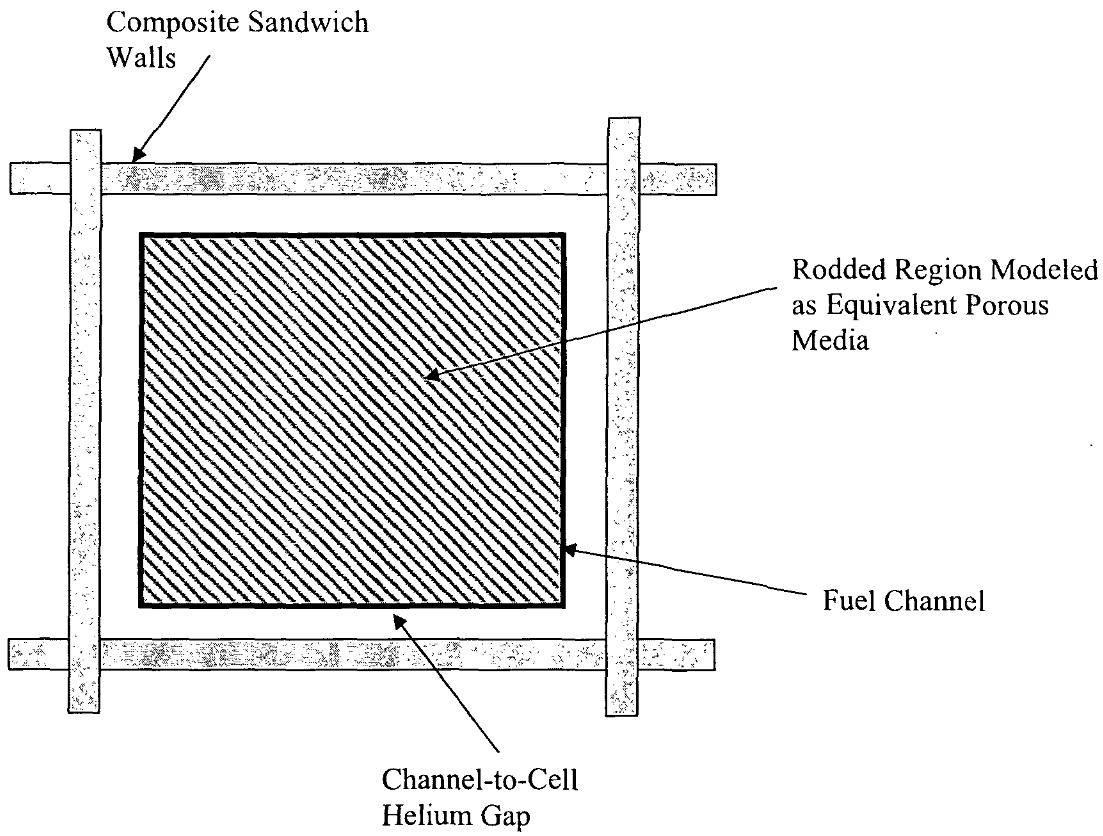


FIGURE 4.4.4: CLOSEUP VIEW OF THE MPC-68 CHANNELED FUEL CELL SPACES

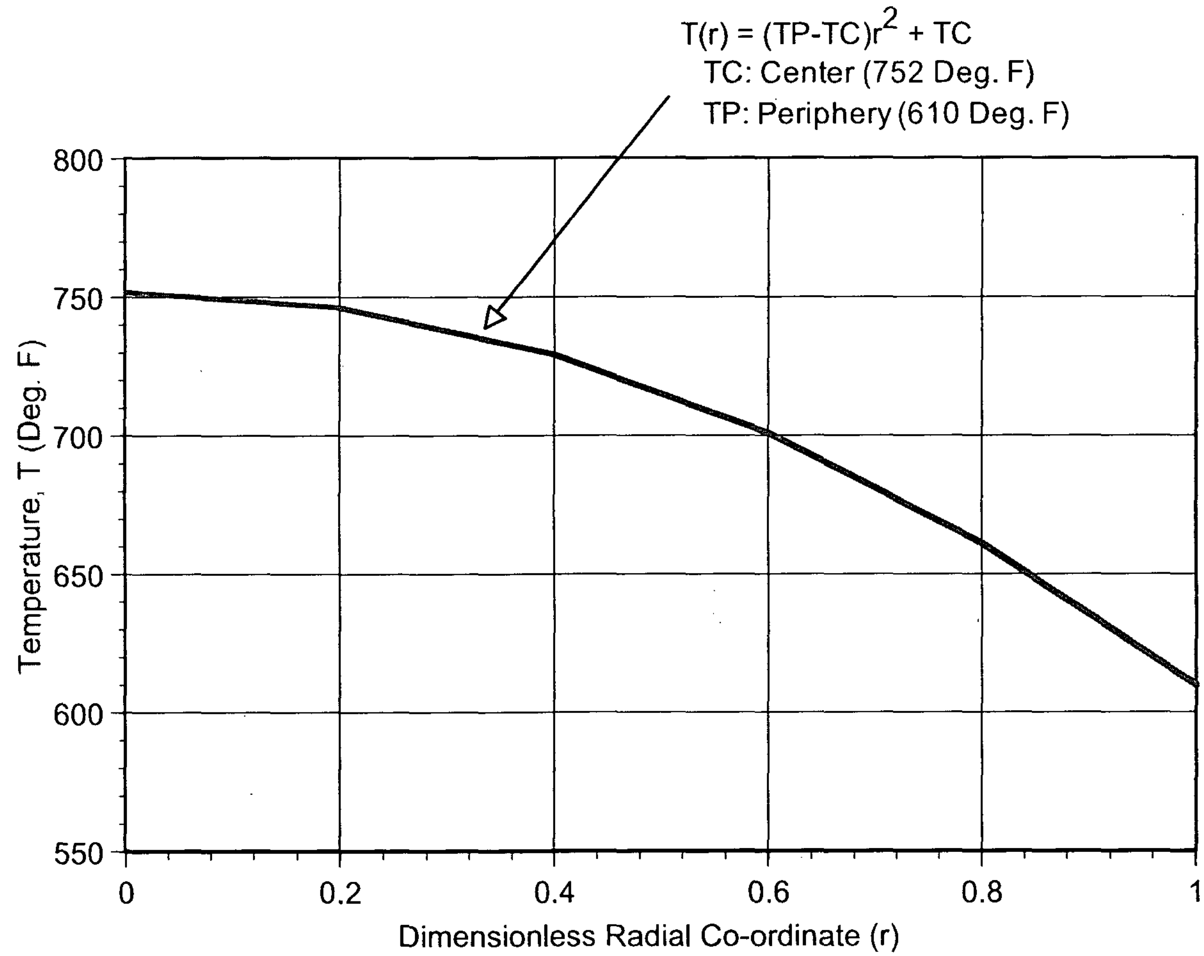


FIGURE 4.4.5: BOUNDING BASKET TEMPERATURE PROFILE FOR DIFFERENTIAL EXPANSION

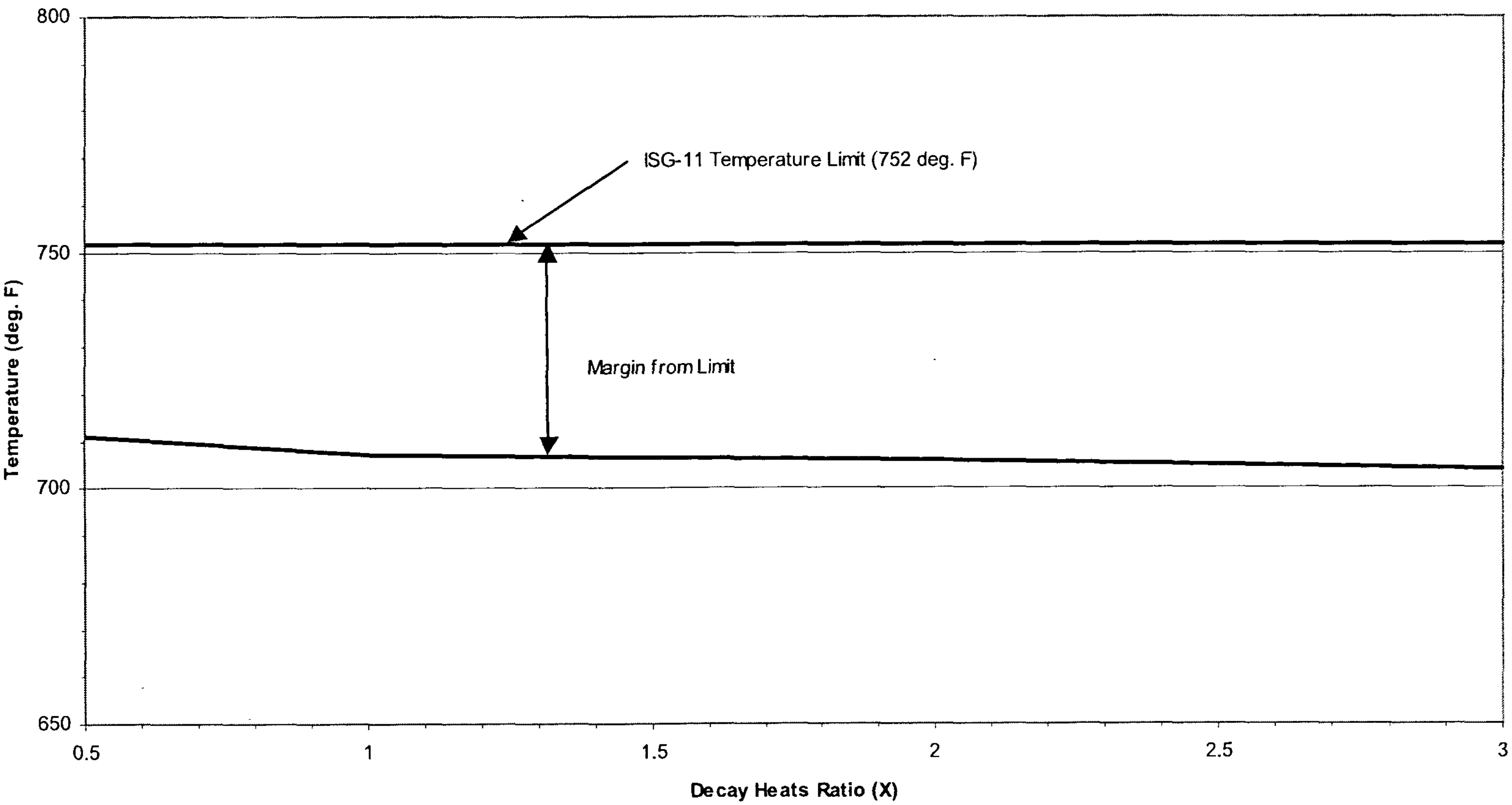


FIGURE 4.4.6: PEAK CLADDING TEMPERATURE VARIATION IN REGIONALIZED STORAGE (MPC 32)

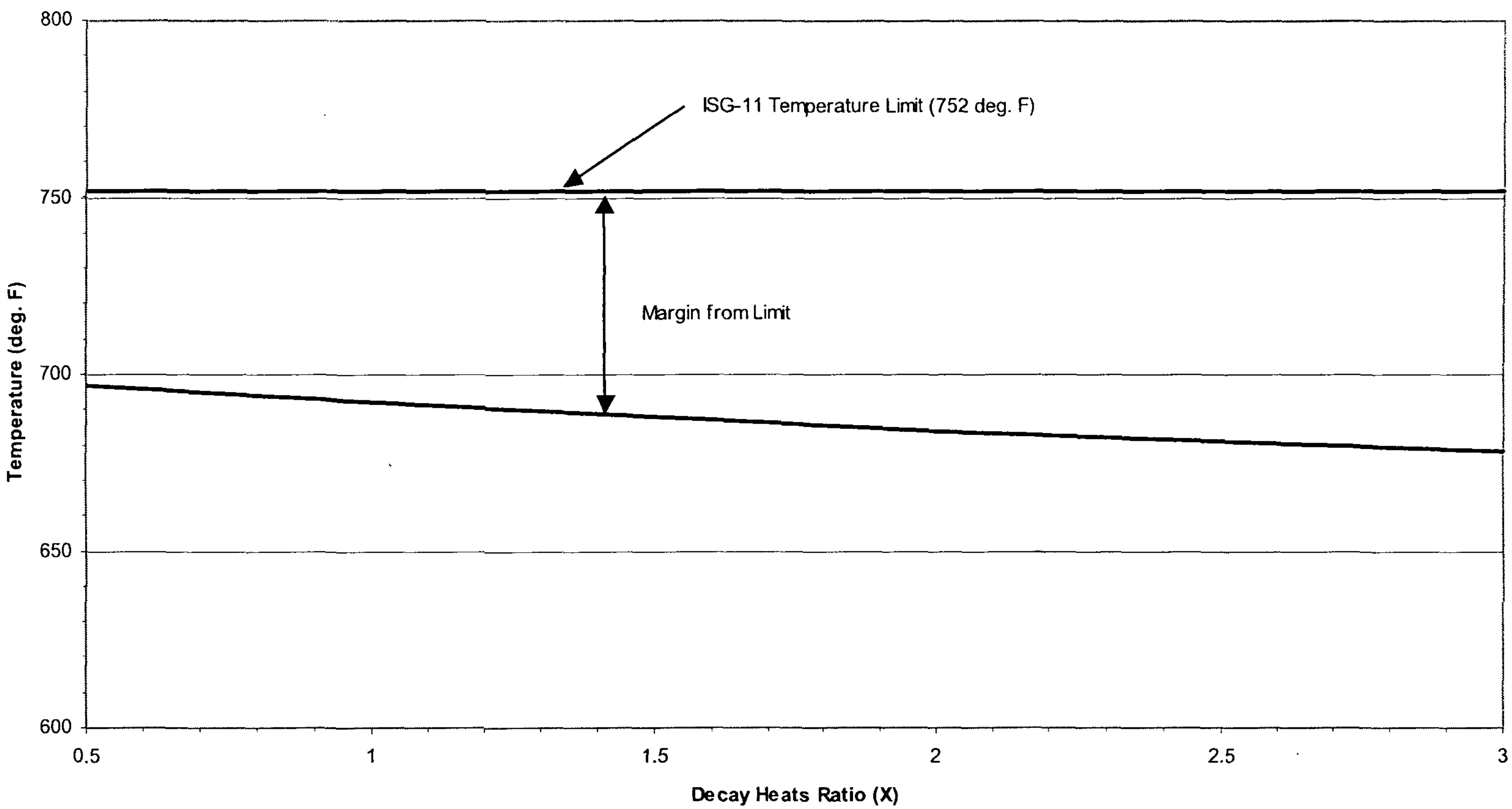


FIGURE 4.4.7: PEAK CLADDING TEMPERATURE VARIATION IN REGIONALIZED STORAGE (MPC-68)

## 4.5 THERMAL EVALUATION OF SHORT TERM OPERATIONS

Prior to placement in a HI-STORM overpack, an MPC must be loaded with fuel, outfitted with closures, dewatered, dried, backfilled with helium and transported to the HI-STORM module. In the unlikely event that the fuel needs to be returned to the spent fuel pool, these steps must be performed in reverse. Finally, if required, transfer of a loaded MPC between HI-STORM overpacks or between a HI-STAR transport overpack and a HI-STORM storage overpack must be carried out in an assuredly safe manner. All of the above operations, henceforth referred to as "short term operations", are short duration events that would likely occur no more than once or twice for an individual MPC.

The device central to all of the above operations is the HI-TRAC transfer cask that, as stated in Chapter 1, is available in two anatomically similar weight ratings (100- and 125-ton). Two different versions of the 100 ton and the 125 ton HI-TRAC, the classical version and the version D, are available for use during fuel transfer operations. The HI-TRAC transfer cask is a short-term host for the MPC; therefore it is necessary to establish that, during all thermally challenging operation events involving either the 100-ton or 125-ton versions of the HI-TRAC, the permissible temperature limits presented in Section 4.3 are not exceeded. The following discrete thermal scenarios, all of short duration, involving the HI-TRAC transfer cask, have been identified as warranting thermal analysis.

i. Post-Loading Wet Transfer Operations
ii. MPC Cavity Vacuum Drying
iii. Normal Onsite Transport in a Vertical Orientation
iv. MPC Cooldown and Reflood for Unloading Operations

Onsite transport of the MPC occurs with the HI-TRAC in the vertical orientation, which preserves the thermosiphon action within the MPC. To avoid excessive temperatures, transport with the HI-TRAC in the horizontal condition is generally not permitted. However, it is recognized that an occasional downending of a HI-TRAC may become necessary to clear an obstruction such as a low egress bay door opening. In such a case the operational imperative for HI-TRAC downending must be ascertained and the permissible duration of horizontal configuration must be established on a site-specific basis and compliance with the thermal limits of ISG-11 [4.1.4] must be demonstrated as a part of the site-specific safety evaluation.

The fuel handling operations listed above place a certain level of constraint on the dissipation of heat from the MPC relative to the normal storage condition. Consequently, for some scenarios, it is necessary to provide additional cooling when decay heat loads are such that long-term cladding temperature limits would be exceeded. For such situations, the Supplemental Cooling System (SCS) is required to provide additional cooling during short term operations. The SCS is required by the CoC for any MPC carrying one or more high burnup fuel assemblies or when the MPC heat load is such that long-term cladding temperature limits would be exceeded. The specific design of an SCS must accord with site-specific needs and resources, including the availability of plant utilities. However, a set of specifications to ensure that the performance objectives of the SCS are satisfied by plant-specific designs are set forth in Appendix 2.C.

### 4.5.1 HI-TRAC Thermal Model

The HI-TRAC transfer cask is used to load and unload the HI-STORM concrete storage overpack, including onsite transport of the MPCs from the loading facility to an ISFSI pad. Section views of the HI-TRAC have been presented in Chapter 1. Within a loaded HI-TRAC, heat generated in the MPC is transported from the contained fuel assemblies to the MPC shell through the fuel basket and the basket-to-shell gaps via conduction and thermal radiation. From the outer surface of the MPC to the ambient air, heat is transported by a combination of conduction, thermal radiation and natural convection. Analytical modeling details of all the various thermal transport mechanisms are provided in the following subsection.

All HI-TRAC transfer cask designs are developed for onsite handling and transport, as discussed in Chapter 1. The designs are principally different in terms of lead thickness and the thickness of radial connectors in the water jacket region. The analytical model developed for HI-TRAC thermal characterization conservatively accounts for these differences by applying the higher shell and lead thicknesses, lowest number of radial connectors, and thinner radial connectors' thickness to the model. In this manner, the HI-TRAC overpack resistance to heat transfer is overestimated, resulting in higher predicted MPC internals and fuel cladding temperature levels.

#### 4.5.1.1 Analytical Model

From the outer surface of the MPC to the ambient atmosphere, heat is transported within HI-TRAC through multiple concentric layers of air, steel and shielding materials. Heat must be transported across a total of six concentric layers, representing the air gap, the HI-TRAC inner shell, the lead shielding, the HI-TRAC outer shell, the water jacket and the enclosure shell. From the surface of the enclosure shell heat is rejected to the atmosphere by natural convection and radiation.

A small diametral air gap exists between the outer surface of the MPC and the inner surface of the HI-TRAC overpack. Heat is transported across this gap by the parallel mechanisms of conduction and thermal radiation. Assuming that the MPC is centered and does not contact the transfer overpack walls conservatively minimizes heat transport across this gap. Additionally, thermal expansion that would minimize the gap is conservatively neglected. Heat is transported through the cylindrical wall of the HI-TRAC transfer overpack by conduction through successive layers of steel, lead and steel. A water jacket, which provides neutron shielding for the HI-TRAC overpack, surrounds the cylindrical steel wall. The water jacket is composed of carbon steel channels with welded, connecting enclosure plates. Conduction heat transfer occurs through both the water cavities and the channels. While the water jacket channels are sufficiently large for natural convection loops to form, this mechanism is conservatively neglected. Heat is passively rejected to the ambient from the outer surface of the HI-TRAC transfer overpack by natural convection and thermal radiation.

In the vertical position, the bottom face of the HI-TRAC is in contact with a supporting surface. This face is conservatively modeled as an insulated surface. Because the HI-TRAC is not used for long-term storage in an array, radiative blocking does not need to be considered. The HI-TRAC top lid is modeled as a surface with convection, radiative heat exchange with air and a constant maximum incident solar heat flux load. Insolation on cylindrical surfaces is conservatively based on 12-hour levels prescribed in 10CFR71 averaged on a 24-hour basis. Concise descriptions of these models are given below.

#### 4.5.1.1.1 Effective Thermal Conductivity of Water Jacket

The classical version HI-TRAC water jackets are composed of an array of radial ribs equispaced along the circumference of the HI-TRAC and welded along their length to the HI-TRAC outer shell. Enclosure plates are welded to these ribs, creating an array of water compartments. The version D HI-TRAC water jackets also have an array of radial ribs connected to enclosure plates with an array of plug welds to form multiple compartments. Holes in the radial ribs connect all the individual compartments in the water jacket. Any combination of rib number and thickness that yields an equal or larger heat transfer area is bounded by the calculation. Thus, the annular region between the HI-TRAC outer shell and the enclosure shell can be considered as an array of steel ribs and water spaces.

The effective radial thermal conductivity of this array of steel ribs and water spaces is determined by combining the heat transfer resistance of individual components in a parallel network. A bounding calculation is assured by using the minimum number of ribs and rib thickness as input values. The thermal conductivity of the parallel steel ribs and water spaces is given by the following formula:

$$K_{ne} = \frac{K_r N_r t_r \ln\left(\frac{r_o}{r_i}\right)}{2\pi L_R} + \frac{K_w N_r t_w \ln\left(\frac{r_o}{r_i}\right)}{2\pi L_R}$$

where:

$K_{ne}$ = effective radial thermal conductivity of water jacket
$r_i$ = inner radius of water spaces
$r_o$ = outer radius of water spaces
$K_r$ = thermal conductivity of carbon steel ribs
$N_r$ = minimum number of radial ribs (equal to number of water spaces)
$t_r$ = minimum (nominal) rib thickness (lower of 125-ton and 100-ton designs)
$L_R$ = effective radial heat transport length through water spaces
$K_w$ = thermal conductivity of water
$t_w$ = water space width (between two carbon steel ribs)

Figure 4.5.1 depicts the resistance network to combine the resistances to determine an effective conductivity of the water jacket. The effective thermal conductivity is computed in the manner of the foregoing, and is provided in Table 4.5.1.

#### 4.5.1.1.2 Heat Rejection from Overpack Exterior Surfaces

The following relationship for the surface heat flux from the outer surface of an isolated cask to the environment is applied to the thermal model:

$$q_s = 0.19\,(T_s - T_A)^{4/3} + 0.1714\varepsilon\,[(\frac{T_s + 460}{100})^4 - (\frac{T_A + 460}{100})^4]$$

where:

$T_S$ = cask surface temperatures (°F)
$T_A$ = ambient atmospheric temperature (°F)
$q_s$ = surface heat flux (Btu/ft$^2$×hr)
$\varepsilon$ = surface emissivity

The second term in this equation the Stefan-Boltzmann formula for thermal radiation from an exposed surface to ambient. The first term is the natural convection heat transfer correlation recommended by Jacob and Hawkins [4.2.9]. This correlation is appropriate for turbulent natural convection from vertical surfaces, such as the vertical overpack wall. Although the ambient air is conservatively assumed to be quiescent, the natural convection is nevertheless turbulent.

Turbulent natural convection correlations are suitable for use when the product of the Grashof and Prandtl (Gr×Pr) numbers exceeds $10^9$. This product can be expressed as $L^3 \times \Delta T \times Z$, where L is the characteristic length, $\Delta T$ is the surface-to-ambient temperature difference, and Z is a function of the surface temperature. The characteristic length of a vertically oriented HI-TRAC is its height of approximately 17 feet. The value of Z, conservatively taken at a surface temperature of 340°F, is $2.6 \times 10^5$. Solving for the value of $\Delta T$ that satisfies the equivalence $L^3 \times \Delta T \times Z = 10^9$ yields $\Delta T$ = 0.78°F. For a horizontally oriented HI-TRAC the characteristic length is the diameter of approximately 7.6 feet (minimum of 100- and 125-ton designs), yielding $\Delta T$ = 8.76°F. The natural convection will be turbulent, therefore, provided the surface to air temperature difference is greater than or equal to 0.78°F for a vertical orientation and 8.76°F for a horizontal orientation.

#### 4.5.1.1.3 Determination of Solar Heat Input

The intensity of solar radiation incident on an exposed surface depends on a number of time varying terms. A twelve-hour averaged insolation level is prescribed in 10CFR71 for curved surfaces. The HI-TRAC cask, however, possesses a considerable thermal inertia. This large thermal inertia precludes the HI-TRAC from reaching a steady-state thermal condition during a twelve-hour period. Thus, it is considered appropriate to use the 24-hour averaged insolation level.

### 4.5.2 Maximum Time Limit During Wet Transfer Operations

In accordance with NUREG-1536, water inside the MPC cavity during wet transfer operations is not permitted to boil. Consequently, uncontrolled pressures in the de-watering, purging, and recharging system that may result from two-phase conditions are completely avoided. This requirement is accomplished by imposing a limit on the maximum allowable time duration for fuel to be submerged in water after a loaded HI-TRAC cask is removed from the pool and prior to the start of vacuum drying operations.

Fuel loading operations are typically conducted with the HI-TRAC and it's contents (water filled MPC) submerged in pool water. Under these conditions, the HI-TRAC is essentially at the pool water temperature. When the HI-TRAC transfer cask and the loaded MPC under water-flooded conditions is removed from the pool, the water, fuel, MPC and HI-TRAC metal absorb the decay heat emitted by the fuel assemblies. This results in a slow temperature rise of the HI-TRAC with time, starting from an initial (pool water) temperature. The rate of temperature rise is limited by the thermal inertia of the HI-TRAC system. To enable a bounding heat-up rate determination, the following conservative assumptions are utilized:

i. Heat loss by natural convection and radiation from the exposed HI-TRAC surfaces to ambient air is neglected (i.e., an adiabatic heat-up calculation is performed).

ii. Design maximum decay heat input from the loaded fuel assemblies is assumed.

iii. The smaller of the two versions of the HI-TRAC transfer cask designs (i.e., 100-ton and 125-ton) is credited in the analysis. The 100-ton design has a significantly smaller quantity of metal mass, which will result in a higher rate of temperature rise.

iv. The water mass in the MPC cavity is understated.

Table 4.5.2 summarizes the weights and thermal inertias of several components in the loaded HI-TRAC transfer cask. The rate of temperature rise of the HI-TRAC transfer cask and contents during an adiabatic heat-up is governed by the following equation:

$$\frac{dT}{dt} = \frac{Q}{C_h}$$

where:

$Q$ = conservatively bounding heat load (Btu/hr) [ 38 kW = $1.3\times10^5$ Btu/hr]
$C_h$ = thermal inertia of a loaded HI-TRAC (Btu/°F)
$T$ = temperature of the HI-TRAC cask (°F)
$t$ = time after HI-TRAC transfer cask is removed from the pool (hr)

A bounding heat-up rate for the HI-TRAC transfer cask contents is determined to be equal to 4.99°F/hr. From this adiabatic rate of temperature rise estimate, the maximum allowable time duration ($t_{max}$) for fuel to be submerged in water is determined as follows:

$$t_{max} = \frac{T_{boil} - T_{initial}}{(dT/dt)}$$

where:

$T_{boil}$ = boiling temperature of water (equal to 212°F at the water surface in the MPC cavity)
$T_{initial}$ = initial HI-TRAC temperature when the transfer cask is removed from the pool

Table 4.5.3 provides a summary of $t_{max}$ at several representative initial temperatures.

As set forth in the HI-STORM operating procedures, in the unlikely event that the maximum allowable time provided in Table 4.5.3 is found to be insufficient to complete all wet transfer operations, a forced water circulation shall be initiated and maintained to remove the decay heat from the MPC cavity. In this case, relatively cooler water will enter via the MPC lid drain port connection 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)
$T_{max}$ = maximum MPC cavity water mass temperature
$T_{in}$ = temperature of pool water supply to MPC

With the MPC cavity water temperature limited to 150°F, MPC inlet water maximum temperature equal to 125°F and at the design basis maximum heat load, the water flow rate is determined to be 5210 lb/hr (10.5 gpm).

### 4.5.3 MPC Temperatures During Moisture Removal Operations

#### 4.5.3.1 Vacuum Drying Operation

The initial loading of SNF in the MPC requires that the water within the MPC be drained and replaced with helium. For MPCs containing moderate burnup fuel assemblies only, this operation may be carried out using the conventional vacuum drying approach. In this method, removal of the last traces of residual moisture from the MPC cavity is accomplished by evacuating the MPC for a short time after draining the MPC. Vacuum drying may not be performed on MPCs containing high burnup fuel assemblies or on MPCs with a decay heat load above a threshold level (see Subsection 4.5.5.2). High burnup or high decay heat fuel drying is performed by a forced flow helium drying process as described in Section 4.5.3.2 and Appendix 2.B.

Prior to the start of the MPC draining operation, both the HI-TRAC annulus and the MPC are full of water. The presence of water in the MPC ensures that the fuel cladding temperatures are lower than design basis limits by large margins. As the heat generating active fuel length is uncovered during the draining operation, the fuel and basket mass will undergo a gradual heat up from the initially cold conditions when the heated surfaces were submerged under water.

The vacuum condition effective fuel assembly conductivity is determined by procedures discussed earlier (Section 4.4) after setting the thermal conductivity of the gaseous medium to a small fraction (one part in one thousand) of helium conductivity. The MPC basket cross sectional effective conductivity is determined for vacuum conditions using a finite-element procedure. Basket periphery-to-MPC shell heat transfer occurs through conduction and radiation.

For total decay heat loads up to and including 20.88 kW for the MPC-24 and 21.52 kW for the MPC-68, vacuum drying of the MPC is performed with the annular gap between the MPC and the HI-TRAC filled with water. The presence of water in this annular gap will maintain the MPC shell temperature approximately equal to the saturation temperature of the annulus water. Thus, the thermal analysis of the MPC during vacuum drying for these conditions is performed with cooling of the MPC shell with water at a bounding maximum temperature of 232°F.

For higher total decay heat loads in the MPC-24 and MPC-68 or for any decay heat load in an MPC-24E or MPC-32, vacuum drying of the MPC is performed with the annular gap between the MPC and the HI-TRAC continuously flushed with water. The water movement in this annular gap will maintain the MPC shell temperature at about the temperature of flowing water. Thus, the thermal analysis of the MPC during vacuum drying for these conditions is performed with cooling of the MPC shell with water at a bounding maximum temperature of 125°F.

In addition, for MPC total decay heat loads greater than 23 kW, the duration of vacuum drying is limited to 40 hours. Imposing this time limit provides additional assurance, to account for uncertainty of 2-D models, that fuel cladding and cask component temperatures will remain below applicable limits.

An axisymmetric FLUENT thermal model of the MPC is constructed, employing the MPC in-plane conductivity as an isotropic fuel basket conductivity (i.e. conductivity in the basket radial and axial directions is equal), to determine peak cladding temperature at design basis heat loads. To avoid excessive conservatism in the computed FLUENT solution, partial recognition for higher axial heat dissipation is adopted in the peak cladding calculations. The boundary conditions applied to this evaluation are:

i. A bounding steady-state analysis is performed with the MPC decay heat load set equal to the largest decay heat load for which vacuum drying is permitted (see Subsection 4.5.5.2). As discussed above, there are two different ranges for the MPC-24 and MPC-68 designs.

ii. The entire outer surface of the MPC shell is postulated to be at a bounding maximum temperature of 232°F or 125°F, as discussed above.

iii. The top and bottom surfaces of the MPC are adiabatic.

Results of vacuum condition analyses are provided in Subsection 4.5.5.2.

4.5.3.2 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. A vapor pressure of 3 torr or less 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. See Appendix 2.B for 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 for normal conditions of storage, which is well below the high burnup cladding temperature limit 752°F (400°C) for all combinations of SNF type, burnup, decay heat, and cooling time. Because the FHD operation induces a state of forced convection heat transfer in the MPC, (in contrast to the quiescent mode of natural convection in long term storage), it is readily concluded that the peak fuel cladding temperature under the latter condition will be greater than that during the FHD operation phase. In the event that the FHD system malfunctions, the forced convection state will degenerate to natural convection, which corresponds to the conditions of normal onsite transport. As a result, the peak fuel cladding temperatures will approximate the values reached during normal onsite transport as described elsewhere in this chapter.

4.5.4 Cask Cooldown and Reflood Analysis During Fuel Unloading Operation

NUREG-1536 requires an evaluation of cask cooldown and reflood procedures to support fuel unloading from a dry condition. Past industry experience generally supports cooldown of cask internals and fuel from hot storage conditions by direct water quenching. Direct MPC cooldown is effectuated by introducing water through the lid drain line. From the drain line, water enters the MPC cavity near the MPC baseplate. Steam produced during the direct quenching process will be vented from the MPC cavity through the lid vent port. To maximize venting capacity, both vent port RVOA connections must remain open for the duration of the fuel unloading operations. As direct water quenching of hot fuel results in steam generation, it is necessary to limit the rate of water addition to avoid MPC overpressurization. For example, steam flow calculations using bounding assumptions (100% steam production and MPC at design pressure) show that the MPC is adequately protected upto a reflood rate of 3715 lb/hr. Limiting the water reflood rate to this amount or less would prevent exceeding the MPC design pressure.

4.5.5 Mandatory Limits for Short Term Operations

4.5.5.1 HI-TRAC Transport in a Vertical Orientation

The requirements and limits are listed in the following table:

| Condition | Fuel in MPC | MPC Heat Load (kW) | SCS Required |
|---|---|---|---|
| 1* | All MBF | ≤ 28.74 | NO |
| 2 | All MBF | > 28.74 | YES |
| 3 | One or more HBF | any | YES |
| * The highest temperatures are reached under this un-assisted cooling threshold heat load scenario. Under other conditions the mandatory use of the Supplemental Cooling System, sized to extract 36.9 kW from the MPC, will lower the fuel temperatures significantly assuring ISG 11, Rev. 3 compliance with large margins. | | | |

Condition 2 mandates the use of the SCS at heat loads greater than 28.74 kW for MBF. This will assure that cladding temperature limits are met at these higher heat loads. See Appendix 2.C for the SCS requirements.

It is recognized that, due to increased thermosiphon action, the temperature in the MPC under 7 atmospheres internal pressure (required in this amendment) will be lower than that for the conservative 5 atmospheres case on which Condition 1 is based. Therefore, there is an additional implicit margin in the fuel cladding temperatures incorporated in the short term operations by the use of the FSAR heat load limits herein.

An axisymmetric FLUENT thermal model of an MPC inside a HI-TRAC transfer cask was developed to evaluate temperature distributions for onsite transport conditions. A bounding steady-state analysis of the HI-TRAC transfer cask has been performed using the hottest MPC, the highest decay heat load for which SCS is not required, and design-basis insolation levels. While the duration of onsite transport may be short enough to preclude the MPC and HI-TRAC from obtaining a steady-state, a steady-state analysis is conservative.

A converged temperature contour plot is provided in Figure 4.5.2. Maximum fuel clad temperatures are listed in Table 4.5.4, which also summarizes maximum calculated temperatures in different parts of the HI-TRAC transfer cask and MPC. As described in Subsection 4.4.4.1, the FLUENT calculated peak temperature in Table 4.5.4 is actually the peak pellet centerline temperature, which bounds the peak cladding temperature. We conservatively assume that the peak clad temperature is equal to the peak pellet centerline temperature.

The maximum computed temperatures listed in Table 4.5.4 are based on the HI-TRAC cask at the maximum heat load that can be handled in HI-TRAC without needing the Supplemental Cooling System (see table above), passively rejecting heat by natural convection and radiation to a hot ambient environment at 100°F in still air in a vertical orientation. In this orientation, there is apt to be less metal-to-metal contact between the physically distinct entitities, viz., fuel, fuel basket, MPC shell and HI-TRAC cask. For this reason, the gaps resistance between these parts is higher than in a horizontally oriented HI-TRAC. To bound gaps resistance, the various parts are postulated to be in a centered configuration. MPC internal convection at a postulated low cavity pressure of 5 atm is included in the thermal model. The peak cladding temperature computed under these adverse Ultimate Heat Sink (UHS) assumptions is 872°F which is substantially lower than the temperature limit of 1058°F for moderate burnup fuel (MBF). Consequently, cladding integrity assurance is provided by large safety margins (in excess of 100°F) during onsite transfer of an MPC containing MBF emplaced in a HI-TRAC cask.

As a defense-in-depth measure, cladding integrity is demonstrated for a theoretical bounding scenario. For this scenario, all means of convective heat dissipation within the canister are neglected in addition to the bounding relative configuration for the fuel, basket, MPC shell and HI-TRAC overpack assumption stated earlier for the vertical orientation. This means that the fuel is centered in the basket cells, the basket is centered in the MPC shell and the MPC shell is centered in the HI-TRAC overpack to maximize gaps thermal resistance. The peak cladding temperature computed for this scenario (1025°F) is below the short-term limit of 1058°F.

For high burnup fuel (HBF), however, the maximum computed fuel cladding temperature reported in Table 4.5.4 is significantly greater than the temperature limit of 752°F for HBF. Consequently, it is necessary to utilize the SCS described at the beginning of this section and in Appendix 2.C during onsite transfer of an MPC containing HBF emplaced in a HI-TRAC transfer cask. As stated earlier, the exact design and operation of the SCS is necessarily site-specific. The design is required to satisfy the specifications and operational requirements of Appendix 2.C to ensure compliance with ISG-11 [4.1.4] temperature limits.

As discussed in Subsection 4.5.4, MPC fuel unloading operations are performed with the MPC inside the HI-TRAC cask. For this operation, a helium cooldown system is engaged to the MPC via lid access ports and a forced helium cooling of the fuel and MPC is initiated. With the HI-TRAC cask external surfaces dissipating heat to a UHS in a manner in which the ambient air access is not restricted by bounding surfaces or large objects in the immediate vicinity of the cask, the temperatures reported in Table 4.5.4 will remain bounding during fuel unloading operations.

#### 4.5.5.2 Moisture Removal Limits and Requirements

Vacuum Drying (VD) is permitted for MBF under certain conditions. If these conditions are not met, or if the MPC also contains HBF, then the FHD must be used for moisture removal. The requirements and limits are listed in the following table:

| Condition | Fuel in MPC | HI-TRAC Annulus Cooling Requirement | MPC Heat Load (kW) | Moisture Removal Method |
|---|---|---|---|---|
| 1 | All MBF | Standing Water | MPC-24: $\leq$ 20.88<br>MPC-24E: N/A**<br>MPC-32: N/A**<br>MPC-68: $\leq$ 21.52 | VD* |
| 2 | All MBF | Circulating Water | $\leq$ 28.74*** | VD* |
| 3 | All MBF | None | > 28.74 | FHD |
| 4 | One or more HBF | None | Any | FHD |

* The FHD drying method is also acceptable under the Condition 1 and Condition 2 heat loads, in which case HI-TRAC annulus cooling is not required.

** These MPC types cannot be vacuum dried with standing water. Circulating water (Condition 2) is required for these types.

*** Vacuum drying for MPC heat loads greater than 23 kW is limited to 40 hours.

Condition 3 mandates the use of the FHD at higher heat loads for MBF drying. This will assure that cladding temperature limits are met at these higher heat loads (See Paragraph 4.5.3.2).

As stated in Subsection 4.5.3.1, above, an axisymmetric FLUENT thermal model of the MPC is developed for the vacuum condition. For the MPC-24E and MPC-32 designs, and for the higher heat load ranges in the MPC-24 and MPC-68 designs, the model also includes an isotropic fuel basket thermal conductivity. Each MPC is analyzed at the maximum heat load for which vacuum drying is permitted. The steady-state peak cladding results, with partial recognition for higher axial heat dissipation where included, are summarized in Table 4.5.5. The peak fuel clad temperatures for moderate burnup fuel during short-term vacuum drying operations with design-basis maximum heat loads are calculated to be less than 1058°F for all MPC baskets by a significant margin.

4.5.6 Maximum Internal Pressure

After fuel loading and vacuum drying, but prior to installing the MPC closure ring, the MPC is initially filled with helium. During handling and on-site transfer operations in the HI-TRAC transfer cask, the gas temperature will correspond to the thermal conditions within the MPC. Based on the calculations described in Subsection 4.5.5.1 that yield conservative temperatures, the MPC internal pressure is determined for normal onsite transport conditions, as well as off-normal conditions of a postulated accidental release of fission product gases caused by fuel rod rupture. Based on NUREG-

1536 [4.4.1] recommended fission gases release fraction data, net free volume and initial fill gas pressure, the bounding maximum gas pressures with 1% and 10% rod rupture are given in Table 4.5.6. The MPC gas pressures listed in Table 4.5.6, based on a lower than prescribed helium backfill level, are all below the MPC design internal pressure listed in Table 2.2.1.

As stated in Section 4.5.5.1, the gas temperature in the MPC at any given heat load will be less than that computed using the conservative model described in this section which credits approximately 30% less helium than that prescribed. In accordance with the ideal gas law, the gas pressure rises in direct proportion to the increase in the average temperature of the MPC cavity from ambient temperature up to operating conditions. A lesser rise in temperature (due to increased thermosiphon action under actual helium backfill requirements) will result in a corresponding smaller rise in gas pressure. An approximately 40% increase in the initial gas pressure based on actual backfill requirements compared to analyzed backfill quantities, therefore, is mitigated by a smaller rise in the gas pressure. Noting that the gas pressure in the analyzed condition (see Table 4.5.6 and discussion in preceding paragraph) had over 100% margin against the analyzed maximum permissible pressure (200 psig per Table 2.2.1) the maximum pressure in the MPC is guaranteed to remain below 200 psig and thus the physical integrity of the confinement boundary is assured.

Table 4.5.1

EFFECTIVE RADIAL THERMAL CONDUCTIVITY OF THE WATER JACKET

| **Temperature (°F)** | **Thermal Conductivity (Btu/ft-hr-°F)** |
|---|---|
| 200 | 1.376 |
| 450 | 1.408 |
| 700 | 1.411 |

Table 4.5.2

HI-TRAC TRANSFER CASK LOWERBOUND WEIGHTS AND THERMAL INERTIAS

| **Component** | **Weight (lbs)** | **Heat Capacity (Btu/lb-°F)** | **Thermal Inertia (Btu/°F)** |
|---|---|---|---|
| Water Jacket | 7,000 | 1.0 | 7,000 |
| Lead | 52,000 | 0.031 | 1,612 |
| Carbon Steel | 40,000 | 0.1 | 4,000 |
| Alloy-X MPC (empty) | 39,000 | 0.12 | 4,680 |
| Fuel | 40,000 | 0.056 | 2,240 |
| MPC Cavity Water* | 6,500 | 1.0 | 6,500 |
| | | | 26,032 (Total) |
| * Conservative lower bound water mass. | | | |

Table 4.5.3

MAXIMUM ALLOWABLE TIME FOR WET TRANSFER OPERATIONS

| Initial Temperature (°F) | Time Duration (hr) |
|---|---|
| 115 | 19.4 |
| 120 | 18.4 |
| 125 | 17.4 |
| 130 | 16.4 |
| 135 | 15.4 |
| 140 | 14.4 |
| 145 | 13.4 |
| 150 | 12.4 |

Table 4.5.4

HI-TRAC TRANSFER CASK STEADY-STATE MAXIMUM TEMPERATURES

| Component | Temperature [°F] |
|---|---|
| Fuel Cladding | 872[1] |
| MPC Basket | 852 |
| Basket Periphery | 600 |
| MPC Outer Shell Surface | 455 |
| HI-TRAC Inner Shell Inner Surface | 322 |
| Water Jacket Inner Surface | 314 |
| Enclosure Shell Outer Surface | 224 |
| Water Jacket Bulk Water | 258 |
| Axial Neutron Shield2 | 258 |

Table 4.5.5

PEAK CLADDING TEMPERATURE IN VACUUM[3] (MODERATE BURNUP FUEL ONLY)

| MPC | Lower Decay Heat Load Range Temperatures (°F) | Higher Decay Heat Load Range Temperature (°F) |
|---|---|---|
| MPC-24 | 827 | 960 |
| MPC-68 | 822 | 1014 |
| MPC-32 | n/a | 1040 |
| MPC-24E | n/a | 942 |

1 This calculated value exceeds the allowable limit for high-burnup fuel. A Supplemental Cooling System that satisfies the criteria in Appendix 2.C shall be used to comply with applicable temperature limits when an MPC contains one or more high burnup fuel assemblies or exceeds a threshold heat load (see Section 4.5.5.1).

2 Local neutron shield section temperature.

3 Steady state temperatures at the MPC design maximum heat load reported.

Table 4.5.6

SUMMARY OF MPC CONFINEMENT BOUNDARY PRESSURES† FOR NORMAL HANDLING AND ONSITE TRANSPORT

| Condition | Pressure (psig) |
|---|---|
| MPC-24: | |
| Assumed initial backfill (at 70°F) | 31.3 |
| Normal condition | 76.0 |
| With 1% rod rupture | 76.8 |
| With 10% rod rupture | 83.7 |
| MPC-68: | |
| Assumed initial backfill (at 70°F) | 31.3 |
| Normal condition | 76.0 |
| With 1% rods rupture | 76.5 |
| With 10% rod rupture | 80.6 |
| MPC-32: | |
| Assumed initial backfill (at 70°F) | 31.3 |
| Normal condition | 76.0 |
| With 1% rods rupture | 77.1 |
| With 10% rod rupture | 86.7 |
| MPC-24E: | |
| Assumed initial backfill (at 70°F) | 31.3 |
| Normal condition | 76.0 |
| With 1% rods rupture | 76.8 |
| With 10% rod rupture | 83.7 |

† Includes gas from BPRA rods for PWR MPCs

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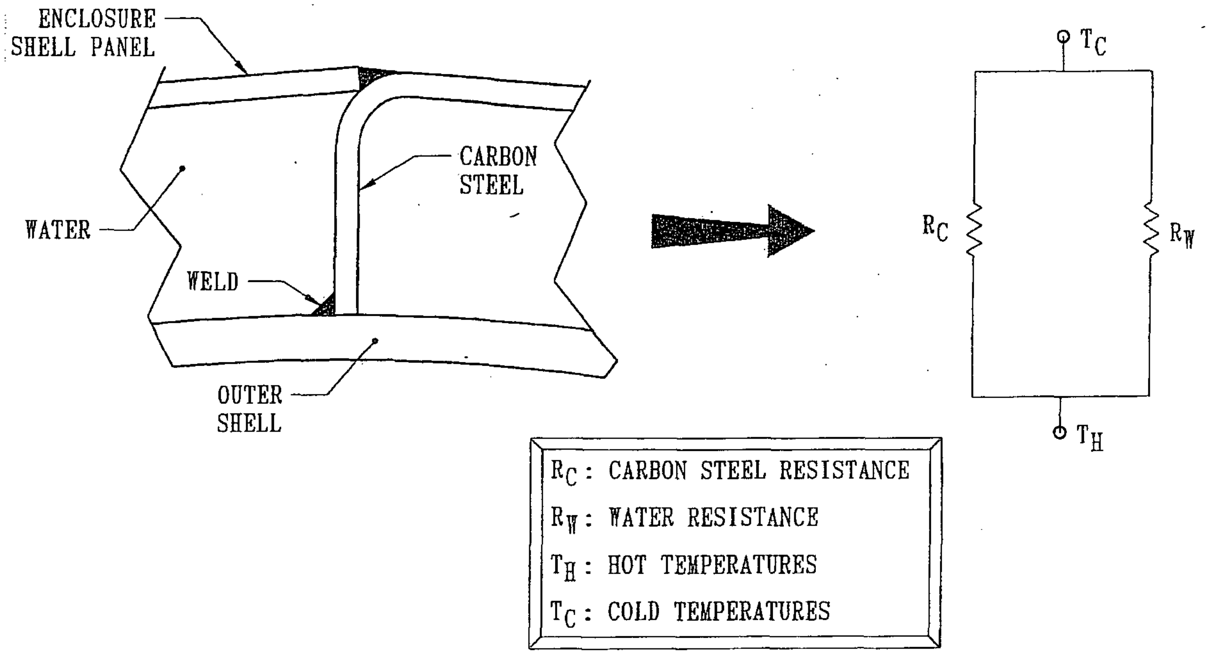


FIGURE 4.5.1; WATER JACKET RESISTANCE NETWORK ANALOGY FOR EFFECTIVE CONDUCTIVITY CALCULATION

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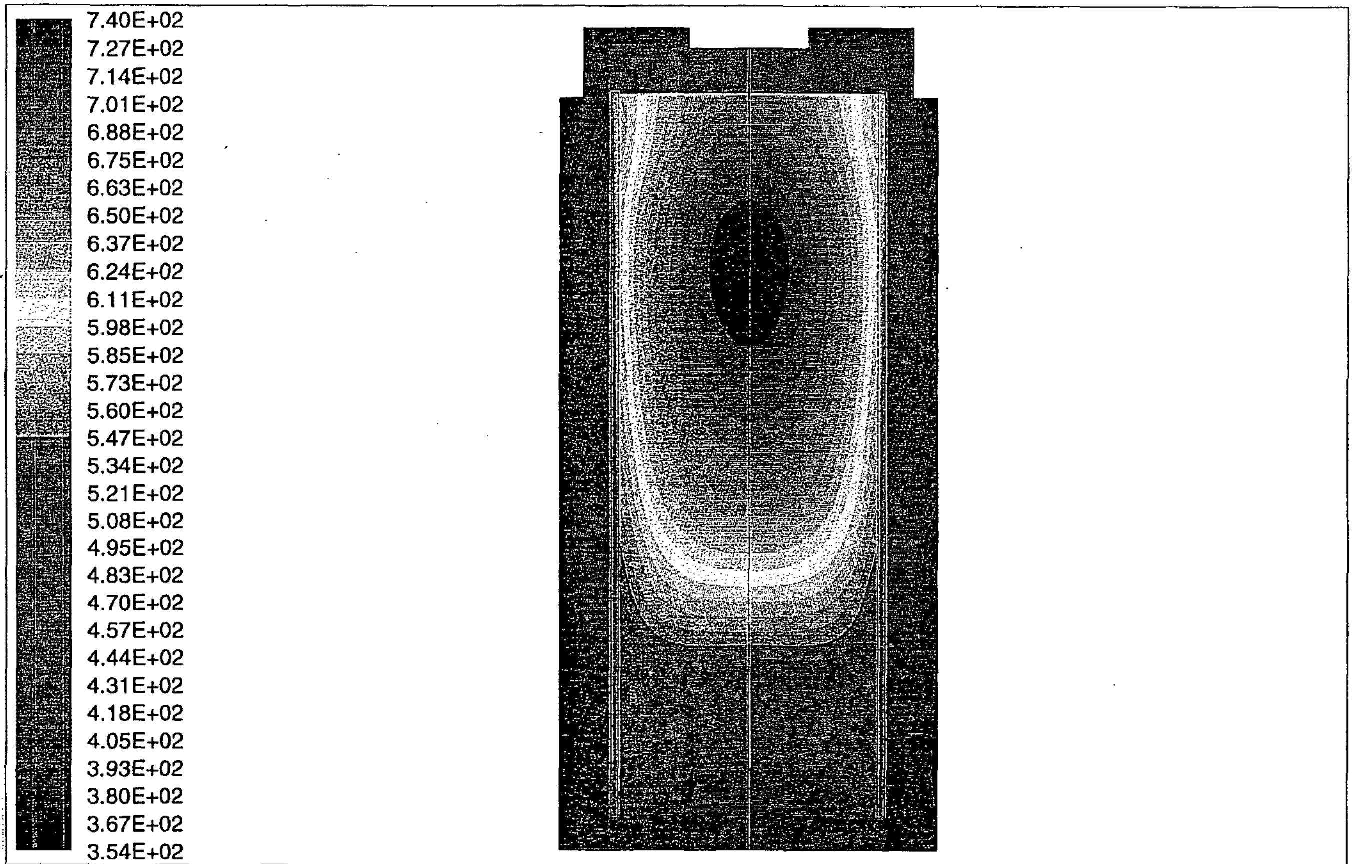


| | | |
|---|---|---|
| | FIGURE 4.5.2: HI-TRAC Temperature Contours Plot<br>Temperature (Degrees Kelvin)<br>Max = 7.398E+02 Min = 3.540E+02 | Aug 24 2000<br>Fluent 4.48<br>Fluent Inc. |

## 4.6 OFF-NORMAL AND ACCIDENT EVENTS[1]

In accordance with NUREG 1536 the HI-STORM 100 System is evaluated for the effects of off-normal and accident events. The design basis off-normal and accident events are defined in Chapter 2. For each event, the cause of the event, means of detection, consequences, and corrective actions are discussed and evaluated in Chapter 11. To support the Chapter 11 evaluations, thermal analyses of limiting off-normal and accident events are provided in the following.

To ensure a bounding evaluation for the array of fuel storage configurations permitted in Section 2.1, a limiting storage condition is evaluated in this section. The limiting storage condition is previously determined in the Section 4.5 and adopted herein for all off-normal and accident evaluations.

### 4.6.1 Off-Normal Events

#### 4.6.1.1 Off-Normal Pressure

This event is defined as a combination of (a) maximum helium backfill pressure (Table 4.4.12), (b) 10% fuel rods rupture, and (c) limiting fuel storage configuration. The principal objective of the analysis is to demonstrate that the MPC off-normal design pressure (Table 2.2.1) is not exceeded. The MPC off-normal pressures are reported in Table 4.4.9. The result[2] is confirmed to be below the off-normal design pressure (Table 2.2.1).

#### 4.6.1.2 Off-Normal Environmental Temperature

This event is defined by a time averaged ambient temperature of 100°F for a 3-day period (Table 2.2.2). The results of this event (maximum temperatures and pressures) are provided in Table 4.6.1 and 4.6.2. The results are below the off-normal condition temperature and pressure limits (Tables 2.2.1 and 2.2.3).

#### 4.6.1.3 Partial Blockage of Air Inlets

The HI-STORM 100 System is designed with debris screens installed on the inlet and outlet openings. These screens ensure the air passages are protected from entry and blockage by foreign objects. As required by the design criteria presented in Chapter 2, it is postulated that the HI-STORM air inlet vents are 50% blocked . The resulting decrease in flow area increases the flow resistance of the inlet ducts. The effect of the increased flow resistance on fuel temperature is analyzed for the normal ambient temperature (Table 2.2.2) and a limiting fuel storage configuration. The computed temperatures are reported in Table 4.6.1 and the corresponding MPC internal pressure in Table 4.6.2. The results are confirmed to be below the temperature limits (Table 2.2.3) and pressure limit (Table 2.2.1) for off-normal conditions.

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1 A new standalone Section 4.6 is added in CoC Amendment 3 to address thermal analysis of off-normal and accident events. The results are evaluated in Chapter 11.

2 Pressures relative to 1 atm absolute pressure (i.e. gauge pressures) are reported throughout this section.

### 4.6.2 Accident Events

#### 4.6.2.1 Fire Accidents

Although the probability of a fire accident affecting a HI-STORM 100 System during storage operations is low due to the lack of combustible materials at an ISFSI, a conservative fire event has been assumed and analyzed. The only credible concern is a fire from an on-site transport vehicle fuel tank. Under a postulated fuel tank fire, the outer layers of HI-TRAC or HI-STORM overpacks are heated for the duration of fire by the incident thermal radiation and forced convection heat fluxes. The amount of fuel in the on-site transporter is limited to a volume of 50 gallons.

(a) HI-STORM Fire

The fuel tank fire is conservatively assumed to surround the HI-STORM Overpack. Accordingly, all exposed overpack surfaces are heated by radiation and convection heat transfer from the fire. Based on NUREG-1536 and 10 CFR 71 guidelines [4.6.1], the following fire parameters are assumed:

1. The average emissivity coefficient must be at least 0.9. During the entire duration of the fire, the painted outer surfaces of the overpack are assumed to remain intact, with an emissivity of 0.85. It is conservative to assume that the flame emissivity is 1.0, the limiting maximum value corresponding to a perfect blackbody emitter. With a flame emissivity conservatively assumed to be 1.0 and a painted surface emissivity of 0.85, the effective emissivity coefficient is 0.85. Because the minimum required value of 0.9 is greater than the actual value of 0.85, use of an average emissivity coefficient of 0.9 is conservative.

2. The average flame temperature must be at least 1475°F (800°C). Open pool fires typically involve the entrainment of large amounts of air, resulting in lower average flame temperatures. Additionally, the same temperature is applied to all exposed cask surfaces, which is very conservative considering the size of the HI-STORM cask. It is therefore conservative to use the 1475°F (800°C) temperature.

3. The fuel source must extend horizontally at least 1 m (40 in), but may not extend more than 3 m (10 ft), beyond the external surface of the cask. Use of the minimum ring width of 1 meter yields a deeper pool for a fixed quantity of combustible fuel, thereby conservatively maximizing the fire duration.

4. The convection coefficient must be that value which may be demonstrated to exist if the cask were exposed to the fire specified. Based upon results of large pool fire thermal measurements [4.6.2], a conservative forced convection heat transfer coefficient of 4.5 Btu/(hr$\times$ft$^2\times$°F) is applied to exposed overpack surfaces during the short-duration fire.

Based on the 50 gallon fuel volume, the overpack outer diameter and the 1 m fuel ring width [4.6.1], the fuel ring surrounding the overpack covers 147.6 $ft^2$ and has a depth of 0.54 in. From this depth and a constant fuel consumption rate of 0.15 in/min, the fire duration is calculated to be 3.62 minutes. The fuel consumption rate of 0.15 in/min is a lowerbound value from a Sandia National Laboratories report [4.6.2]. Use of a lowerbound fuel consumption rate conservatively maximizes the duration of the fire.

To evaluate the impact of fire heating of the HI-STORM overpack, a thermal model of the overpack cylinder was constructed using the ANSYS computer code. The initial temperature of the overpack was conservatively assumed to be the maximum temperature field during storage (Table 4.4.7).. In this model the outer surface and top surface of the overpack were subjected for the duration of fire (3.62 minutes) to the fire conditions defined in this subsection. In the post-fire phase, the ambient conditions preceding the fire were restored. The transient study was conducted for a period of 5 hours, which is sufficient to allow temperatures in the overpack to reach their maximum values and begin to recede.

Due to the severity of the fire condition radiative heat flux, heat flux from incident solar radiation is negligible and is not included. Furthermore, the smoke plume from the fire would block most of the solar radiation. It is recognized that the ventilation air in contact with the inner surface of the HI-STORM Overpack with design-basis decay heat and normal ambient temperature conditions varies between 80°F at the bottom and 220°F at the top of the overpack. It is further recognized that the inlet and outlet ducts occupy a miniscule fraction of area of the cylindrical surface of the massive HI-STORM Overpack. Due to the short duration of the fire event and the relative isolation of the ventilation passages from the outside environment, the ventilation air is expected to experience little intrusion of the fire combustion products. As a result of these considerations, it is conservative to assume that the air in the HI-STORM Overpack ventilation passages is held constant at a substantially elevated temperature (300°F) during the entire duration of the fire event.

The thermal transient response of the storage overpack is determined using the ANSYS finite element program. Time-histories for points in the storage overpack are monitored for the duration of the fire and the subsequent post-fire equilibrium phase.

Heat input to the HI-STORM Overpack while it is subjected to the fire is from a combination of an incident radiation and convective heat fluxes to all external surfaces. This can be expressed by the following equation:

$$q_F = h_{fc}(T_A - T_S) + \sigma\varepsilon[(T_A + C)^4 - (T_S + C)^4]$$

where:

- $q_F$ =Surface Heat Input Flux (Btu/$ft^2$-hr)
- $h_{fc}$ = Forced Convection Heat Transfer Coefficient (4.5 Btu/$ft^2$-hr-°F)
- $\sigma$ = Stefan-Boltzmann Constant
- $T_A$ = Fire Temperature (1475°F)
- C= Conversion Constant (460 (°F to °R))
- $T_S$ = Surface Temperature (°F)

ε = Average Emissivity (0.90 per 10 CFR 71.73)

The forced convection heat transfer coefficient is based on the results of large pool fire thermal measurements [4.6.2].

After the fire event, the ambient temperature is restored and the storage overpack cools down (post-fire temperature relaxation). Heat loss from the outer surfaces of the storage overpack is determined by the following equation:

$$q_S = h_S (T_S - T_A) + \sigma\varepsilon[(T_S + C)^4 - (T_A + C)^4]$$

where:

$q_S$ =Surface Heat Loss Flux (W/m$^2$ (Btu/ft$^2$-hr))
$h_S$ = Natural Convection Heat Transfer Coefficient (Btu/ft$^2$-hr-$^o$F)
$T_S$ = Surface Temperature ($^o$F))
$T_A$ = Ambient Temperature ($^o$F)
σ = Stefan-Boltzmann Constant
ε = Surface Emissivity
C= Conversion Constant (460 ($^o$F to $^o$R))

In the post-fire temperature relaxation phase, $h_s$ is obtained using literature correlations for natural convection heat transfer from heated surfaces [4.2.9].

During the fire the overpack external shell temperatures are substantially elevated (~550$^o$F) and an outer layer of concrete approximately 1 inch thick reaches temperatures in excess of short term temperature limit. This condition is addressed specifically in NUREG-1536 (4.0,V,5.b), which states that:

> "The NRC accepts that concrete temperatures may exceed the temperature criteria of ACI 349 for accidents if the temperatures result from a fire."

These results demonstrate that the fire accident event analyzed in a most conservative manner is determined to have a minor affect on the HI-STORM Overpack. Localized regions of concrete are exposed to temperatures in excess of accident temperature limit. The bulk of concrete remains below the short term temperature limit. The temperatures of steel structures are within the allowable temperature limits.

Having evaluated the effects of the fire on the overpack, we now evaluate the effects on the MPC and contained fuel assemblies. Guidance for the evaluation of the MPC and its internals during a fire event is provided by NUREG-1536 (4.0,V,5.b), which states:

> "For a fire of very short duration (i.e., less than 10 percent of the thermal time constant of the cask body), the NRC finds it acceptable to calculate the fuel temperature increase by assuming that the cask inner wall is adiabatic. The fuel

temperature increase should then be determined by dividing the decay energy released during the fire by the thermal capacity of the basket-fuel assembly combination."

The time constant of the cask body (i.e., the overpack) can be determined using the formula:

$$\tau = \frac{c_p \times \rho \times L_c^2}{k}$$

where:

$c_p$ = Overpack Specific Heat Capacity (Btu/lb-°F)
$\rho$ = Overpack Density (lb/ft$^3$)
$L_c$ = Overpack Characteristic Length (ft)
k = Overpack Thermal Conductivity (Btu/ft-hr-°F)

The concrete contributes the majority of the overpack mass and volume, so we will use the specific heat capacity (0.156 Btu/lb-°F), density (142 lb/ft$^3$) and thermal conductivity (1.05 Btu/ft-hr-°F) of concrete for the time constant calculation. The characteristic length of a hollow cylinder is its wall thickness. The characteristic length for the HI-STORM Overpack is therefore 29.5 in, or approximately 2.46 ft. Substituting into the equation, the overpack time constant is determined as:

$$\tau = \frac{0.156 \times 142 \times 2.46^2}{1.05} = 128\, hrs$$

One-tenth of this time constant is approximately 12.8 hours (768 minutes), substantially longer than the fire duration of 3.62 minutes, so the MPC is evaluated by considering the MPC canister as an adiabatic boundary. The fuel temperature rise is computed next.

Table 4.5.2 lists lower-bound thermal inertia values for the MPC and the contained fuel assemblies. Applying a conservative upperbound decay heat load (38 kW (1.3x10$^5$ Btu/hr)) and adiabatic heating for the 3.62 minutes fire, the fuel temperature rise computes as:

$$\Delta T_{fuel} = \frac{\text{Decay heat} \times \text{Time duration}}{\text{(MPC + Fuel) heat capacities}} = \frac{1.3 \times 10^5 \text{ Btu/hr} \times (3.62/60)hr}{(2240 + 4680)\text{ Btu/}^\circ F} = 1.1^\circ F$$

This is a very small increase in fuel temperature. Consequently, the impact on the MPC internal helium pressure will be quite small. Based on a conservative analysis of the HI-STORM 100 System response to a hypothetical fire event, it is concluded that the fire event does not adversely affect the temperature of the MPC or contained fuel. We conclude that the ability of the HI-STORM 100 System to cool the spent nuclear fuel within design temperature limits during and after fire is not compromised.

(b) HI-TRAC Fire

The acceptability of fire-accident HI-TRAC condition following a 50-gallon fuel spill fire at a co-incident decay heat load of 28.74 kW has been ascertained under the HI-STORM CoC 1014, Amendment 2, as supported by HI-STORM FSAR Rev. 4. This fire accident evaluation is bounding up to the HI-TRAC un-assisted cooling threshold heat load, 28.74 kW, defined in Section 4.5.5 . At greater heat loads forced cooling of the MPC using the Supplemental Cooling System (SCS) defined in Section 2.C is mandatory (See Subsection 4.5.5.1, Conditions 2 and 3). The SCS, sized for 36.9 kW heat removal capacity, will insure that the cladding temperatures will be well below the temperatures under the threshold heat load scenario, when the SCS is not used. As such the SCS cooled HI-TRAC pre-fire thermal condition is bounded by the threshold heat load scenario. The principal HI-TRAC thermal loading during this accident (50-gallon fire heat input) is bounded by the CoC 1014-2 evaluation referenced above. Therefore the fire accident consequences are likewise bounded.

4.6.2.2 Jacket Water Loss

In this subsection, the fuel cladding and MPC boundary integrity is evaluated for a postulated loss of water from the HI-TRAC water jacket. The HI-TRAC is equipped with an array of water compartments filled with water. For a bounding analysis, all water compartments are assumed to lose their water and be replaced with air. As an additional measure of conservatism, the air in the water jacket is assumed to be motionless (i.e. natural convection neglected) and radiation heat transfer in the water jacket spaces ignored. The HI-TRAC is assumed to have the maximum thermal payload (design heat load) and assumed to have reached steady state (maximum) temperatures. Under these assumed set of adverse conditions, the maximum temperatures are computed and reported in Table 4.6.3. The results of jacket water loss evaluation confirm that the cladding, MPC and HI-TRAC component temperatures are below the limits prescribed in Chapter 2 (Table 2.2.3). The co-incident MPC pressure is also computed and compared with the MPC accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

4.6.2.3 Extreme Environmental Temperatures

To evaluate the effect of extreme weather conditions, an extreme ambient temperature (Table 2.2.2) is postulated to persist for a 3-day period. For a conservatively bounding evaluation the extreme temperature is assumed to last for a sufficient duration to allow the HI-STORM 100 System to reach steady state conditions. Because of the large mass of the HI-STORM 100 System, with its corresponding large thermal inertia and the limited duration for the extreme temperature, this assumption is conservative. Starting from a baseline condition evaluated in Section 4.4 (normal ambient temperature and limiting fuel storage configuration) the temperatures of the HI-STORM 100 System are conservatively assumed to rise by the difference between the extreme and normal ambient temperatures (45°F). The HI-STORM extreme ambient temperatures computed in this manner are reported in Table 4.6.4. The co-incident MPC pressure is also computed (Table 4.6.2) and compared with the accident design pressure (Table 2.2.1). The result is confirmed to be below the accident limit.

4.6.2.4 100% Blockage of Air Inlets

This event is defined as a complete blockage of all four bottom inlets. The immediate consequence of a complete blockage of the air inlets is that the normal circulation of air for cooling the MPC is stopped. An amount of heat will continue to be removed by localized air circulation patterns in the overpack annulus and outlet ducts, and the MPC will continue to radiate heat to the relatively cooler storage overpack. As the temperatures of the MPC and its contents rise, the rate of heat rejection will increase correspondingly. Under this condition, the temperatures of the overpack, the MPC and the stored fuel assemblies will rise as a function of time.

As a result of the considerable inertia of the storage overpack, a significant temperature rise is possible if the inlets are substantially blocked for extended durations. This accident condition is, however, a short duration event that is identified and corrected through scheduled periodic surveillance. Nevertheless, this event is conservatively analyzed assuming a substantial duration of blockage. The event is analyzed using the FLUENT CFD code. The HI-STORM thermal model is the same 3-Dimensional model constructed for normal storage conditions (see Section 4.4) except for the bottom inlet ducts, which are assumed to be impervious to air. Using this model, a transient thermal solution of the HI-STORM 100 System starting from normal storage conditions is obtained. The results of the blocked ducts transient analysis are presented in Table 4.6.5 and confirmed to be below the accident temperature limits (Table 2.2.3). The co-incident MPC pressure is also computed and compared with the accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

4.6.2.5 Burial Under Debris

Burial of the HI-STORM 100 System under debris is not a credible accident. During storage at the ISFSI there are no structures over the casks. Minimum regulatory distances from the ISFSI to the nearest ISFSI security fence precludes the close proximity of substantial amount of vegetation. There is no credible mechanism for the HI-STORM 100 System to become completely buried under debris. However, for conservatism, complete burial under debris is considered.

To demonstrate the inherent safety of the HI-STORM 100 System, a bounding analysis that considers the debris to act as a perfect insulator is considered. Under this scenario, the contents of the HI-STORM 100 System will undergo a transient heat up under adiabatic conditions. The minimum available time ($\Delta\tau$) for the fuel cladding to reach the accident limit depends on the following: (i) thermal inertia of the cask, (ii) the cask initial conditions, (iii) the spent nuclear fuel decay heat generation and (iv) the margin between the initial cladding temperature and the accident temperature limit. To obtain a lowerbound on $\Delta\tau$, the HI-STORM 100 Overpack thermal inertia (item i) is understated, the cask initial temperature (item ii) is maximized, decay heat overstated (item iii) and the cladding temperature margin (item iv) is understated. A set of conservatively postulated input parameters for items (i) through (iv) are summarized in Table 4.6.6. Using these parameters $\Delta\tau$ is computed as follows:

$$\Delta\tau = \frac{m \times c_p \times \Delta T}{Q}$$

where:

$\Delta\tau$ = Allowable burial time (hr)
m = Mass of HI-STORM System (lb)
$c_p$ = Specific heat capacity (Btu/lb-°F)
$\Delta T$ = Permissible temperature rise (°F)
Q = Decay heat load (Btu/hr)

Substituting the parameters in Table 4.6.6, a substantial burial time (34.6 hrs) is obtained. The co-incident MPC pressure is also computed and compared with the accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

Table 4.6.1
OFF-NORMAL CONDITION MAXIMUM
HI-STORM TEMPERATURES[3]

| **Location[4]** | **Off-Normal Ambient Temperature[5] (°F)** | **Partial Inlet Ducts Blockage (°F)** |
|---|---|---|
| Fuel Cladding | 731 | 725 |
| MPC Basket | 728 | 721 |
| MPC Shell | 489 | 478 |
| Overpack Inner Shell | 342 | 339 |
| Lid Concrete Bottom Plate | 322 | 321 |
| Lid Concrete Section Temperature | 266 | 260 |

Table 4.6.2
OFF-NORMAL AND ACCIDENT CONDITION MAXIMUM MPC PRESSURES

| **Condition** | **Pressure (psig)** |
|---|---|
| Off-Normal Conditions | |
| Off-Normal Ambient | 101.4 |
| Partial Blockage of Inlet Ducts | 100.4 |
| Accident Conditions | |
| Extreme Ambient Temperature | 104.4 |
| 100% Blockage of Air Inlets | 118.1 |
| Burial Under Debris | 134.8 |
| HI-TRAC Jacket Water Loss | 112.2 |

[3] The temperatures reported in this table are below the off-normal temperature limits specified in Chapter 2, Table 2.2.3.
[4] Temperatures of limiting components reported.
[5] Obtained by adding the off-normal-to-normal ambient temperature difference of 20°F (11.1°C) to normal condition HI-STORM temperatures reported in Section 4.4.

Table 4.6.3
HI-TRAC JACKET WATER LOSS ACCIDENT MAXIMUM TEMPERATURES

| Component | Temperature (°F) |
|---|---|
| Fuel Cladding | 824 |
| MPC Basket | 820 |
| MPC Shell | 526 |
| HI-TRAC Inner Shell | 463 |
| HI-TRAC Enclosure Shell | 281 |

Table 4.6.4
EXTREME ENVIRONMENTAL CONDITION MAXIMUM HI-STORM TEMPERATURES

| Component | Temperature[6] (°F) |
|---|---|
| Fuel Cladding | 756 |
| MPC Basket | 753 |
| MPC Shell | 514 |
| Overpack Inner Shell | 367 |
| Lid Concrete Bottom Plate | 347 |
| Lid Concrete Section Temperature | 291 |

6 Obtained by adding the extreme ambient to normal temperature difference (45°F) to normal condition temperatures reported in Section 4.4.

Table 4.6.5

32-HOURS BLOCKED INLET
DUCTS MAXIMUM HI-STORM TEMPERATURES

| Component | Temperatures@32 hrs (°F) |
|---|---|
| Fuel Cladding | 890 |
| MPC Basket | 884 |
| MPC Shell | 583 |
| Overpack Inner Shell | 480 |
| Lid Concrete Bottom Plate | 433 |
| Lid Concrete Section Temperature | 328 |

Table 4.6.6

SUMMARY OF INPUTS FOR BURIAL UNDER DEBRIS ANALYSIS

| | |
|---|---|
| Thermal Inertia Inputs:<br>M (Lowerbound HI-STORM 100 Weight)<br>Cp (Carbon steel heat capacity)[7] | <br>150000 lb<br>0.1 Btu/lb-°F |
| Cask initial temperature[8] | 728°F |
| Q (Decay heat) | $1.3 \times 10^5$ Btu/hr |
| $\Delta T$ (clad temperature margin)[9] | 300°F |

[7] Carbon steel has the lowest heat capacity among the principal materials employed in MPC and overpack construction (carbon steel, stainless steel and concrete).
[8] Conservatively overstated.
[9] The clad temperature margin is conservatively understated in this table.

Table 4.6.7

[Intentionally Deleted]

## 4.7 REGULATORY COMPLIANCE

### 4.7.1 Normal Conditions of Storage

NUREG-1536 [4.4.1] and ISG-11 [4.1.4] define several thermal acceptance criteria that must be applied to evaluations of normal conditions of storage. These items are addressed in Sections 4.1 through 4.4. Each of the pertinent criteria and the conclusion of the evaluations are summarized here.

As required by ISG-11 [4.1.4], the fuel cladding temperature at the beginning of dry cask storage is maintained below the anticipated damage-threshold temperatures for normal conditions for the licensed life of the HI-STORM System. Maximum clad temperatures for long-term storage conditions are reported in Section 4.4.

As required by NUREG-1536 (4.0,IV,3), the maximum internal pressure of the cask remains within its design pressure for normal, off-normal, and accident conditions, assuming rupture of 1 percent, 10 percent, and 100 percent of the fuel rods, respectively. Assumptions for pressure calculations include release of 100 percent of the fill gas and 30 percent of the significant radioactive gases in the fuel rods. Maximum internal pressures are reported in Sections 4.4, 4.5 and 4.6 for normal, short term operations, and off-normal & accident conditions. Design pressures are summarized in Table 2.2.1.

As required by NUREG-1536 (4.0,IV,4), all cask and fuel materials are maintained within their minimum and maximum temperature for normal and off-normal conditions in order to enable components to perform their intended safety functions. Maximum and minimum temperatures for long-term storage conditions are reported in Section 4.4. Design temperature limits are summarized in Table 2.2.3. HI-STORM System components defined as important to safety are listed in Table 2.2.6.

As required by NUREG-1536 (4.0,IV,5), the cask system ensures a very low probability of cladding breach during long-term storage. For long-term normal conditions, the maximum CSF cladding temperature is below the ISG-11 [4.1.4] limit of 400°C (752°F).

As required by NUREG-1536 (4.0,IV,7), the cask system is passively cooled. All heat rejection mechanisms described in this chapter, including conduction, natural convection, and thermal radiation, are completely passive.

As required by NUREG-1536 (4.0,IV,8), the thermal performance of the cask is within the allowable design criteria specified in FSAR Chapters 2 and 3 for normal conditions. All thermal results reported in Section 4.4 are within the design criteria allowable ranges for all normal conditions of storage.

### 4.7.2 Short Term Operations

Evaluation of short term operations is presented in Section 4.5. This section establishes complete compliance with the provisions of ISG-11 [4.1.4]. In particular, the ISG-11 requirement to ensure that maximum cladding temperatures under all fuel loading and short term operations be below 400°C (752°F) for high burnup fuel and below 570°C (1058°F) for moderate burnup fuel is demonstrated as stated below.

Specifically as required by ISG-11, the fuel cladding temperature is maintained below the applicable limits for HBF and MBF (Table 4.3.1) during short term operations.

As required by NUREG-1536 (4.0,IV,3), the maximum internal pressure of the cask remains within its design pressure for normal and off-normal conditions, assuming rupture of 1 percent and 10 percent of the fuel rods, respectively. Assumptions for pressure calculations include release of 100 percent of the fill gas and 30 percent of the significant radioactive gases in the fuel rods.

As required by NUREG-1536 (4.0,IV, 4), all cask and fuel materials are maintained within their minimum and maximum temperature for all short term operations in order to enable components to perform their intended safety functions.

As required by NUREG-1536 (4.0,IV,8), the thermal performance of the cask is within the allowable design criteria specified in FSAR Chapters 2 and 3 for all short term operations.

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# APPENDIX 4.A:

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# APPENDIX 4.B

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## SUPPLEMENT 4.I

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SUPPLEMENT 4.II

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