CHAPTER 4* THERMAL EVALUATION

4.0 OVERVIEW

The HI-STORM FW system is designed for long-term storage of spent nuclear fuel (SNF) in a vertical orientation. The design envisages an array of HI-STORM FW systems laid out in a rectilinear pattern stored on a concrete ISFSI pad in an open environment. In this chapter, compliance of HI-STORM FW system's thermal performance to 10CFR72 requirements for outdoor storage at an ISFSI using 3-D thermal simulation models is established. The analyses consider passive rejection of decay heat from the stored SNF assemblies to the environment under normal, off-normal, and accident conditions of storage. 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 FW system are quantified. Safe thermal performance during on-site loading, unloading and transfer operations, collectively referred to as "short-term operations" utilizing the HI-TRAC VW transfer cask is also evaluated.

The HI-STORM FW thermal evaluation follows the guidelines of NUREG-1536 [4.4.1] and ISG-11 [4.1.4]. These guidelines provide specific limits on the permissible maximum cladding temperature in the stored commercial spent fuel (CSF)† 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 must meet the temperature limit under normal, off-normal and accident conditions appropriate to its burnup level and condition of storage or handling set forth in Table 4.3.1.
2. The maximum internal pressure of the MPC should remain within its design pressures for normal, off-normal, and accident conditions set forth in Table 2.2.1.
3. The temperatures of the cask materials shall remain below their allowable limits set forth in Table 2.2.3 under all scenarios.

As demonstrated in this chapter, the HI-STORM FW 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 of storage, handling and on-site transfer operations. All thermal analyses to evaluate normal conditions of storage in a HI-STORM FW storage module are described in Section 4.4. All thermal analyses to evaluate normal handling and on-site transfer in a HI-TRAC VW 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 SAR chapter is in full

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* 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. All terms-of-art used in this chapter are consistent with the terminology of the Glossary. Finally, all evaluations and results presented in this Chapter are supported by calculation packages cited herein (References [4.1.9] and [4.1.10]).

† Defined as nuclear fuel that is used to produce energy in a commercial nuclear reactor (See Glossary).

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

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

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

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

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

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

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

4.1 DISCUSSION

The aboveground HI-STORM FW 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 (see Figure 4.1.1). The SNF assemblies reside inside the MPC, which is sealed with a welded lid to form the Confinement Boundary. The MPC contains a Metamic-HT egg-crate 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. The MPC is backfilled with helium to the design-basis pressures (Table 4.4.8). This provides a stable, inert environment for long-term storage of the SNF. Heat is rejected from the SNF in the HI-STORM FW 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 4.1.2. 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 4.1.1. To ensure that the helium gas is retained and is not diluted by lower conductivity air, the MPC Confinement Boundary is designed as an all-seal-welded pressure vessel with redundant closures. It is demonstrated in Section 12.1 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 is credited in the thermal analyses.

An important thermal design criterion imposed on the HI-STORM FW system is to limit the maximum fuel cladding temperature as well as the fuel basket temperature to within design basis limits 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, as summarized below.

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 egg-crate basket structure. The MPC design incorporates top and bottom plenums with interconnected downcomer paths formed by the annulus gap in the aluminum shims. The top plenum is formed by the gap between the bottom of the MPC lid and the top of the honeycomb fuel basket. The bottom plenum is formed by flow holes near the base of all cell walls. The MPC basket is designed to minimize 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.

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

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

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

Table 4.1.1

HI-STORM FW OPERATING CONDITION PARAMETERS

Condition	**Value**
MPC Decay Heat, max.	Tables 1.2.3 and 1.2.4
MPC Operating Pressure	Note 1
Normal Ambient Temperature	Table 2.2.2
Helium Backfill Pressure	Table 4.4.8

Note 1: The MPC operating pressure used in the thermal analysis is based on the minimum helium backfill pressure specified in Table 4.4.8 and MPC cavity average temperature.

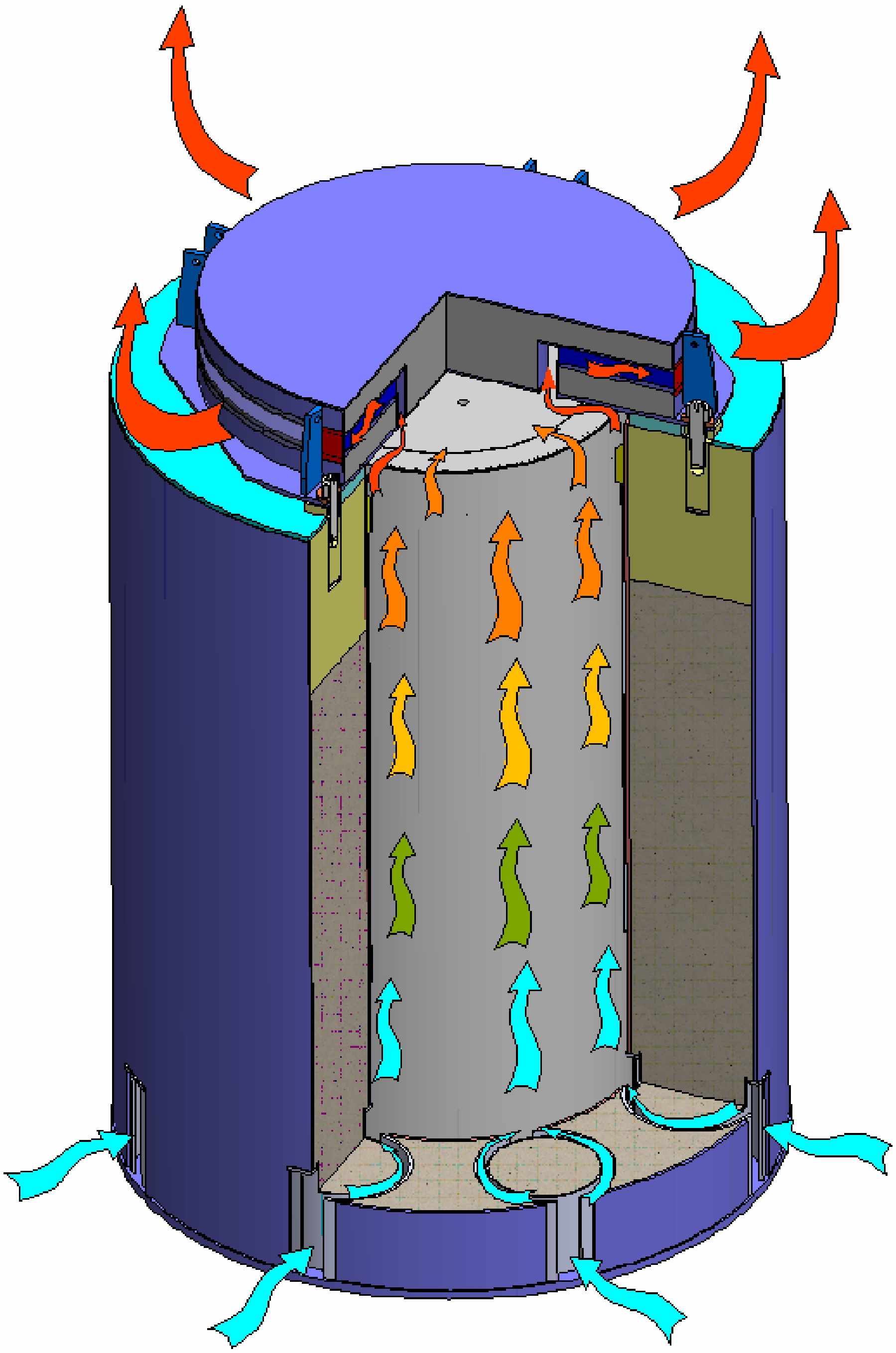

Figure 4.1.1: Ventilation Flow in the HI-STORM FW System

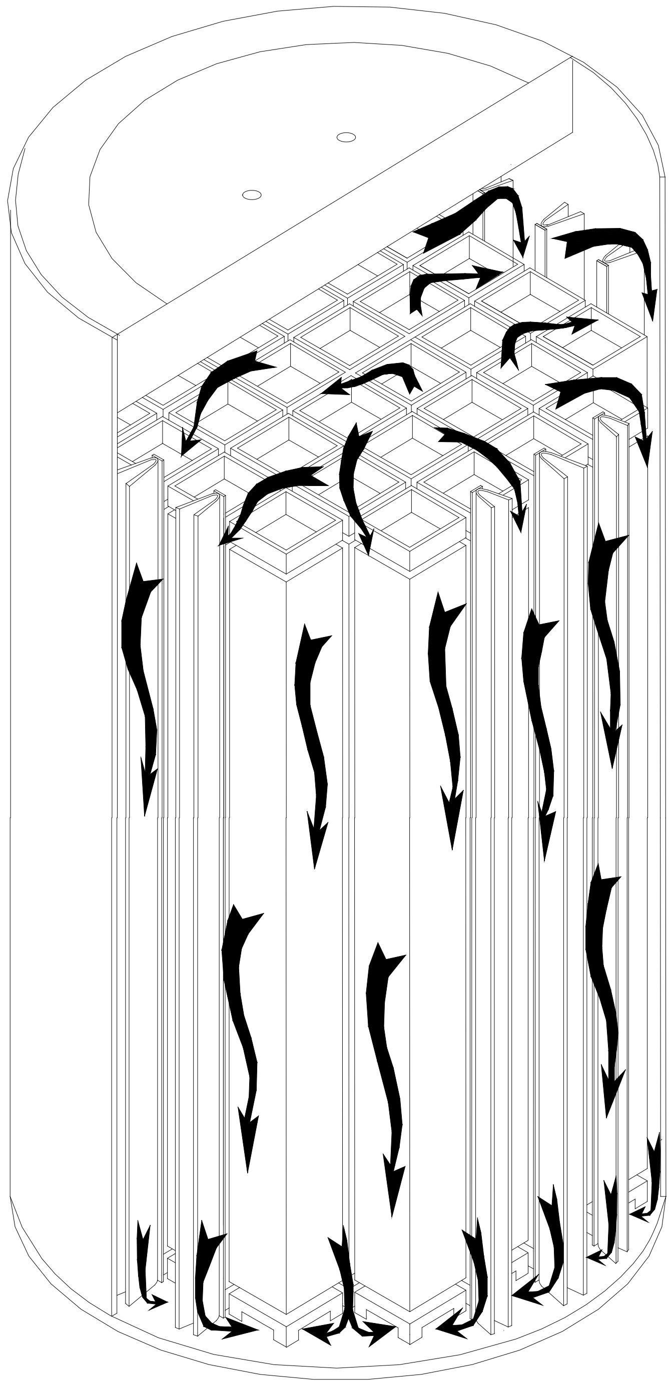

Figure 4.1.2: Illustration of MPC Internal Helium Circulation

4.2 SUMMARY OF THERMAL PROPERTIES OF MATERIALS

The thermo-physical properties listed in the tables in this section are identical to those used in the HI-STORM 100 FSAR [4.1.8], except for Metamic-HT and aluminum shims. Materials present in the MPCs include Alloy X*, Metamic-HT, aluminum alloy 2219, and helium. Materials present in the HI-STORM FW storage overpack include carbon steels and concrete. Materials present in the HI-TRAC VW transfer cask include carbon steel, lead, air, 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.

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 FW thermal analysis, an emissivity of 0.85† is applied to painted surfaces. The solar absorbtivity, α_s of paints are generally low. The NASA technical publication [4.2.20] reports α_s in the range of 0.03 to 0.54. For a robustly bounding analysis α_s equal to 0.85 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 $L^3 \Delta T Z$, where L is height of the overpack, ΔT 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.

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* Alloy X is defined in Appendix 1.A to designate a group of stainless steel alloys permitted for use in the HI-STORM FW system. In this chapter the terms Alloy X and stainless steel are used interchangeably.

† 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 FW SYSTEM MATERIALS
THERMAL PROPERTY REFERENCES

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

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

Note 2: Used in the MPC lid.

Note 3: Used in the MPC shell and baseplate.

Table 4.2.2

SUMMARY OF HI-STORM FW SYSTEM MATERIALS
THERMAL CONDUCTIVITY DATA

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

* 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

* See Table 4.2.1 for cited references.

Table 4.2.4

SUMMARY OF MATERIALS SURFACE EMISSIVITY DATA*

Material	Emissivity
Zircaloy	0.80
Painted surfaces	0.85
Stainless steel (machined forgings)	0.36
Stainless Steel Plates	0.587**
Carbon Steel	0.66
Metamic-HT***	Table 1.2.8
Aluminum Alloy 2219 ***	Table 1.2.8

* See Table 4.2.1 for cited references.

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

*** [**Withheld in Accordance with 10 CFR 2.390**]

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
Air	(Ideal Gas Law)	0.24
Zircaloy	409	0.0728
Fuel (UO_2)	684	0.056
Carbon steel	489	0.1
Stainless steel	501	0.12
Concrete	140**	0.156
Lead	710	0.031
Water	62.4	0.999
Metamic-HT	Table 1.2.8	Table 1.2.8
Aluminum Alloy 2219	177.3	0.207

* See Table 4.2.1 for cited references.

** Conservatively understated value.

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 ($ft^{-3}{}^{\circ}F^{-1}$)***
40	2.1×10^{6}
140	9.0×10^{5}
240	4.6×10^{5}
340	2.6×10^{5}
440	1.5×10^{5}

* Obtained from Jakob and Hawkins [4.2.9]

4.3 SPECIFICATIONS FOR COMPONENTS

HI-STORM FW 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) are summarized in Tables 2.2.3. The thermal bases supporting the temperature limits are provided in Table 4.3.1. Long-term integrity of SNF is ensured by the HI-STORM FW system thermal evaluation which demonstrates that fuel cladding temperatures are maintained below design basis limits. [

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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 FW system thermal performance, material temperature limits under normal, short-term operations, and off-normal and accident conditions are provided in Table 2.2.3. Fuel temperature limits mandated by ISG-11 [4.1.4] are adopted for evaluation of cladding integrity under normal, short term operations, off-normal and accident conditions. These limits are applicable to all fuel types, burnup levels and cladding materials approved by the NRC for power generation.

Table 4.3.1 TEMPERATURE LIMITS OF CRITICAL COMPONENTS, ºF		
Fuel Cladding (Note 1)		
Condition	MBF	HBF
Normal storage	Table 2.2.3	Table 2.2.3
Short-term operations	Table 2.2.3	Table 2.2.3
Off-normal and Accident conditions	Table 2.2.3	Table 2.2.3
Metamic-HT (Note 2)		
Normal storage	Table 2.2.3	
Short term operations, Off-Normal and Accident conditions	Table 2.2.3	
Aluminum Shims (Note 3)		
Normal storage	Table 2.2.3	
Short term operations, Off-normal and Accident conditions	Table 2.2.3	
HI-TRAC VW Jacket		
Short term operations and off-normal conditions	Table 2.2.3 (Note 4)	
Accident condition	NA (Note 5)	

Notes:
1. Temperature limits per ISG-11, Rev. 3 [4.1.4].
2. The B_4C component in Metamic-HT is a refractory material that is unaffected by high temperature (on the order of 1000ºF) and the aluminum component is solid at temperatures in excess of 1000ºF.
3. To preclude melting the temperature limits are set well below the melting temperature of Aluminum Alloys.
4. Temperature limit is defined by the saturation temperature of water at water jacket design pressure specified in Table 2.2.1.
5. The jacket water is assumed to be lost under accident conditions.

4.4 THERMAL EVALUATION FOR NORMAL CONDITIONS OF STORAGE

The HI-STORM FW Storage System (i.e., HI-STORM FW overpack and MPC) and HI-TRAC VW transfer cask thermal evaluation is performed in accordance with the guidelines of NUREG-1536 [4.4.1] and ISG-11 [4.1.4]. To ensure a high level of confidence in the thermal evaluation, 3-dimensional models of the MPC, HI-STORM FW overpack and HI-TRAC VW transfer cask are constructed to evaluate fuel integrity under normal (long-term storage), off-normal and accident conditions and in the HI-TRAC VW transfer cask under short-term operation and hypothetical accidents. The principal features of the thermal models are described in this section for HI-STORM FW and Section 4.5 for HI-TRAC VW. Thermal analyses results for the long-term storage scenarios are obtained and reported in this section. The evaluation addresses the design basis thermal loadings defined in Chapter 1, Tables 1.2.3 (MPC-37, Patterns A and B) and 1.2.4 (MPC-89). Based on these evaluations the limiting thermal loading condition is defined in Subsection 4.4.4 and adopted for evaluation of on-site transfer in the HI-TRAC (Section 4.5) and off-normal and accident events defined in Section 4.6.

4.4.1 Overview of the Thermal Model

As illustrated in the drawings in Section 1.5, the basket is a matrix of interconnected square compartments designed to hold the fuel assemblies in a vertical position under long term storage conditions. The basket is a honeycomb structure of Metamic-HT plates that are slotted and arrayed in an orthogonal configuration to form an integral basket structure. [

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

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

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

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 lowest values reached at the periphery of the basket.

As noted in Chapter 1 and in Section 3.2, the height of the PWR MPC cavity can vary within a rather large range to accommodate spent nuclear fuel of different lengths. The heat load limits in Table 1.2.3 (PWR MPC) and Table 1.2.4 (BWR MPC) for regionalized storage are, however, fixed regardless of the fuel (and hence MPC cavity) length. Because it is not a'priori obvious whether the shortest or the longest fuel case will govern, thermal analyses are performed for the lowerbound, upperbound and reference-height MPCs.

4.4.1.1 Description of the 3-D Thermal Model

i. Overview

The HI-STORM FW System is equipped with two MPC designs, MPC-37 and MPC-89 engineered to store 37 and 89 PWR and BWR fuel assemblies respectively. 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]. Because the fuel basket is made of a single isotropic material (Metamic-HT), the 3-D thermal model requires no idealizations of the fuel basket structure. However, 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 cell cross-section is discussed under item (ii) below. 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). The methodology to represent the spent fuel storage space as a homogeneous region with equivalent conductivities is identical to that used in the HI-STORM 100 Docket No. 72-1014 [4.1.8].

ii. Details of the 3-D Model

The HI-STORM FW fuel basket is modeled in the same manner as the model described in the HI-STAR 180 SAR (NRC Docket No. 71-9325) [4.1.11]. Modeling details are provided in the following:

<u>Fuel Basket 3D Model</u>
The MPC-37 and MPC-89 fuel baskets are essentially an array of square cells within an irregularly shaped basket outline. The fuel basket is confined inside a cylindrical cavity of the

MPC shell. Between the fuel basket-to-shell spaces, thick Aluminum basket shims are installed to facilitate heat dissipation. To ensure an adequate representation of the fuel basket a geometrically accurate 3D model of the array of square cells and Metamic-HT plates is constructed using the FLUENT pre-processor. Other than the representation of fuel assemblies inside the storage cell spaces as porous region with effective thermal-hydraulic properties as described in the next paragraph, the 3D model includes an explicit articulation of other canister parts... The basket shims are explicitly modeled in the peripheral spaces. The fuel basket is surrounded by the MPC shell and outfitted with a solid welded lid above and a baseplate below. All of these physical details are explicitly articulated in a quarter-symmetric 3D thermal model of the HI-STORM FW.

Fuel Region Effective Planar Conductivity

In the HI-STORM FW thermal modeling, the cross section bounded by the inside of a PWR storage cell and the channeled area of a BWR storage cell is replaced with an "equivalent" square section characterized by an effective thermal conductivity in the planar and axial directions. Figure 4.4.1 pictorially illustrates this concept. The two conductivities are unequal because while in the planar direction heat dissipation is interrupted by inter-rod gaps; in the axial direction heat is dissipated through a continuous medium (fuel cladding). The equivalent planar conductivity of the storage cell space is obtained using a 2D conduction-radiation model of the bounding PWR and BWR fuel storage scenarios defined in the table below. The fuel geometry, consisting of an array of fuel rods with helium gaps between them residing in a storage cell, is constructed using the ANSYS code [4.1.1] and lowerbound conductivities under the assumed condition of stagnant helium (no-helium-flow-condition) are obtained. In the axial direction, an area-weighted average of the cladding and helium conductivities is computed. Axial heat conduction in the fuel pellets is conservatively ignored.

The effective fuel conductivity is computed under three bounding fuel storage configurations for PWR fueled MPC-37 and one bounding scenario for BWR fueled MPC-89. The fuel storage configurations are defined below:

Storage Scenario	MPC	Fuel
PWR: Short Fuel	Minimum Height MPC-37	14x14 Ft. Calhoun
PWR: Standard Fuel	Reference Height MPC-37	W-17x17
PWR: XL Fuel	Maximum Height MPC-37	AP1000
BWR	MPC-89	GE-10x10

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

Heat Rejection from External Surfaces

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

Turbulent range:

$$h = 0.19\,(\Delta T)^{1/3}\ (\text{Vertical}, GrPr > 10^9)$$
$$h = 0.18\,(\Delta T)^{1/3}\ (\text{Horizontal Cylinder}, GrPr > 10^9)$$
$$(\text{in conventional U.S. units})$$

Laminar range:

$$h = 0.29\,\left(\frac{\Delta T}{L}\right)^{1/4}\ (\text{Vertical}, GrPr < 10^9)$$
$$h = 0.27\,\left(\frac{\Delta T}{D}\right)^{1/4}\ (\text{Horizontal Cylinder}, GrPr < 10^9)$$
$$(\text{in conventional U.S. Units})$$

where ΔT is the temperature differential between the cask's exterior surface and ambient air and GrPr is the product of Grashof and Prandtl numbers. During storage conditions, the cask cylinder and top surfaces are cooled by natural convection. The corresponding length scales L for these surfaces are the cask diameter and length, respectively. As described in Section 4.2, Gr×Pr can be expressed as $L^3\Delta TZ$, where Z (from Table 4.2.7) is at least 2.6×10^5 at a conservatively high surface temperature of 340°F. Thus the turbulent condition is always satisfied assuming a lowerbound L (8 ft) and a small ΔT (~10°F).

Determination of Solar Heat Input

The intensity of solar radiation incident on exposed surfaces depends on a number of time varying parameters. The solar heat flux strongly depends upon the time of the day as well as on latitude and day of the year. Also, the presence of clouds and other atmospheric conditions (dust, haze, etc.) can significantly attenuate solar intensity levels. In the interest of conservatism, the effects of dust, haze, angle of incidence, latitude, etc. that act to reduce insolation, are neglected.

The insolation energy absorbed by the HI-STORM FW is the product of incident insolation and surface absorbtivity. To model insolation heating a reasonably bounding absorbtivity equal to 0.85 is incorporated in the thermal models. The HI-STORM FW thermal analysis is based on 12-hour daytime insolation specified in Article 71.71(c) (1) of the Transport Regulations [4.6.1].

During long-term storage, the HI-STORM FW Overpack is cyclically subjected to solar heating during the 12-hour daytime period followed by cooling during the 12-hour nighttime. Due to the large mass of metal and the size of the cask, the dynamic time lag exceeds the 12-hour heating period. Accordingly, the HI-STORM FW model includes insolation on exposed surfaces averaged over a 24-hour time period.

HI-STORM FW Annulus

The HI-STORM FW is engineered with internal flow passages to facilitate heat dissipation by ventilation action. During fuel storage ambient air is drawn from intake ducts by buoyancy forces generated by the heated column of air in the HI-STORM FW annulus. The upward moving air extracts heat from the MPC external surfaces by convection heat transfer. As great bulk of the heat is removed by the annulus air, the adequacy of the grid deployed to model annulus heat transfer must be confirmed prior to performing design basis calculations. To this end a grid sensitivity study is conducted in Subsection 4.4.1.6 to define the converged grid discretization of the annulus region. The converged grid is deployed to evaluate the thermal state of the HI-STORM FW system under normal, off-normal and accident conditions of storage.

iii. Principal Attributes of the 3D Model

The 3-D model implemented to analyze the HI-STORM FW system is entirely based on the HI-STORM 100 thermal model except that the radiation effect is simulated by the more precise "DO" model (in lieu of the DTRM model used in HI-STORM 100) in FLUENT in the manner of HI-STAR 180 in docket 71-9325. This model has the following key attributes:

a) The fuel storage spaces are modeled as porous media having effective thermal-hydraulic properties.

b) In the case of BWR MPC-89, 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 channeled space within is also referred to as the "rodded region" that is modeled as a porous medium. The fuel assembly is assumed to be positioned coaxially with respect to its storage cell. The MPC-89 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 models for both the BWR and PWR storage geometries are constructed for the Design Basis fuel defined in Table 2.1.4. The model contains comprehensive details of the fuel which includes grid straps, BWR water rods and PWR guide and instrument tubes (assumed to be plugged for conservatism).

c) The effective conductivities of the MPC storage spaces are computed for bounding fuel storage configurations defined in Paragraph 4.4.1.1(ii). The in-plane thermal conductivities 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) is enabled in these models. Using these models the effective conduction-radiation conductivities are obtained and reported in Table 4.4.1. For heat transfer in the axial direction an area weighted mean of cladding and helium conductivities are computed (see Table 4.4.1). 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. In the interest of conservatism, thermal analysis of normal storage condition in HI-STORM FW and normal onsite transfer condition in HI-TRAC VW (Section 4.5) are performed with a 10% reduced effective thermal conductivity of fuel region.

d) The internals of the MPC, including the basket cross-section, aluminum shims, bottom flow holes, top plenum, and circumferentially irregular downcomer formed by the annulus gap in the aluminum shims are modeled explicitly. For simplicity, the flow holes are modeled as rectangular openings with an understated flow area.

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

g) A limited number of fuel assemblies (upto 12 in MPC-37 and upto 16 in MPC-89) classified as damaged fuel are permitted to be stored in the MPC inside Damaged Fuel Containers (DFCs). A DFC can be stored in the outer peripheral locations of both MPC-37 and MPC-89 as shown in Figures 2.1.1 and 2.1.2, respectively. DFC emplaced fuel assemblies have a higher resistance to helium flow because of the debris screens. However, DFC fuel storage does not affect temperature of hot fuel stored in the core of the basket because DFC storage is limited by Technical Specifications for placement in the peripheral storage locations away from hot fuel. For this reason the thermal modeling of the fuel basket under the assumption of all storage spaces populated with intact fuel is justified.

h) As shown in HI-STORM FW drawings in Section 1.5 the HI-STORM FW overpack is equipped with a heat shield to protect the inner shell and concrete from radiation heating by the emplaced MPC. The heat shield, inner and outer shells and concrete are explicitly modeled.

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

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

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

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

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

1) The storage cell spaces are loaded with high flow resistance design basis fuel assemblies (See Table 2.1.4).
2) Each storage cell is generating heat at its limiting value under the regionalized storage scenarios defined in Chapter 2, Section 2.1.
3) Axial dissipation of heat by conduction in the fuel pellets is neglected.
4) Dissipation of heat from the fuel rods by radiation in the axial direction is neglected.
5) The fuel assembly channel length for BWR fuel is overstated.
6) The most severe environmental factors for long-term normal storage - ambient temperature of 80°F and 10CFR71 insolation levels - were coincidentally imposed on the system.
7) Reasonably bounding solar absorbtivity of HI-STORM FW overpack external surfaces is applied to the thermal models.
8) To understate MPC internal convection heat transfer, the helium pressure is understated.
9) No credit is taken for contact between fuel assemblies and the MPC basket wall or between the MPC basket and the basket supports.
10) Heat dissipation by fuel basket peripheral supports is neglected.
11) Lowerbound fuel basket emissivity function defined in the Metamic-HT Sourcebook [4.2.6] is adopted in the thermal analysis.

12) Lowerbound stainless steel emissivity obtained from cited references (See Table 4.2.1) are applied to MPC shell.
13) The k-ω model used for simulating the HI-STORM FW annulus flow yields uniformly conservative results [4.1.6].
14) Fuel assembly length is conservatively modeled equal to the height of the fuel basket.

The effect of crud resistance on fuel cladding surfaces has been evaluated and found to be negligible [4.1.8]. The evaluation assumes a thick crud layer (130 μm) with a bounding low conductivity (conductivity of helium). The crud resistance increases the clad temperature by a very small amount (~0.1^{o}F) [4.1.8]. Accordingly this effect is neglected in the thermal evaluations.

4.4.1.2 Fuel Assembly 3-Zone Flow Resistance Model*

The HI-STORM FW System is evaluated for storage of representative PWR and BWR fuel assemblies determined by a separate analysis, to provide maximum resistance to the axial flow of helium. These are (i) PWR fuel: W17x17 and (ii) BWR fuel: GE10x10. 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 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 FW 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:

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

where $\Delta P/L$ is the hydraulic pressure loss per unit length, D is the flow resistance coefficient, μ is the fluid viscosity and V is the superficial fluid velocity. In the HI-STORM FW thermal

* This Sub- section duplicates the methodology used in the HI-STORM FSAR, Rev. 7, supporting CoC Amendment # 5 in Docket 72-1014 [4.1.8].

models the fuel storage cell length between the bottom and top plenums* 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 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

The flow resistance coefficients computed from the 3D flow models [4.4.2] are adopted herein for an MPC-89. In the interest of conservatism, a flow resistance of 1×10^{6} m^{-2} adopted for thermal hydraulic analysis in Docket 72-1014 CoC amendment 9 is used for PWR fuel assemblies.

4.4.1.3 Bounding Flow Resistance Data

Holtec report [4.4.2] has identified W17x17 OFA and GE 12/14 10x10 fuel assemblies as the design basis fuel for computing the flow resistance coefficients required to compute the in-cell flow of helium in PWR storage cells and of in-channel flow of channeled BWR assemblies placed in a BWR storage cell (See Figure 4.4.4). These resistance coefficients form the basis for the thermal-hydraulic analyses in Docket 72-1014 in the CoC amendments 5. These resistance coefficients are appropriate and conservative for HI-STORM FW analysis because of the following reasons:

i. The coefficients define the upperbound pressure drop per unit length of fueled space (Eq. 1 in Section 4.4.1.2).
ii. The storage cell opening in the MPC-37 (PWR fuel) is equal to or greater than the cell openings of the PWR MPCs (such as MPC-32) licensed in the HI-STORM 100 System in Docket 72-1014 [4.1.8]. In the case of BWR fuel storage the channeled fuel located inside the storage cell is modeled explicitly as shown in Figure 4.4.4. The bounding flow resistance coefficients obtained from the cited reference above is applied to the channeled space porous media.

* These are the flow hole openings at the lower end of the fuel basket and a top axial gap to facilitate helium circulation. The flow holes are explicitly included in the 3D thermal models with an understated flow area.

iii. The length of porous media incorporated in the HI-STORM FW FLUENT models meets or exceeds the fuel assembly length of the longest fuel listed in this SAR.

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

4.4.1.4 Evaluation of Flow Resistance in Enlarged Cell MPCs

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

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

However, as mentioned in Sub-section 4.4.1.2, a flow resistance of 1×10^6 m^{-2} through PWR fuel assemblies is used in the thermal analysis.

4.4.1.5 Screening Calculations to Ascertain Limiting Storage Scenario

To define the thermally most limiting HI-STORM FW storage scenario the following cases are evaluated under the limiting heat load patterns defined in Tables 1.2.3* and 1.2.4:

(i) MPC-89

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

(ii) Minimum height MPC-37
(iii) Reference height MPC-37
(iv) Maximum height MPC-37

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

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

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

4.4.1.6 Grid Sensitivity Studies

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

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

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

As can be seen from the above table, the PCT is essentially the same for all the meshes. The solutions from the different grids used are in the asymptotic range. Therefore, it can be concluded that the Mesh 1 is reasonably converged. To provide further assurance of convergence, the sensitivity results are evaluated in accordance with the ASME V&V 20-2009

[4.4.3]. Towards this end, the Grid Convergence Index (GCI), which is a measure of the solution uncertainty, is computed to be 0.181% for these meshes. The apparent order of the method calculated as 2.1, is similar to the order of the method.

Based on the above results, Run No 1 grid layout is adopted for the thermal analysis of the HI-STORM FW.

4.4.2 Effect of Neighboring Casks

HI-STORM FW casks are typically stored on an ISFSI pad in regularly spaced arrays (See Section 1.4, Figures 1.4.1 and 1.4.2). Relative to an isolated HI-STORM FW the heat dissipation from a HI-STORM FW cask placed in an array is somewhat disadvantaged. However, as the analysis in this Sub-section shows, the effect of the neighboring casks on the peak cladding temperature in the "surrounded" cask is insignificant.

(i) Effect of Insolation
The HI-STORM FW casks are subject to insolation heating during daytime hours. Presence of surrounding casks has the salutary effect of partially blocking insolation flux. This effect, results in lower temperatures and in the interest of conservatism is ignored in the analysis.

(ii) Effect of Radiation Blocking
The presence of surrounding casks has the effect of partially blocking radiation heat dissipation from the Overpack cylindrical surfaces. Its effect is evaluated in Sub-section 4.4.2.1.

(iii) Effect of Flow Area Reduction
The presence of surrounding casks have the effect of reducing the access flow area around the casks from an essentially unbounded space around it to certain lateral flow passages defined by the spacing between casks (See Figures 1.4.1 and 1.4.2). A reduction in flow area for ventilated casks is not acceptable if the access area falls below the critical flow area in the ventilation flow passages. The HI-STORM FW critical flow area is reached in the narrow annular passage. The lateral flow passages access flow area defined by the product of minimum gap between casks and cask height is computed below. The calculation uses the lowerbound 180 inch cask pitch defined in Table 1.4.1.

Annulus Area (A_{min}):
- MPC OD: 75.5 in
- Overpack ID: 81 in
- A_{min}: 676.0 in^2

Lateral Access Area (A_o):
- Cask Pitch: 180 in
- Overpack OD: 139 in
- Overpack Body Height: 187.25 in
- Min. cask spacing: 180 – 139 = 41 in

A_o: 7677.2 in^2

The above numerical exercise shows that $A_o >> A_{min}$ and therefore there is an adequate access area surrounding the interior casks for the ventilation air to feed the inlet ducts..

4.4.2.1 Analytical Evaluation of the Effect of Surrounding Casks

In a rectilinear array of HI-STORM FW casks the unit situated in the center of the grid is evidently hydraulically most disadvantaged, because of potential interference to air intake from surrounding casks. Furthermore, the presence of surrounding casks has the effect of partially blocking radiation heat dissipation from the centrally located cask. This situation is illustrated in Figure 4.4.5. To simulate these effects in a conservative manner, a hypothetical square cavity defined by the tributary area A_o of cask shown in Figure 4.4.5 is erected around the centrally located HI-STORM FW. The hypothetical square cavity has the following attributes:

1. The hypothetical square cavity (with the subject HI-STORM FW situated co-axially in it) is constructed for the15 ft minimum cask pitch defined in Section 1.4.1.
2. The cavity walls are impervious to air. In this manner as shown in Figure 4.4.6 lateral access to ambient air is choked.
3. The cavity walls are defined as reflecting surfaces from the inside and insulated from the outside. In this manner lateral dissipation of heat by radiation is blocked.
4. The hypothetical square cavity is open at the top as shown in Figure 4.4.6 to allow ambient air access for ventilation cooling in a conservative manner.

The principal results of the hypothetical square cavity thermal model are tabulated below and compared with the baseline thermal results tabulated in Section 4.4.4.

Model	Peak Clad Temperature (^{o}F)	Margin-to-Limit (^{o}F)
Single Cask Model	703	49
Hypothetical Square Cavity Thermal Model	702*	50
Peak cladding temperature reported for the limiting heat load MPC-37 Pattern A (See Subsection 4.4.4.1)		

The results show that the presence of surrounding casks has essentially no effect on the fuel cladding temperatures (the difference in the results is within the range of numerical round-off).

* The lower computed temperature is an artifact of the use of overstated inlet and outlet loss coefficients in the single cask model. The result supports the conclusion that surrounding casks have essentially no effect on the Peak Cladding Temperatures.

These results are in line with prior thermal evaluations of the effect of surrounding casks in the NRC approved HI-STORM 100 System in Docket 72-1014.

4.4.3 Test Model

The HI-STORM FW 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 FW thermal evaluations, the FLUENT code has been 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. FLUENT has also been used in all Holtec International Part 71 and Part 72 dockets since 1996.

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 both MPC-89 and MPC-37. Tables 4.4.2, 4.4.3 and 4.4.5 provide key thermal and pressure results from the FLUENT simulations, respectively. The peak fuel cladding result in these tables is actually overstated by the fact that the 3-D FLUENT cask model incorporates the effective conductivity of the fuel assembly sub-model. Therefore the FLUENT models report the peak temperature *in the fuel storage cells.* Thus, as the fuel assembly models include the fuel pellets, the FLUENT calculated peak temperatures are actually peak pellet centerline temperatures which bound the peak cladding temperatures with a modest margin.

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

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

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

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

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

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

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

4.4.4.2 Minimum Temperatures

In Table 2.2.2 of this report, the minimum ambient temperature condition for the HI-STORM FW 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^{o}F) evaluation of the HI-STORM FW is provided in Chapter 3. All HI-STORM FW storage overpack and MPC materials of construction will satisfactorily perform their intended function in the storage mode under this minimum temperature condition.

4.4.4.3 Effect 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^{o}F
2000	13.66	7.1^{o}F
4000	12.69	14.3^{o}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 FW 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 under the reduced ambient temperature and pressure at 1500 feet elevation for the limiting regionalized storage scenario evaluated in Table 4.4.2. The results are presented in Table 4.4.9.

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 ISFSI elevation constraints for HI-STORM FW 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 7.1 and 7.0 atmospheres (absolute) respectively for loading patterns A and B during normal storage conditions defined in Table 4.1.1. 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 (70ºF). The minimum backfill pressure for each MPC type is provided in Table 4.4.7. 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 4.4.7. To bound the minimum and maximum backfill pressures listed in Table 4.4.7 with a margin, a helium backfill specification is set forth in Table 4.4.8.

To provide additional helium backfill range for less than design basis heat load canisters a Sub-Design-Basis (SDB) heat load scenario is defined below:

(i) MPC-37 under 80% Pattern A Heat Load (Table 1.2.3)
(ii) MPC-37 under 90% Pattern A Heat Load (Table 1.2.3)
(iii) MPC-89 under 80% Design Heat Load (Table 1.2.4)
(iv) MPC-37 under vacuum drying threshold heat load in Table 4.5.1*.
(v) MPC-89 under vacuum drying threshold heat load in Table 4.5.1*.

The storage cell and MPC heat load limits under the SDB scenario (i), (ii) & (iii) are specified in Table 4.4.11. Calculations for bounding scenarios (i), (ii) & (iii) show that the maximum cladding temperature under the SDB scenario meet the ISG-11 temperature limits. The helium backfill pressure limits supporting this scenario are defined in Table 4.4.10. These backfill limits maybe optionally adopted by a cask user if the decay heats of the loaded fuel assemblies meet the SDB decay heat limits stipulated above.

* Threshold scenarios (iv) and (v) are bounded by scenarios (i) and (iii) respectively because the core Region 1 assembly heat loads and total cask heat loads are bounded by the Sub-Design Basis heat loads in Table 4.4.11.

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 and pressure of the helium gas at the MPC's exit provides a reliable means to compute the inventory of helium. 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 range specified in Table 4.4.8 or Table 4.4.10 (as applicable).

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^{o}F) and a target pressure that lies in the mid-range of the Table 4.4.8 pressures.

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. The MPC gas pressure is also subject to substantial pressure rise under hypothetical rupture of fuel rods and large gas inventory non-fuel hardware (PWR BPRAs). To minimize MPC gas pressures the number of BPRA containing fuel assemblies must be limited to 30.

Table 4.4.4 presents a summary of the MPC free volumes determined for the fixed height MPC-89 and lowerbound height MPC-37 fuel storage scenarios. 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. A concomitant effect of rod ruptures is the increased pressure and molecular weight of the cavity gases with enhanced rate of heat dissipation by internal helium convection and lower cavity temperatures. As these effects are substantial under large rod ruptures the 100% rod rupture accident is evaluated with due credit for increased heat dissipation under increased pressure and molecular weight of the cavity gases. 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 4.4.5. The results of the calculations support the following conclusions:

(i) The maximum computed gas pressures reported in Table 4.4.5 under all design basis thermal loadings defined in Section 4.4 are all below the MPC internal design pressures for normal, off-normal and accident conditions specified in Table 2.2.1.

(ii) The MPC gas pressure obtained under loading Pattern A is essentially same as in Pattern B. Accordingly Pattern A loading condition for pressure boundary evaluation of MPC in the HI-TRAC and under off-normal and accident conditions is retained.

<u>Evaluation of Non-Fuel Hardware</u>

The inclusion of PWR non-fuel hardware (BPRA control elements and thimble plugs) to the PWR basket 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 FW thermal analysis, the computed temperature field (with non-fuel hardware <u>excluded</u>) has been determined to provide a conservatively bounding temperature field for the PWR baskets. The MPC cavity free space is computed based on conservatively computed volume displacement by fuel with non-fuel hardware <u>included</u>. 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 temperatures 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. They 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 BPRA containing fuel assembly. For a bounding evaluation the maximum permissible number of BPRA containing fuel assemblies (see discussion at the beginning of this Section) are assumed to be loaded. The MPC cavity pressures (including helium from BPRAs) are summarized in Table 4.4.5 for the bounding MPC-37 (shortest MPC height and heat load Patterns A and B) and MPC-89 (design heat load) storage scenarios.

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 FW 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 FW System are adequate to accommodate thermal expansion of the fuel basket and MPC.

The HI-STORM FW System is engineered with gaps for the fuel basket and MPC to expand thermally without restraint of free end expansion. 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

The FLUENT thermal model provides the 3-D temperature field in the HI-STORM FW system from which the changes in the above gaps are directly computed. Table 4.4.6 provides the initial minimum gaps and their corresponding value during long-term storage conditions. Significant margins against restraint to free-end expansion are available in the design.

4.4.7 Evaluation of System Performance for Normal Conditions of Storage

The HI-STORM FW System thermal analysis is based on a detailed 3-D heat transfer model that conservatively accounts for all modes of heat transfer in the MPC and overpack. The thermal model incorporates conservative assumptions that render the results for long-term storage to be conservative.

Temperature distribution results obtained from this 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. As justified next the long-term impact of elevated temperatures reached in the HI-STORM FW system is minimal. The maximum MPC basket temperatures are below the recommended limits for susceptibility to stress, corrosion and creep-induced degradation. A complete evaluation of all material failure modes and causative mechanisms has been performed in Chapter 8 which shows that all selected materials for use in the HI-STORM FW system will render their intended function for the service life of the system. Furthermore, stresses induced due to the associated temperature gradients are modestly low (See Structural Evaluation Chapter 3).

Table 4.4.1

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

	Conductivity (Btu/hr-ft-°F)			
	PWR: Short Fuel		**PWR: Standard Fuel**	
Temperature (°F)	Planar	Axial	Planar	Axial
200	0.247	0.813	0.231	0.759
450	0.443	0.903	0.387	0.845
700	0.730	1.016	0.601	0.951
	PWR: XL Fuel		**BWR Fuel**	
	Planar	Axial	Planar	Axial
200	0.239	0.787	0.283	0.897
450	0.393	0.875	0.426	0.988
700	0.599	0.984	0.607	1.104
Thermal Inertia Properties				
	Density (lb/ft^3)		Heat Capacity (Btu/lb-°F)[Note 2]	
PWR: Short Fuel	165.8		0.056	
PWR: Standard Fuel	176.2		0.056	
PWR: XL Fuel	187.5		0.056	
BWR Fuel	255.6		0.056	

Note 1: Bounding fuel storage configurations defined in 4.4.1.1(ii).

Note 2: The lowerbound heat capacity of principal fuel assembly construction materials tabulated in Table 4.2.5 (UO_2 heat capacity) is conservatively adopted.

Note 3: The fuel properties tabulated herein are used in screening calculations to define the limiting scenario for fuel storage (See Table 4.4.2).

Table 4.4.2

RESULTS OF SCREENING CALCULATIONS UNDER NORMAL STORAGE CONDITIONS

Storage Scenario	Peak Cladding Temperature, ^{o}C (^{o}F)
MPC-37 Minimum Height* Reference Height Maximum Height	 **353 (667)** 342 (648) 316 (601)
MPC-89	333 (631)

Notes:

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

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

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

Table 4.4.3 MAXIMUM TEMPERATURES IN HI-STORM FW UNDER LONG-TERM NORMAL STORAGE*	
Component	**Temperature, °C (°F) Pattern A / Pattern B**
Fuel Cladding	373 (703) / 368 (694)
MPC Basket	358 (676) / 354 (669)
Basket Periphery	290 (554) / 292 (558)
Aluminum Basket Shims	267 (513) / 267 (513)
MPC Shell	240 (464) / 242 (468)
MPC Lid[Note 1]	235 (455) / 232 (450)
Overpack Inner Shell	126 (259) / 127 (261)
Overpack Outer Shell	65 (149) / 65 (149)
Overpack Body Concrete[Note 1]	89 (192) / 90 (194)
Overpack Lid Concrete[Note 1]	111 (232) / 112 (234)
Area Averaged Air outlet†	103 (217) / 103 (217)
Note 1: Maximum section average temperature is reported.	

* The temperatures reported in this table (all for shortest fuel scenario of MPC-37) are below the design temperatures specified in Table 2.2.3, Chapter 2. These temperatures bound MPC-89 temperatures.

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

Table 4.4.4 MINIMUM MPC FREE VOLUMES		
Item	**Lowerbound Height MPC-37 (ft^3)**	**MPC-89 (ft^3)**
Net Free Volume*	211.89	210.12
**Net free volumes are obtained by subtracting basket, fuel, aluminum shims, spacers, basket supports and DFCs metal volume from the MPC cavity volume.*		

Table 4.4.5 SUMMARY OF MPC INTERNAL PRESSURES UNDER LONG-TERM STORAGE*		
Condition	**MPC-37 (psig) Pattern A/Pattern B**	**MPC-89 (psig)**
Initial backfill** (at 70°F)	45.5/46.0	47.5
Normal: intact rods 1% rods rupture	 96.6/97.9 97.7/99.0	 98.4 99.0
Off-Normal (10% rods rupture)	107.5/108.9	104.0
Accident (100% rods rupture)	191.5/194.4	155.0
* Per NUREG-1536, pressure analyses with ruptured fuel rods (including BPRA rods for PWR fuel) is performed with release of 100% of the ruptured fuel rod fill gas and 30% of the significant radioactive gaseous fission products. ** Conservatively assumed at the Tech. Spec. maximum value (see Table 4.4.8).		

Table 4.4.6

SUMMARY OF HI-STORM FW DIFFERENTIAL THERMAL EXPANSIONS

Gap Description	**Cold Gap U (in)**	**Differential Expansion δ_i (in)**	**Is Free Expansion Criterion Satisfied (i.e., U > δ_i)**
Fuel Basket-to-MPC Radial Gap	0.125	0.112	Yes
Fuel Basket-to-MPC Axial Gap	1.5	0.421	Yes
MPC-to-Overpack Radial Gap	5.5	0.128	Yes
MPC-to-Overpack Minimum Axial Gap	3.5	0.372	Yes

Table 4.4.7

THEORETICAL LIMITS* OF MPC HELIUM BACKFILL PRESSURE**

MPC	**Minimum Backfill Pressure (psig)**	**Maximum Backfill Pressure (psig)**
MPC-37 Pattern A	41.0	47.3
MPC-37 Pattern B	40.8	47.1
MPC-89	41.9	48.4

* The helium backfill pressures are set forth in the Technical Specifications with a margin (see Table 4.4.8).

** The pressures tabulated herein are at 70^{o}F reference gas temperature.

Table 4.4.8 MPC HELIUM BACKFILL PRESSURE SPECIFICATIONS		
MPC	**Item**	**Specification**
MPC-37 Pattern A	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	45.5 psig @ 70^{o}F Reference Temperature
MPC-37 Pattern B	Minimum Pressure	41.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	46.0 psig @ 70^{o}F Reference Temperature
MPC-89	Minimum Pressure	42.5 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	47.5 psig @ 70^{o}F Reference Temperature

Table 4.4.9 MAXIMUM HI-STORM FW TEMPERATURES AT ELEVATED SITES*	
Component	**Temperature, ^{o}C (^{o}F)**
Fuel Cladding	374 (705)
MPC Basket	360 (680)
Aluminum Basket Shims	275 (527)
MPC Shell	246 (475)
MPC Lid[Note 1]	242 (468)
Overpack Inner Shell	126 (259)
Overpack Body Concrete[Note 1]	86 (187)
Overpack Lid Concrete[Note 1]	112 (234)
Note 1: Maximum section average temperature is reported.	

* The temperatures reported in this table (all for the bounding scenario defined in Table 4.4.2) are below the design temperatures specified in Table 2.2.3, Chapter 2.

Table 4.4.10
MPC HELIUM BACKFILL PRESSURE LIMITS UNDER THE
SUB-DESIGN-BASIS HEAT LOAD SCENARIO[Note 1]

MPC	Item	Specification
MPC-37 80% of Pattern A	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	50.0 psig @ 70^{o}F Reference Temperature
MPC-37 90% of Pattern A	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	47.8 psig @ 70^{o}F Reference Temperature
MPC-89 80% of Table 1.2.4	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	50.0 psig @ 70^{o}F Reference Temperature
MPC-37 Table 4.5.1 Threshold Heat Load	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	50.0 psig @ 70^{o}F Reference Temperature
MPC-89 Table 4.5.1 Threshold Heat Load	Minimum Pressure	42.0 psig @ 70^{o}F Reference Temperature
	Maximum Pressure	50.0 psig @ 70^{o}F Reference Temperature

Note 1: The Sub-Design-Basis heat load scenario is defined in Section 4.4.5.1.

Note 2: Sub-design-basis heat load MPCs are sufficiently backfilled to yield an absolute operating pressure of 6 atm in 80% heat load cases and 6.9 atm in 90% heat load cases.

Note 3: The 80% heat load backfill specifications are suitably adopted for threshold heat load scenarios because the thermal scenarios bound the latter (See Subsection 4.4.5.1).

Table 4.4.11 SUB-DESIGN BASIS HEAT LOAD LIMITS	
MPC-37 (80% of Pattern A in Table 1.2.3) Region 1 Cells Region 2 Cells Region 3 Cells Total	0.840 kW/assy 1.360 kW/assy 0.712 kW/assy 35.27 kW
MPC-37 (90% of Pattern A in Table 1.2.3) Region 1 Cells Region 2 Cells Region 3 Cells Total	0.945 kW/assy 1.530 kW/assy 0.801 kW/assy 39.68 kW
MPC-89 (80% of Table 1.2.4) Region 1 Cells Region 2 Cells Region 3 Cells Total	0.352 kW/assy 0.496 kW/assy 0.352 kW/assy 37.1 kW
Note: The MPC-37 and MPC-89 storage cell regions are defined in Figures 1.2.1 and 1.2.2 respectively.	

TABLE 4.4.12

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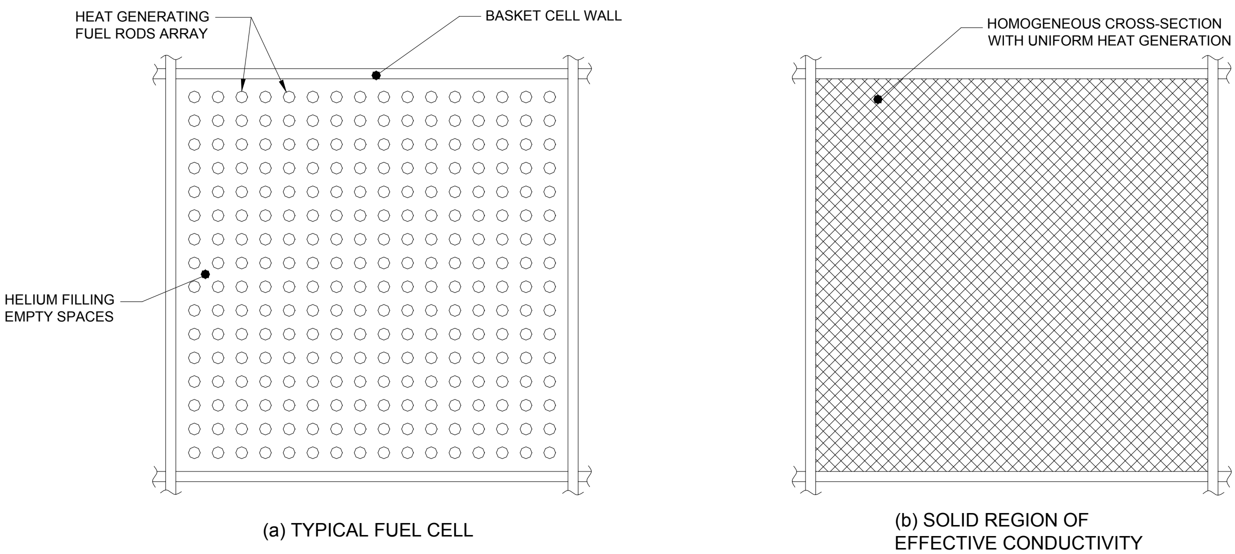


Figure 4.4.1: Homogenization of the Storage Cell Cross-Section

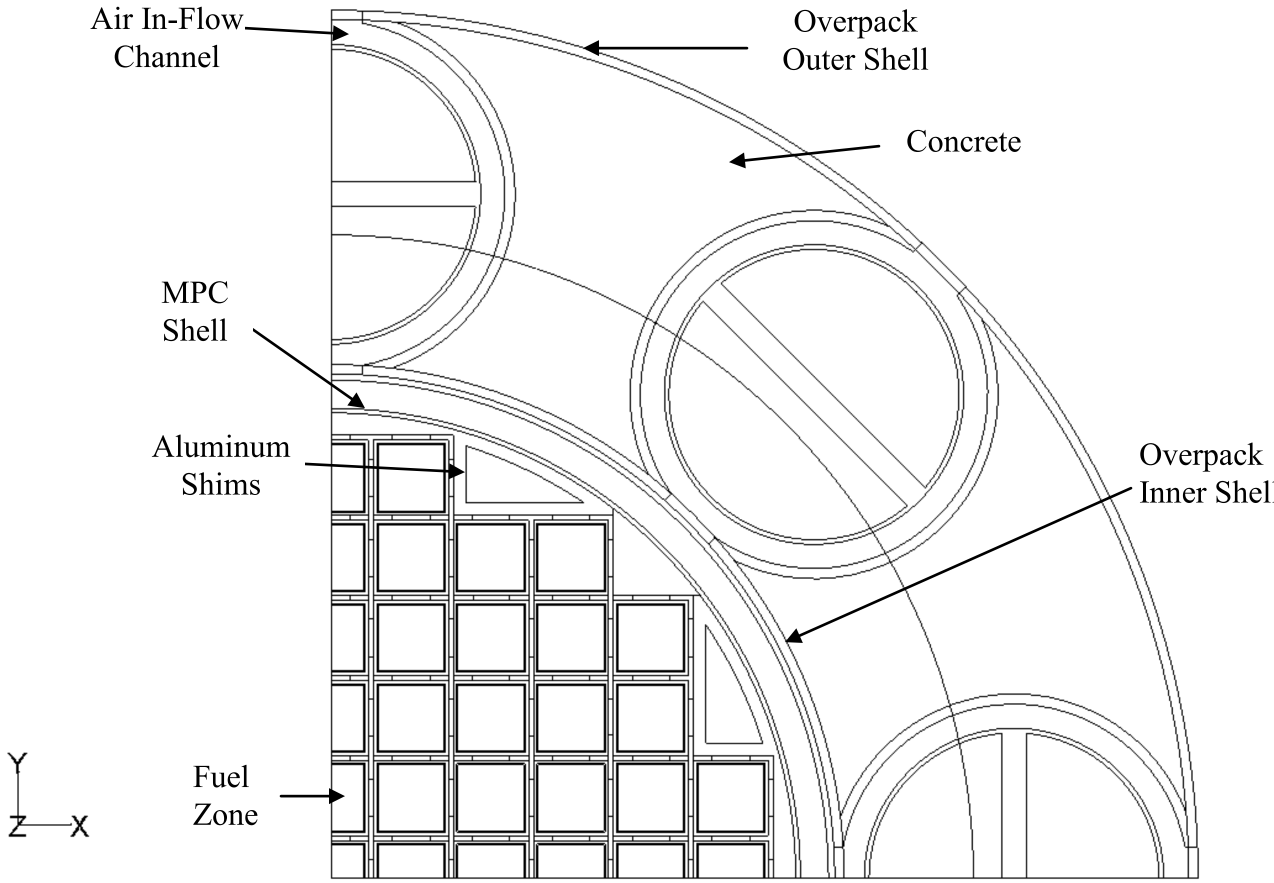


Figure 4.4.2: Planar View of HI-STORM FW MPC-89 Quarter Symmetric 3-D Model

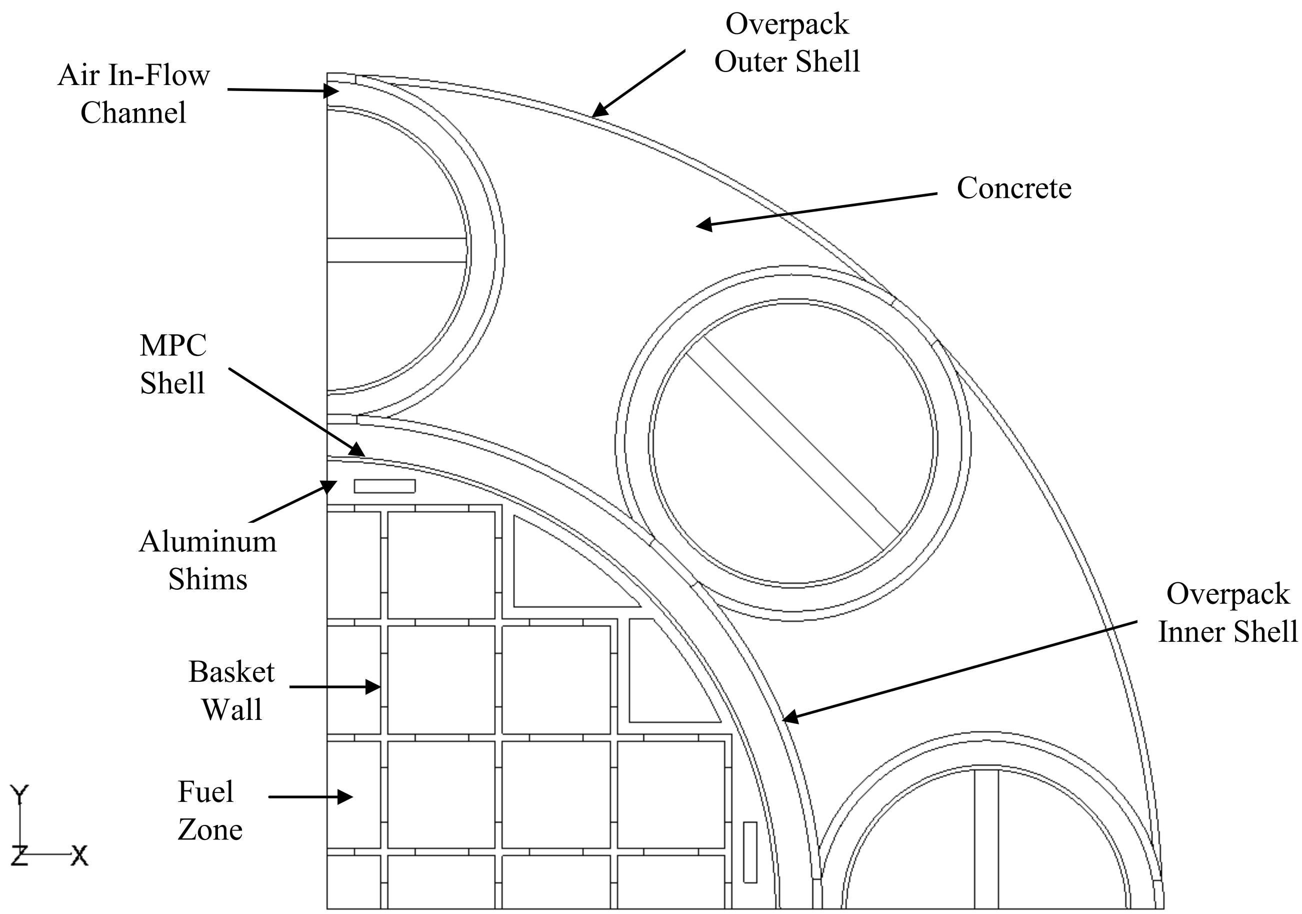


Figure 4.4.3: Planar View of HI-STORM FW MPC-37 Quarter Symmetric 3-D Model

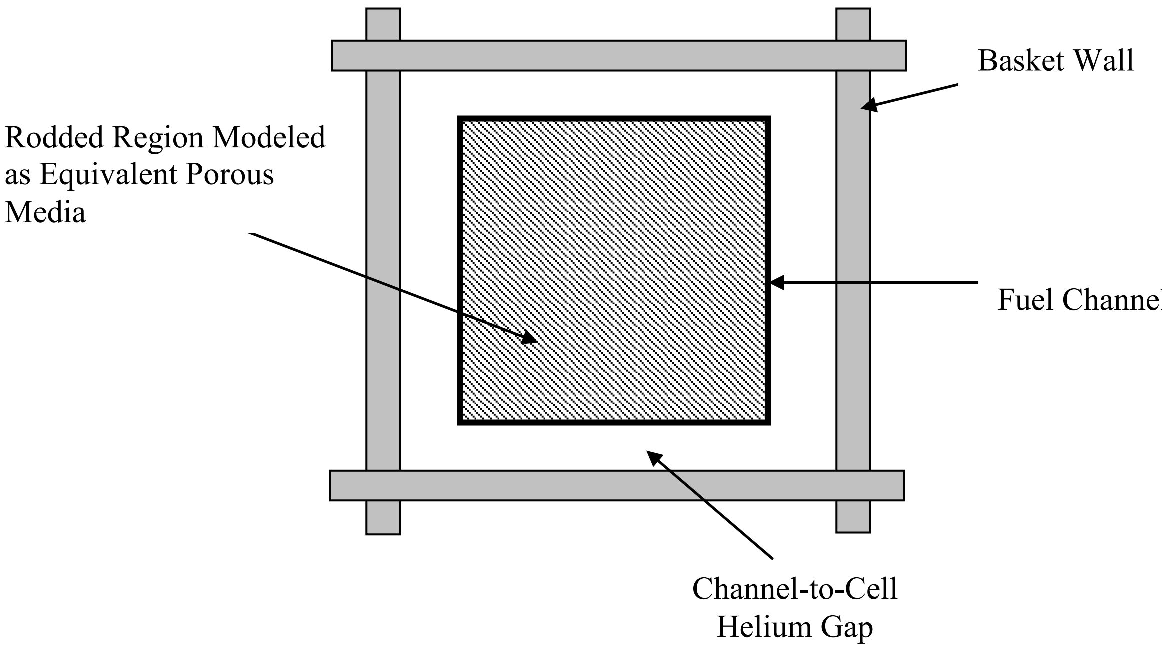
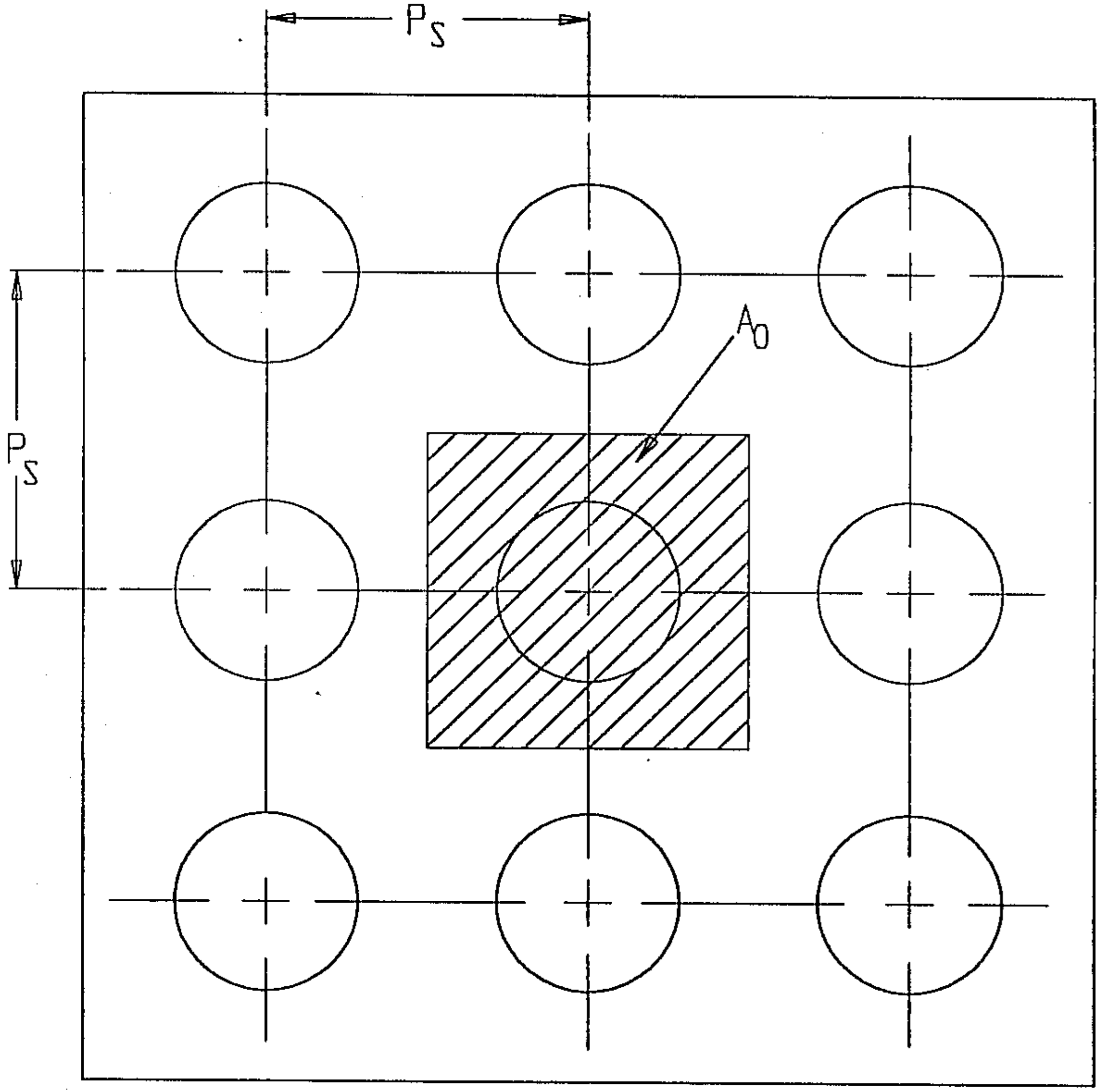


Figure 4.4.4: Closeup View of the MPC-89 Channeled Fuel Spaces



Legend:
P_s: Cask pitch
A_o: Tributary area

Figure 4.4.5: Illustration of a Centrally Located Cask in a Cask Array

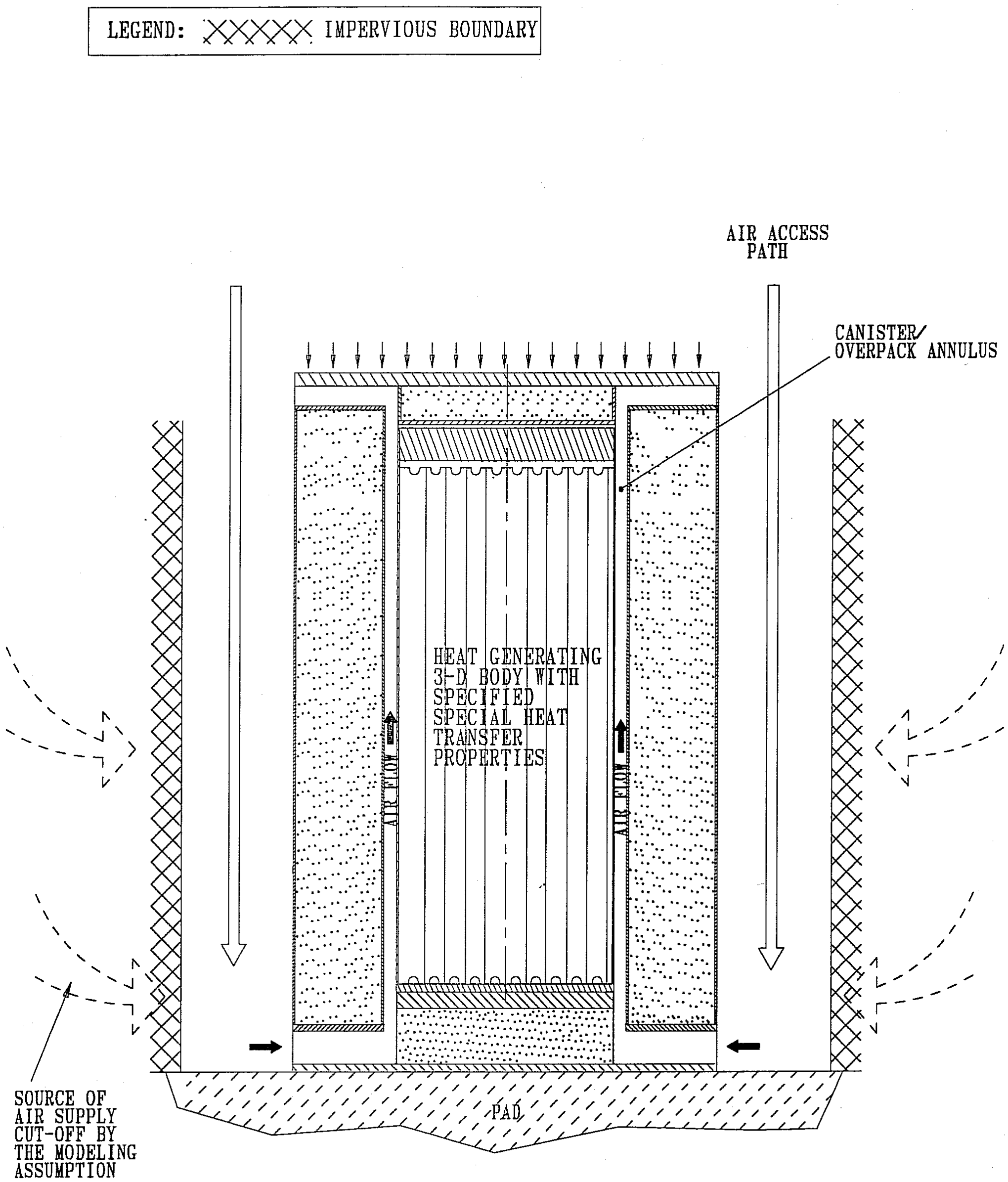


Figure 4.4.6: Illustration of the Hypothetical Square Cavity Thermal Model

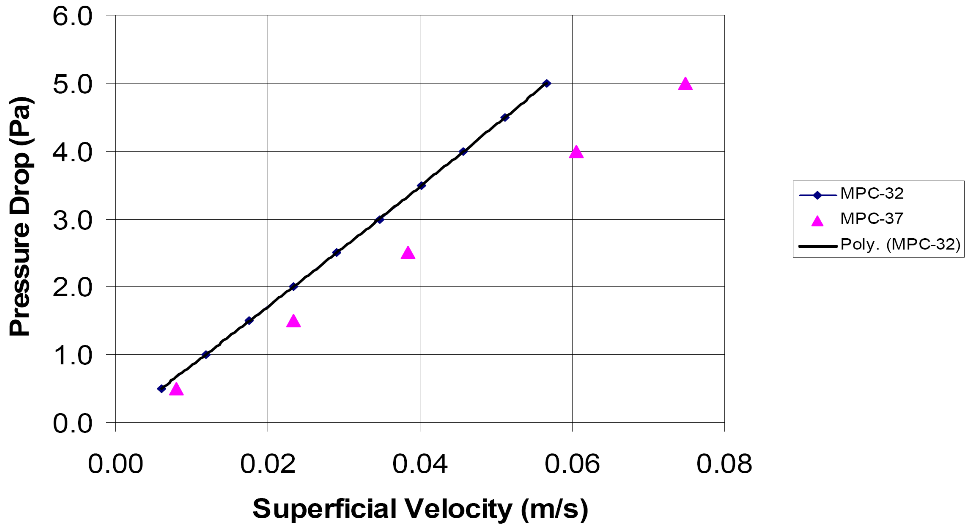


Figure 4.4.7: Storage Cell Pressure Drop as a Function of In-Cell Helium Velocity

4.5 THERMAL EVALUATION OF SHORT-TERM OPERATIONS

4.5.1 Thermally Limiting Evolutions During Short-Term Operations

Prior to placement in a HI-STORM FW overpack, an MPC must be loaded with fuel, outfitted with closures, dewatered, dried, backfilled with helium and transported to the HI-STORM FW 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 FW overpacks or between a HI-STAR transport overpack and a HI-STORM FW storage overpack must be carried out in a 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.

Chapter 9 provides a description of the typical loading steps involved in moving nuclear fuel from the spent fuel pool to dry storage in the HI-STORM FW system. The transition from a wet to a dry environment, to comply with ISG-11, Rev. 3, must occur without exceeding the short-term operation temperature limits (see Table 4.3.1).

The loading steps that present the limiting thermal condition during short term operations for the fuel are those when either one or both of the following conditions exist:

i. The MPC’s fuel storage space is evacuated of fluids resulting in a significant decease in internal heat transmission rates. This condition obtains if the vacuum drying method for removing moisture from the canister is employed.

ii. The removal of heat from the external surfaces of the MPC is impeded because of the air gap between the canister and HI-TRAC VW. This condition exists, for example, when the loaded MPC is being moved inside HI-TRAC VW for staging and transfer of the MPC to the HI-STORM FW overpack.

In this section, the thermally limiting scenarios during short-term operations are identified and analyzed.

Because onsite transport of the MPC occurs with the HI-TRAC VW in the vertical orientation, the thermosiphon action within the MPC is preserved at all times. The only (rare) departure from a purely vertical orientation occurs if a tilting of the HI-TRAC VW is needed to clear an obstruction such as a low egress bay door opening at a plant. In such a case the operational imperative for HI-TRAC VW tilting must be ascertained and the permissible duration of non-vertical 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 under 10CFR72.212.

4.5.2 HI-TRAC VW Thermal Model

4.5.2.1 On-Site Transfer

The HI-TRAC VW transfer cask is used to load and unload the HI-STORM FW concrete storage overpack, including onsite transport of the MPCs from the loading facility to an ISFSI pad. Within a loaded HI-TRAC VW, 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 atmosphere, heat is transported within across multiple concentric layers, representing the air gap, the HI-TRAC VW inner shell, the lead shielding, the HI-TRAC VW outer shell, the water jacket space and the jacket shell. From the surface of the HI-TRAC VW's enclosure shell heat is rejected to the atmosphere by natural convection and radiation.

A small diametral gap exists between the outer surface of the MPC and the inner surface of the HI-TRAC VW overpack which may be filled with water during an operational state to serve as a heat sink and radiation absorber. The water jacket, which provides neutron shielding for the HI-TRAC VW overpack, surrounds the outer cylindrical steel wall of the HI-TRAC VW body. Heat is transported through the water jacket by a combination of conduction through steel ribs and convection heat transfer in the water spaces. The bottom face of the HI-TRAC VW is in contact with a supporting surface which is a thermal heat sink. This face is conservatively modeled as an insulated surface. The HI-TRAC VW is an open top construction which is modeled as an opening to allow air exchange with the ambient.

The HI-TRAC VW Transfer Cask thermal analysis is based on a detailed heat transfer model that conservatively accounts for all modes of heat transfer in the MPC and HI-TRAC VW. The thermal model incorporates several conservative features listed below:

i. Severe levels of environmental factors - bounding ambient temperature, 32.2°C (90°F), and constant solar flux - were coincidentally imposed on the thermal design. A bounding solar absorbtivity of 0.85 is applied to all exposed surfaces.

ii. The HI-TRAC VW Transfer Cask-to-MPC annular gap is analyzed based on the nominal design dimensions. No credit is considered for the gap reduction that would occur as a result of differential thermal expansion with design basis fuel at hot conditions. The MPC is considered to be concentrically aligned with the cask cavity and the annulus is filled with air. This scenario maximizes thermal resistance.

iii. The HI-TRAC VW baseplate is in thermally communicative contact with supporting surfaces. For conservatism an insulated boundary condition is applied to the baseplate.

iv. The HI-TRAC VW fluid columns (namely air in the annulus and water in the water jacket) are allowed to move. In other words natural convection heat transfer by annulus air and water is credited in the analysis.

v. To maximize lateral resistance to heat dissipation in the fuel basket conservatively postulated 0.8 mm full length panel gaps are assumed at all intersections. This approach is similar to the approach in the approved HI-STAR 180 Package in Docket 71-9325. The shims installed in the MPC peripheral spaces (See MPC-37 and MPC-89 drawings in Section 1.5) are explicitly modeled. For conservatism reasonably bounding gaps (2.5 mm basket-to-shims and 2.5 mm shims-to-shell) are incorporated in the thermal models.

vi. The Raleigh number of air flow in the annulus between the MPC and HI-TRAC VW indicates that the flow regime in this region is laminar. Therefore, the air flow in this region is modeled as laminar in the thermal model.

The grid deployed in the HI-TRAC VW thermal model is confirmed to be grid independent through mesh sensitivity studies. The studies refined the radial mesh in HI-TRAC VW annulus and water jacket regions. The thermal solutions obtained show that the temperatures are essentially unchanged.

To evaluate on-site transfer operations in a conservative manner a HI-TRAC VW thermal model is constructed under the limiting scenario of fuel storage in the minimum height MPC-37 (See Section 4.4.1.5) and limiting Pattern A heat load specified in Chapter 1, Section 1.2 (See Section 4.4.4). The model adopts the MPC thermal modeling methodology described in Section 4.4 and the properties of design basis 14x14 Ft. Calhoun fuel defined in Table 4.4.1 under the limiting fuel storage scenario cited above. Results of on-site transfer analyses are provided in Subsection 4.5.4.3.

4.5.2.2 Grid Sensitivity Studies

Cognizant to the grid sensitivity studies performed for the HI-STORM FW System discussed in Section 4.4, a similar study is performed for the HI-TRAC VW System. This study is also performed in accordance with the ASME V&V method [4.4.3]. The grid sensitivity study is performed for the limiting thermal scenario i.e. MPC-37 with minimum fuel length and loaded with pattern A. All the three meshes used for this study satisfy the recommended criterion of 1.3 as the grid refinement factor [4.4.3]. The predicted PCT from these three meshes is essentially the same and are reported in the table below:

Mesh No	Total Mesh Size	PCT (^oC)	Permissible Limit (^oC)	Clad Temperature Margin (^oC)
1 (Licensing Basis Mesh)	1,267,474	389	400	11
2	2,678,012	390	400	10
3	5,797,030	389	400	11

The solutions from these grids are in the asymptotic range. The finest mesh (Mesh 3) has about 4.6 times the total mesh size of the licensing basis mesh (Mesh 1). Even with such a large mesh refinement, the PCT is essentially same for all the three meshes. Since the difference of PCT for all these meshes is close to zero, it indicates that an oscillatory convergence or that the "exact" solution has been attained [4.5.1]. To provide further assurance of convergence, grid convergence index (GCI), which is a measure of the solution uncertainty, is computed as 0.566%. The apparent order of the method is calculated as 1.2.

Based on the above results, it can be concluded that the Mesh 1 is reasonably converged and is adopted as the licensing basis converged mesh.

4.5.2.3 Vacuum Drying

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 upto design basis heat load. In this method, removal of moisture from the MPC cavity is accomplished by evacuating the MPC after completion of MPC draining operation. Vacuum drying of MPCs containing high burnup fuel assemblies is permitted up to threshold heat loads defined in Table 4.5.1. High burnup fuel drying in MPCs generating greater than threshold heat load is performed by a forced flow helium drying process as discussed in Section 4.5.4.

Prior to the start of the MPC draining operation, both the HI-TRAC VW 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. To minimize fuel temperatures during vacuum drying operations the HI-TRAC VW annulus must be water filled. The necessary operational steps required to ensure this requirement are set forth in Chapter 9.

A 3-D FLUENT thermal model of the MPC is constructed in the same manner as described in

Section 4.4*. The principal input to this model is the effective conductivity of fuel under vacuum drying operations. To bound the vacuum drying operations the effective conductivity of fuel is computed assuming the MPC is filled with water vapor at a very low pressure (1 torr). The methodology for computing the effective conductivity is given in Section 4.4.1 and effective properties of design basis fuel under vacuum conditions tabulated in Table 4.5.8. To ensure a conservative evaluation the thermal model is incorporated with the following assumptions:

i. Bounding steady-state condition is reached with the MPC decay heat load set equal to the limiting heat load (Pattern A in Table 1.2.3 and 1.2.4) for MPCs fueled with Moderate Burnup Fuel and threshold heat load defined in Table 4.5.1 for MPCs fueled with one or more High Burnup fuel assemblies.

ii. The external surface of the MPC shell is postulated to be at the boiling temperature of water $100^{o}C$ ($212^{o}F$).

iii. The bottom surface of the MPC is insulated.

iv. MPC internal convection heat transfer is suppressed.

Results of vacuum condition analyses are provided in Subsection 4.5.4.1.

4.5.3 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. This requirement is met by imposing time limits for fuel to remain submerged in water after a loaded HI-TRAC VW cask is removed from the pool.

Fuel loading operations are typically conducted with the HI-TRAC VW and its contents (water filled MPC) submerged in pool water. Under these conditions, the HI-TRAC VW is essentially at the pool water temperature. When the HI-TRAC VW transfer cask and the loaded MPC under water-flooded conditions is removed from the pool, the water, fuel, MPC and HI-TRAC VW metal absorb the decay heat emitted by the fuel assemblies. This results in a slow temperature rise of the HI-TRAC VW with time, starting from an initial (pool water) temperature. The rate of temperature rise is limited by the thermal inertia of the HI-TRAC VW 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 VW surfaces to ambient air is neglected (i.e., an adiabatic heat-up calculation is performed).

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

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* The MPC thermal model adopted for vacuum drying analysis in this sub-section includes the gap between the intersecting basket panels as 0.4 mm. A sensitivity study of the most limiting thermal scenario (least margins to fuel temperature limit) of vacuum drying condition is performed with this gap as 0.8 mm and discussed in Sub-section 4.5.4.4.

iii. The shortest allowable HI-TRAC VW is credited in the analysis to impart the lowest thermal inertia on the system, which will result in the highest rate of temperature rise.

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

Table 4.5.3 summarizes the weights and thermal inertias of several components in the loaded HI-TRAC VW transfer cask that corresponds to the shortest allowable fuel assembly. The rate of temperature rise of the HI-TRAC VW 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)
C_h = thermal inertia of a loaded HI-TRAC VW (Btu/°F)
T = temperature of the HI-TRAC VW transfer cask (°F)
t = time after MPC lid is placed (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 pool water temperature when the lid is placed on the MPC (°F)

The time-to-boil clock starts when the lid is placed on the MPC and the HI-TRAC is in the spent fuel pool, while it ends when the MPC is drained (See section 9.2.4). Table 4.5.4 provides a summary of t_{max} at several representative initial temperatures. The time-to-boil calculations are conservatively performed for the HI-TRAC VW that corresponds to shortest allowed fuel assembly since lowerbound thermal inertia results in lower time limits. A site-specific time-to-boil calculation can be performed using the above equations based on the actual canister heat load and thermal inertia of the specific HI-TRAC VW System.

As set forth in the HI-STORM FW 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 MPC lid ports and heated water will exit from the vent port. The minimum water flow rate required to maintain the MPC cavity water temperature below boiling with an adequate subcooling margin is determined as follows:

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

where:

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

4.5.4 Analysis of Limiting Thermal States During Short-Term Operations

4.5.4.1 Vacuum Drying

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

4.5.4.2 Forced Helium Dehydration

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

The FHD system provides concurrent fuel cooling during the moisture removal process through forced convective heat transfer. The attendant forced convection-aided heat transfer occurring during operation of the FHD system ensures that the fuel cladding temperature will remain below the applicable peak cladding temperature limit in Table 2.2.3. Because the FHD operation induces a state of forced convection heat transfer in the MPC, (in contrast to the quiescent mode 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 transfer. As a result, if the FHD machine fails then the peak fuel cladding temperatures will approximate the value reached during normal onsite transfer, discussed below.

4.5.4.3 Normal On-site Transfer

An MPC-37 situated inside a HI-TRAC VW is evaluated under the design heat load defined in Section 1.2. The MPC-37 is evaluated because it yields the highest fuel and cask temperatures (See Table 4.4.2). This scenario is analyzed using the same 3D FLUENT model of the MPC-37 articulated in Section 4.4 for normal storage with due recognition of it situated in the HI-TRAC VW transfer cask. The HI-TRAC VW model discussed in Section 4.5.2 is adopted to construct a global model of an MPC-37 situated inside the HI-TRAC VW and dissipating heat by natural convection and radiation to ambient air.

While the duration of onsite transport is generally short to preclude the MPC and HI-TRAC VW from reaching a steady-state, a conservative approach is adopted herein by assuming steady state maximum temperatures are reached. The principle objectives of the HI-TRAC VW analyses are to demonstrate:

i) Cladding integrity
ii) Confinement integrity
iii) Neutron shield integrity

The appropriate criteria are provided in Tables 2.2.1 (pressure limits) and 2.2.3 (temperature limits).

The results of thermal analyses tabulated in Table 4.5.2 show that the cladding temperatures are below the ISG-11 temperature limits of High and Moderate Burnup Fuel (Table 4.3.1). Actual margins during HI-TRAC VW operations will be much larger due to the many conservative assumptions incorporated in the analysis.

The water in the water jacket surrounding the HI-TRAC VW body provides necessary neutron shielding. During normal handling and onsite transfer operations this shielding water is contained within the water jacket at elevated internal pressure. The water jacket is equipped with two pressure relief devices set to an adequately high pressure to prevent boiling. Under HI-TRAC VW operations, the bulk temperature of water remains below the temperature limit specified in Table 2.2.3. Accordingly, water is in the liquid state and the neutron shielding function is maintained. The cladding, neutron shield and HI-TRAC VW component temperatures are provided in Table 4.5.2. The confinement boundary integrity is evaluated in the Section 4.5.6.

4.5.4.4 Effect of Increase in Basket Panel Gap

As described in Subsection 4.5.2.3, a sensitivity study is performed for the vacuum drying condition of high burnup fuel at threshold heat load with the basket panel notch gap equal to 0.8 mm. The results of the steady state analysis vacuum drying condition are summarized in Table 4.5.10. The PCT and cask component temperatures during vacuum drying are below their respective temperature limits. Therefore, the effect of increasing the panel gap is small and leaves sufficient safety margins during vacuum drying conditions.

4.5.5 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 under a reflood rate of 3715 lb/hr. Limiting the water reflood rate to this amount or less would prevent exceeding the MPC design pressure.

4.5.6 Maximum Internal Pressure (Load Case NB in Table 2.2.7)

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 VW transfer cask, the gas temperature will correspond to the thermal conditions within the MPC analyzed in Section 4.5.4.3. Based on this analysis the MPC internal pressure is computed under the assumption of maximum helium backfill specified in Table 4.4.8 and confirmed to comply with the short term operations pressure limit in Table 2.2.1. The results are tabulated in Table 4.5.5.

TABLE 4.5.1 THRESHOLD HEAT LOADS UNDER VACUUM DRYING OF HIGH BURNUP FUEL (See Figures 1.2.1 and 1.2.2)			
MPC-37			
Number of Regions: 3			
Number of Storage Cells: 37			
Maximum Heat Load: 34.36			
Region No.	Decay Heat Limit per Cell, kW	Number of Cells per Region	Decay Heat Limit per Region, kW
1	0.80	9	7.2
2	0.97	12	11.64
3	0.97	16	15.52
MPC-89			
Number of Regions: 3			
Number of Storage Cells: 89			
Maximum Heat Load: 34.75			
Region No.	Decay Heat Limit per Cell, kW	Number of Cells per Region	Decay Heat Limit per Region, kW
1	0.35	9	3.15
2	0.35	40	14.00
3	0.44	40	17.60

Table 4.5.2

HI-TRAC VW TRANSFER CASK STEADY STATE MAXIMUM TEMPERATURES

Component	**Temperature, ^oC (^oF)**
Fuel Cladding	389 (732)
MPC Basket	374 (705)
Basket Periphery	299 (570)
Aluminum Basket Shims	272 (522)
MPC Shell	247 (477)
MPC Lid[Note 1]	240 (464)
HI-TRAC VW Inner Shell	138 (280)
HI-TRAC VW Radial Lead Gamma Shield	138 (280)
Water Jacket Bulk Water	129 (264)

Note 1: Maximum section average temperature is reported.

Table 4.5.3 HI-TRAC VW TRANSFER CASK LOWERBOUND WEIGHTS AND THERMAL INERTIAS[Note 1]			
Component	**Weight (lbs)**	**Heat Capacity (Btu/lb-°F)**	**Thermal Inertia (Btu/°F)**
Lead	45627	0.031	1414
Carbon Steel	43270	0.1	4327
Stainless Steel	19561	0.12	2347
Aluminum	6734	0.207	1394
Metamic-HT	7349	0.22	1617
Fuel	46250	0.056	2590
MPC Cavity Water	6611	0.999	6604
Total	175402	-	20294
Note 1: Values presented in this table are based on the shortest HI-TRAC VW height determined in accordance with Table 3.2.1 using the minimum PWR fuel height from Table 3.2.2.			

Table 4.5.4 MAXIMUM ALLOWABLE TIME FOR WET TRANSFER OPERATIONS[Note 1]	
Initial temperature °F	**Time Duration (hr)**
100	14.2
110	12.9
120	11.6
130	10.4
140	9.1
150	7.8
Note 1: The time-to-boil limits provided herein are based on the shortest allowed HI-TRAC VW height and maximum design basis heat load. A site-specific calculation based on the methodology described in Section 4.5.3 can be performed to determine the time-to-boil limits.	

Table 4.5.5

MPC CONFINEMENT BOUNDARY PRESSURE UNDER ON-SITE TRANSPORT

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

Table 4.5.6

MAXIMUM TEMPERATURES OF MPC-37 DURING VACUUM DRYING CONDITIONS

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

Note 1: Addresses vacuum drying of Moderate Burnup Fuel under limiting heat load (Pattern A) defined in Section 1.2.
Note 2: Addresses vacuum drying of High Burnup Fuel under threshold heat load (Table 4.5.1).
Note 3: Maximum section temperature reported.

Table 4.5.7 MAXIMUM TEMPERATURES OF MPC-89 DURING VACUUM DRYING CONDITIONS		
Component	**Temperatures @DB Heat Load[Note 1]** **^{o}C (^{o}F)**	**Temperatures @ Threshold Heat Load[Note 2]** **^{o}C (^{o}F)**
Fuel Cladding	464 (867)	376 (709)
MPC Basket	449 (840)	359 (678)
Basket Periphery	348 (658)	286 (547)
Aluminum Basket Shims	275 (527)	232 (450)
MPC Shell	158 (316)	144 (291)
MPC Lid[Note 3]	127 (261)	110 (230)

Note 1: Addresses vacuum drying of Moderate Burnup Fuel under Design Basis heat load defined in Section 1.2.
Note 2: Addresses vacuum drying of High Burnup Fuel under threshold heat load (Table 4.5.1).
Note 3: Maximum section temperature reported.

Table 4.5.8 EFFECTIVE CONDUCTIVITY OF DESIGN BASIS FUEL[Note 1] UNDER VACUUM DRYING OPERATIONS (Btu/hr-ft-ºF)		
Temperature (^{o}F)	Planar	Axial
200	0.111	0.737
450	0.273	0.805
700	0.538	0.900
1000	0.977	1.040

Note 1: Ft. Calhoun 14x14 fuel is defined as the design basis fuel under the limiting condition of fuel storage in the minimum height MPC-37 (See Table 4.4.2).

Table 4.5.9

UNUSED

Table 4.5.10

EFFECT OF INCREASE IN BASKET PANEL GAP ON MAXIMUM TEMPERATURES OF MPC-37 DURING VACUUM DRYING CONDITION AT THRESHOLD HEAT LOAD

Component	Temperatures[Note 1], ^{o}C (^{o}F)
Fuel Cladding	389 (732)
MPC Basket	373 (703)
Basket Periphery	292 (558)
Aluminum Basket Shims	234 (453)
MPC Shell	142 (288)

Note 1: The predicted temperatures for the increased panel gap are slightly higher than the licensing basis temperatures for threshold heat load reported in Table 4.5.6.

4.6 OFF-NORMAL AND ACCIDENT EVENTS

In this Section thermal evaluation of HI-STORM FW System under off-normal and accident conditions defined in Sections 4.6.1 and 4.6.2 is provided. To ensure a bounding evaluation the limiting Pattern A thermal loading scenario defined in Section 4.4.4 is adopted in the evaluation.

4.6.1 Off-Normal Events

4.6.1.1 Off-Normal Pressure (Load Case NB in Table 2.2.7)

This event is defined as a combination of (a) maximum helium backfill pressure (Table 4.4.8), (b) 10% fuel rods rupture, (c) limiting fuel storage configuration and (d) off-normal ambient temperature. 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 4.6.7. The result is 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^{o}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 4.6.7. The results are below the off-normal condition temperature and pressure limits (Tables 2.2.3 and 2.2.1).

4.6.1.3 Partial Blockage of Air Inlets

The HI-STORM FW 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 FW 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 4.6.7. 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.

4.6.1.4 FHD Malfunction

This event is defined in Subsection 12.1.5 as stoppage of the FHD machine following loss of power or active component trip. The principal effect of this event is stoppage of helium circulation through the MPC and transitioning of heat dissipation in the MPC from forced convection to natural circulation cooling. To bound this event an array of adverse conditions are assumed to have developed coincidentally, as noted below:

a. Steady state maximum temperatures have been reached.
b. Design maximum heat load in the limiting MPC-37 is assumed.
c. Air (not water) is in the HI-TRAC FW annulus.
d. The helium pressure in the MPC is at the minimum possible value of 20 psig.

Under the FHD malfunction condition the principal requirement to ensure the off-normal cladding temperature limits mandated by ISG-11, Rev. 3 (see Table 2.2.3) must be demonstrated. For this purpose an array of adverse conditions are defined above and the Peak Cladding Temperature (PCT) computed using the 3D FLUENT model of the transfer cask articulated in Section 4.5. The PCT computes as 433^{o}C which is significantly below the 570^{o}C off-normal temperature limit.

4.6.2 Accident Events

4.6.2.1 Fire Accident (Load Case AB in Table 2.2.13)

Although the probability of a fire accident affecting a HI-STORM FW 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 VW or HI-STORM FW 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. The data necessary to define the fire event is provided in Table 2.2.8.

<u>(a) HI-STORM FW Fire</u>

The fuel tank fire is conservatively assumed to surround the HI-STORM FW 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 (802°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 FW cask. It

is therefore conservative to use the 1475°F (802°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 (specified in Table 2.2.8).

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×ft^2×°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 154.1 ft^2 and has a depth of 0.52 inch. From this depth and the fuel consumption rate of 0.15 in/min, the calculated fire duration is provided in Table 2.2.8. 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 FW overpack, a thermal model of the overpack cylinder was constructed using FLUENT. A transient study is conducted for the duration of fire and post-fire of sufficient duration to reach maximum temperatures. The bounding steady state HI-STORM FW normal storage temperatures (shortest fuel scenario in MPC-37, see Table 4.4.3) are adopted as the initial condition for the fire accident (fire and post-fire) evaluation. The transient study was conducted for a sufficiently long period 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.

The thermal transient response of the storage overpack is determined using FLUENT. 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 FW overpack while it is subjected to the fire is from a combination of incident radiation and convective heat flux 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)
σ = 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/m² (Btu/ft²-hr))
h_S = Natural Convection Heat Transfer Coefficient (Btu/ft²-hr-°F)
T_S = Surface Temperature (°F))
T_A = Ambient Temperature (°F)
σ = Stefan-Boltzmann Constant
ε = Surface Emissivity
C= Conversion Constant (460 (°F to °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]. Solar insolation was included during post-fire event. An emissivity of bare carbon steel (see Table 4.2.4) is used for all the cask outer surfaces during post-fire analysis.

The results of the fire and post-fire events are reported in Table 4.6.2. These results demonstrate that the fire accident event has a minor affect on the fuel cladding temperature. Localized regions of concrete upto 1 inch depth are exposed to temperatures in excess of accident temperature limit. The bulk concrete temperature remains below the short-term temperature limit. The temperatures of the basket and components of MPC and HI-STORM FW overpack (see Table 4.6.2) are within the allowable temperature limits.

Table 4.6.2 shows a slight increase in fuel temperature following the fire event. Thus the impact on the MPC internal helium pressure is correspondingly small. Based on a conservative analysis of the HI-STORM FW 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. Thus, the ability of the HI-STORM FW system to maintain the spent nuclear fuel within design temperature limits during and after fire is assured.

(b) HI-TRAC VW Fire

In this subsection the fuel cladding and MPC pressure boundary integrity under an exposure to a short duration fire event is demonstrated. The HI-TRAC VW is initially (before fire) assumed to be loaded to design basis decay heat and has reached steady-state maximum temperatures. The analysis assumes a fire from a 50 gallon transporter fuel tank spill. The fuel spill, as discussed in Subsection 4.6.2.1(a) is assumed to surround the HI-TRAC VW in a 1 m wide ring. The fire parameters are same as that assumed for the HI-STORM FW fire discussed in this preceding subsection. In this analysis, the HI-TRAC VW and its contents are conservatively postulated to undergo a transient heat-up as a lumped mass from the decay heat and heat input from the fire.

Based on the specified 50 gallon fuel volume, HI-TRAC VW cylinder diameter (7.9 ft) and the 1 m fuel ring width, the fuel ring area is 115.2 ft^2 and has a depth of 0.696 in. From this depth and the fuel consumption rate of 0.15 in/min, the fire duration τ_f is calculated to be 4.64 minutes (279 seconds). The fuel consumption rate of 0.15 in/min is a lowerbound value from Sandia Report [4.6.1]. Use of a lowerbound fuel consumption rate conservatively maximizes the duration of the fire.

From the HI-TRAC VW fire analysis, a bounding rate of temperature rise 2.722^{o}F per minute is determined. Therefore, the total temperature rise is computed as the product of the rate of temperature rise and τ_f is 12.6^{o}F. Because the cladding temperature at the start of fire is substantially below the accident temperature limit, the fuel cladding temperature limit during HI-TRAC VW fire is not exceeded. To confirm that the MPC pressure remains below the design accident pressure (Table 2.2.1) the MPC pressure resulting from fire temperature rise is computed using the Ideal Gas Law. The result (see Table 4.6.7) is below the pressure limit (see Table 2.2.1).

4.6.2.2 Jacket Water Loss

In this subsection, the fuel cladding and MPC boundary integrity is evaluated under a postulated (non-mechanistic) loss of water from the HI-TRAC VW water jacket. For a bounding analysis, all water compartments are assumed to lose their water and be replaced with air. The HI-TRAC VW 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 VW 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 4.6.7) shows a positive margin of safety.

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 FW system to reach steady state conditions. Because of the large mass of the HI-STORM FW 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 FW system are conservatively assumed to rise by the difference between the extreme and normal ambient temperatures (45^{o}F). The HI-STORM FW extreme ambient temperatures computed in this manner are reported in Table 4.6.4. The co-incident MPC pressure is also computed (Table 4.6.7) and compared with the accident design pressure (Table 2.2.1), which shows a positive safety margin. 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 eight bottom inlets for a significant duration (32 hours). 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 HI-STORM FW 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 FW system starting from normal storage conditions is obtained. The results of the blocked ducts transient analysis are presented in Table 4.6.5 and compared against the accident temperature limits (Table 2.2.3). The co-incident MPC pressure (Table 4.6.7) is also computed and compared with the accident design pressure (Table 2.2.1). All computed results are well below their respective limits.

4.6.2.5 Burial Under Debris (Load Case AG in Table 2.2.13)

Burial of the HI-STORM FW system under debris is not a credible accident. During storage at the ISFSI there are no structures that loom over the casks whose collapse could completely bury the casks in debris. 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 FW system to become completely buried under debris. However, for conservatism, the scenario of complete burial under debris is considered.

For this purpose, an exceedingly conservative analysis that considers the debris to act as a perfect insulator is considered. Under this scenario, the contents of the HI-STORM FW 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 FW 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:

$\Delta\tau$ = minimum available burial time (hr)
m = Mass of HI-STORM FW System (lb)
c_p = Specific heat capacity (Btu/lb-^{o}F)
ΔT = Permissible temperature rise (^{o}F)
Q = Decay heat load (Btu/hr)

Substituting the parameters in Table 4.6.6, the minimum available burial time is computed as 89 hours. The co-incident MPC pressure (see Table 4.6.7) is also computed and compared with the accident design pressure (Table 2.2.1). These results indicate that HI-STORM FW has a substantial thermal sink capacity to withstand complete burial-under-debris events.

4.6.2.6 Evaluation of Smart Flood (Load Case AD in Table 2.2.13)

A number of design measures are taken in the HI-STORM FW system to limit the fuel cladding temperature rise under a most adverse flood event (i.e., one that is just high enough to block the inlet duct). An unlikely adverse flood accident is assumed to occur with flood water upto the inlet height and is termed as ‘smart flood’. The inlet duct is narrow and tall so that blocking the inlet ducts completely would require that flood waters wet the bottom region of the MPC creating a heat sink.

The inlet duct is configured to block radiation efficiently even if the radiation emanating from the MPC is level (coplanar) with the duct penetration. The MPC stands on the base plate, which is welded to the inner and outer shell of the overpack. Thus, if the flood water rises high enough to block air flow through the bottom ducts, the lower region of the MPC will be submerged in the water. Although heat transport through air circulation is cut off in this scenario, the reduction is substantially offset by flood water cooling.

The MPCs are equipped with the thermosiphon capability, which brings the heat emitted by the fuel to the bottom region of the MPC as the circulating helium flows along the downcomer space around the basket. This places the heated helium in close thermal communication with the flood water, further enhancing convective cooling via the flood water.

The most adverse flood condition exists when the flood waters are high enough to block the inlet ducts but no higher. In this scenario, the MPC surface has minimum submergence in water and the ventilation air is completely blocked. In fact, as the flood water begins to accumulate on the ISFSI pad, the air passage size in the inlet vents is progressively reduced. Therefore, the rate of floodwater rise with time is necessary to analyze the thermal-hydraulic problem. For the reference design basis flood (DBF) analysis in this FSAR, the flood waters are assumed to rise instantaneously to the height to block the inlet vents and stay at that elevation for 32 hours. The consequences of the DBF event is bounded by the 100% blocked ducts events evaluated in Section 4.6.2.4. If the duration of the flood blockage exceeds the DBF blockage duration then a site specific evaluation shall be performed in accordance with the methodology presented in this Chapter and evaluated for compliance with Subsection 2.2.3 criteria.

Table 4.6.1 OFF-NORMAL CONDITION MAXIMUM HI-STORM FW TEMPERATURES		
Component	**Off-Normal Ambient Temperature ^{o}C (^{o}F)**	**Partial Inlets Duct Blockage ^{o}C (^{o}F)**
Fuel Cladding	384 (723)	385 (725)
MPC Basket	369 (696)	371 (700)
Aluminum Basket Shims	301 (574)	285 (545)
MPC Shell	251 (484)	257 (495)
MPC Lid*	246 (475)	252 (486)
Overpack Inner Shell	137 (279)	141 (286)
Overpack Outer Shell	76 (169)	62 (144)
Overpack Body Concrete*	100 (212)	95 (203)
Overpack Lid Concrete*	122 (252)	122 (252)

* Obtained by adding the difference between extreme ambient and normal temperature difference (11.1^{o}C (20^{o}F)) to normal condition temperatures reported in Table 4.4.3.

Table 4.6.2

HI-STORM FW FIRE AND POST-FIRE ACCIDENT ANALYSIS RESULTS

Component	Initial Condition °C (°F)	End of Fire Condition °C (°F)	Post-Fire Cooldown °C (°F)
Fuel Cladding	375 (707)	375 (707)	377 (711)
MPC Basket	361 (682)	361 (682)	363 (685)
Basket Periphery	297 (567)	297 (567)	299 (570)
Aluminum Basket Shims	276 (529)	276 (529)	278 (532)
MPC Shell	246 (475)	251 (484)	251 (484)
MPC Lid [Note 1]	243 (469)	245 (473)	245 (473)
Overpack Inner Shell	128 (262)	140 (284)	140 (284)
Overpack Outer Shell	60 (140)	340 (644) [Note 2]	340 (644) [Note 2]
Overpack Body Concrete [Note 1]	88 (190)	100 (212)	100 (212)
Overpack Lid Concrete [Note 1]	113 (235)	125 (257)	125 (257)

Note 1: Maximum section average temperature is reported.
Note 2: Surface average temperature is reported.

Table 4.6.3 HI-TRAC VW JACKET WATER LOSS MAXIMUM TEMPERATURES	
Component	**Temperature** **^oC (^oF)**
Fuel Cladding	432 (810)
MPC Basket	416 (781)
Basket Periphery	342 (648)
Aluminum Basket Shims	314 (597)
MPC Shell	290 (554)
MPC Lid*	263 (505)
HI-TRAC VW Inner Shell	205 (401)
HI-TRAC VW Radial Lead Gamma Shield	204 (399)

* Maximum section average temperature is reported.

Table 4.6.4 EXTREME ENVIRONMENTAL CONDITION MAXIMUM HI-STORM FW TEMPERATURES	
Component	**Temperature*** **°C (°F)**
Fuel Cladding	398 (748)
MPC Basket	383 (721)
Basket Periphery	315 (599)
Aluminum Basket Shims	292 (558)
MPC Shell	265 (509)
MPC Lid[Note 1]	260 (500)
Overpack Inner Shell	151 (304)
Overpack Outer Shell	90 (194)
Overpack Body Concrete[Note 1]	114 (237)
Overpack Lid Concrete[Note 1]	136 (277)
Average Air Outlet	128 (262)
Note 1: Maximum section average temperature is reported.	

* Obtained by adding the difference between extreme ambient and normal temperature difference (25°C (45°F)) to normal condition temperatures reported in Table 4.4.3.

Table 4.6.5 RESULTS OF HI-STORM FW 32-HOURS BLOCKED INLET DUCTS THERMAL ANALYSIS		
Component*	**Initial Condition ^{o}C (^{o}F)**	**Final Condition ^{o}C (^{o}F)**
Fuel Cladding	375 (707)	484 (903)
MPC Basket	361 (682)	468 (874)
Basket Periphery	297 (567)	404 (759)
Aluminum Basket Shims	276 (529)	380 (716)
MPC Shell	246 (475)	358 (676)
MPC Lid[Note 1]	243 (469)	313 (595)
Overpack Inner Shell	128 (262)	247 (477)
Overpack Outer Shell	60 (140)	105 (221)
Overpack Body Concrete[Note 1]	88 (190)	130 (266)
Overpack Lid Concrete[Note 1]	113 (235)	165 (329)
Note 1: Maximum section average temperature is reported.		

* For a bounding evaluation, temperatures are computed at the lowerbound helium backfill pressure defined in Table 4.4.8. Temperatures of limiting components reported.

Table 4.6.6 SUMMARY OF INPUTS FOR BURIAL UNDER DEBRIS ANALYSIS	
Thermal Inertia Inputs*: M (Lowerbound HI-STORM FW Weight) Cp (Carbon steel heat capacity)†	 215000 kg 419 J/kg-^{o}C
Clad initial temperature[Note 1]	390^{o}C
Q (Decay heat)	45 kW
ΔT (clad temperature margin)‡	160^{o}C
Note 1: Initial temperature conservatively postulated to bound the maximum cladding temperature.	

* Thermal inertia of fuel is conservatively neglected.

† Used carbon steel's specific heat since it has the lowest heat capacity among the principal materials employed in MPC and overpack construction (carbon steel, stainless steel, Metamic-HT and concrete).

‡ The clad temperature margin is conservatively understated in this table.

Table 4.6.7

OFF-NORMAL AND ACCIDENT CONDITION MAXIMUM MPC PRESSURES

Condition	**Pressure (psig)**
Off-Normal Conditions	
Off-Normal Pressure*	110.0
Partial Blockage of Inlet Ducts	99.9
Accident Conditions	
HI-TRAC VW fire accident	103.3
Extreme Ambient Temperature	101.7
100% Blockage of Air Inlets	116.4
Burial Under Debris	130.8
HI-TRAC VW Jacket Water Loss	109.5

* The off-normal pressure event defined in Section 4.6.1.1 bounds the off-normal ambient temperature event (Section 4.6.1.2)

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 FW 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 conditions, assuming rupture of 1 percent of the fuel rods. 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 Section 4.4 and shown to remain below the normal design pressures specified 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 which are shown to be well below their respective Design temperature limits summarized in Table 2.2.3.

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 shown to be 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 SAR Chapters 2 and 3 for normal conditions. All thermal results reported in Section 4.4 are within the design criteria under all normal conditions of storage.

4.7.2 Short-Term Operations

Evaluation of short-term operations is presented in Section 4.5 wherein complete compliance with the provisions of ISG-11 [4.1.4] is demonstrated. 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 (Table 4.3.1) is demonstrated.

Further, 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 SAR Chapters 2 and 3 for all short-term operations.

4.7.3 Off-Normal and Accident Conditions

As required by NUREG-1536 (4.0,IV,3), the maximum internal pressure of the cask is evaluated in Section 4.6 and shown to remain within its off-normal and accident design pressure, assuming rupture of 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.

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