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

1) The storage cell spaces are loaded with high flow resistance design basis fuel assemblies (See Table 2.1.4).
2) Each storage cell is generating heat at its limiting value under the regionalized storage scenarios defined in Chapter 2, Section 2.1.
3) Axial dissipation of heat by conduction in the fuel pellets is neglected.
4) Dissipation of heat from the fuel rods by radiation in the axial direction is neglected.
5) The fuel assembly channel length for BWR fuel is overstated.
6) The most severe environmental factors for long-term normal storage – ambient temperature of 80°F and 10CFR71 insolation levels – were coincidentally imposed on the system.
7) Reasonably bounding solar absorbtivity of HI-STORM FW overpack external surfaces is applied to the thermal models.
8) To understate MPC internal convection heat transfer, the helium pressure is understated.
9) No credit is taken for contact between fuel assemblies and the MPC basket wall or between the MPC basket and the basket supports.
10) Heat dissipation by fuel basket peripheral supports is neglected.
11) 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°F) [4.1.8]. Accordingly this effect is neglected in the thermal evaluations.

iv. Principal Attributes of MPC-31C 3D Thermal Model

The 3-D thermal model implemented to analyze MPC-31C in HI-STORM FW system has the following key attributes:

a) The hexagonal basket storage cell is modelled explicitly with the fuel storage spaces modeled as a solid region. In this manner flow through the basket storage cell containing fuel assemblies is conservatively ignored.

b) The effective conductivities of the MPC-31C storage spaces are computed for bounding fuel storage configuration defined in Paragraph 4.4.1.1(ii). This method is similar to that adopted for MPC-37. The in-plane thermal conductivities are obtained using FLUENT [4.4.2] computer models of an array of fuel rods enclosed by a hexagonal box 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). In the interest of conservatism, thermal analysis of normal storage condition in HI-STORM FW is performed with a 10% reduced effective thermal conductivity of fuel region.

c) Similar to MPC-37, 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.

d) The thermal model and methodology outside the MPC is same as that adopted for MPC-37.

e) A limited number of fuel assemblies defined in Table 1.2.1 classified as damaged fuel are permitted to be stored in the MPC inside Damaged Fuel Containers (DFCs). DFC storage is restricted to the outer peripheral locations of MPC-31C as shown in Figure 2.1.1c.

f) To maximize lateral resistance to heat dissipation in the fuel basket, 0.8 mm inter-panel gaps are conservatively assumed to exist at all intersections. This approach is identical to that used for MPC-37. The shims installed in the MPC peripheral spaces (See MPC-31C 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.

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

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

v. Principal Attributes of MPC-32ML 3D Thermal Model

The 3-D thermal model implemented to analyze MPC-31C in HI-STORM FW system follows the same methodology as MPC-37 discussed previously in this sub-section. A summary of the modeling attributes is provided below:

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

b) The entire cross-section of the storage cell is modeled as porous medium. The flow resistance through the storage cell is discussed in Paragraph 4.4.1.10.

c) The effective conductivities of the MPC-32ML storage spaces are computed for bounding fuel storage configuration defined in Paragraph 4.4.1.1(ii). The in-plane thermal conductivities are obtained using FLUENT [4.4.2] computer models of an array of fuel rods enclosed by a square box 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). In the interest of conservatism, thermal analysis of normal storage condition in HI-STORM FW is performed with a 10% reduced effective thermal conductivity of fuel region.

d) Similar to MPC-37, 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 thermal model and methodology outside the MPC is same as that adopted for MPC-37.

f) A limited number of fuel assemblies defined in Table 1.2.1 classified as damaged fuel are permitted to be stored in the MPC inside Damaged Fuel Containers (DFCs). DFC storage is restricted to outer peripheral locations of MPC-32ML as shown in Figure 2.1.1b.

g) To maximize lateral resistance to heat dissipation in the fuel basket, 0.8 mm inter-panel gaps are conservatively assumed to exist at all intersections. This approach is identical to that used in the thermal analysis of MPC-37 basket. The shims installed in the MPC peripheral spaces (See MPC-32ML 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.

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

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

4.4.1.2 Fuel Assembly 3-Zone Flow Resistance Model[1]

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 models the fuel storage cell length between the bottom and top plenums[2] is replaced by porous media. As discussed below the porous media length is partitioned in three zones with discrete flow resistances.

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[1] 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].

[2] 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.

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- The channel is present and attached to the fuel assembly in the standard fashion; and
- The channel is essentially undamaged; and
- The maximum planar average enrichment of the assembly is less than or equal to 3.3 wt% ^{235}U

This analysis covers older assemblies, where the cladding integrity is uncertain, and where a verification of the cladding condition is prohibitive. An example of this type of fuel is the so-called CILC fuel, which has potential corrosion-induced damaged to the cladding but does not have grossly breached spent fuel rods.

The presence of the essentially undamaged and attached channel confines the fuel rods to a limited volume and the low enrichment, required for all assemblies in the MPC, limits the reactivity of the fuel even under optimum moderation conditions. Due to the uncertain cladding condition, the analysis of this fuel follows essentially the same approach as that for the Damaged Fuel and Fuel Debris, i.e. bare fuel rod arrays of varying sizes are analyzed within the confines of the channel. This is an extremely conservative modeling approach for this condition, since reconfiguration is not expected and cladding would still be present. The results of this conservative analysis are listed in Table 6.4.8 and show that the system remains below the regulatory limit with these assemblies in all cells of the MPC-89, without DFCs.

These results confirm that even with unknown cladding condition the maximum k_{eff} values are below the regulatory limit when fully flooded and loaded with any of the BWR candidate fuel assemblies, therefore if the cladding is not grossly breached and the fuel assembly structurally sound it can be considered undamaged when loading in an MPC-89.

6.4.10 BWR Fuel with a Partial Gadolinium Credit

6.4.10.1 Introduction and Background

Traditionally, criticality safety calculations for dry storage and transport of BWR fuel have been performed assuming fresh fuel, and neglecting any burnable absorbers in the fuel. With respect to burnable absorbers, modern BWR fuel assemblies rely solely on integral neutron absorbers in the fuel assemblies for long term reactivity control in the reactor. As a result, every modern BWR fuel assembly contains a substantial amount of burnable absorbers, in the form of Gadolinia (Gd_2O_3) mixed into the UO_2 for a number of the fuel rods, hereinafter referred to as Gd rods. This is in contrast to PWR fuel which primarily utilizes soluble boron in the water for long term reactivity control, optionally supported by removable and/or integral burnable poison. Hence not all PWR assemblies contain any integral burnable absorbers, and even if they do, the amount is not as significant as in BWR assemblies. In the past, credit for burnable poison, or for burnup for that matter, was generally not necessary for BWR dry storage and transportation system, since the enrichment limits resulting from the criticality safety evaluations where high enough to encompass a large fraction of the fuel inventories (For modern 10x10 BWR assemblies the enrichment limit is about 4.6 to 4.8 wt%, depending on the assembly type). However, by now assemblies exceed those values. And, if after the shutdown of a nuclear plant the entire inventory of spent fuel is moved into dry storage, it is no longer sufficient to cover just a substantial fraction of assemblies, all assemblies need to be qualified.

By now, gadolinium credit methodologies are available, and supported by regulatory guidance documents (NUREG/CR-7194 [6.4.2]), to increase the permissible initial enrichment for dry storage and transportation. One of the complications in such methodologies is the fact that the typically large amount of gadolinium results in a "peak reactivity" condition, where the most reactive condition is no longer the fresh condition, but the condition at a burnup where the poison is burned out, typically at burnups around 10 to 15 GWd/mtU. This then requires a depletion calculation of the fuel in order to identify the most reactive condition of the fuel assembly. However, for the MPC-89, only a limited reactivity benefit is needed from the gadolinium, since the qualified enrichment (see Table 6.1.2) even without such credit is already very close to the maximum enrichment of 5 wt%. This allows a significant simplification of the gadolinium credit: only a small fraction of the gadolinium needs to be credited, and in this case the "peak reactivity" condition is not applicable, i.e. the fresh condition is the most reactive condition. And since only a small fraction of the available amount of gadolinium in the fuel assembly is credited, this methodology is characterized as the "partial gadolinium credit".

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6.4.10.2 Generic Approach

The analysis is performed and documented in this subsection to qualify all 10x10 assembly classes with the increased enrichment up to 5.0 wt% ^{235}U using a partial credit for Gd rods. The limiting conditions are determined, and the administrative requirements are set forth to ensure that the maximum k_{eff} value, including all applicable biases and uncertainties, is below 0.95 with a substantial safety margin, sufficient to offset any potential uncertainties in the condition of the BWR fuel assembly with Gd rods.

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6.4.10.3 Conclusion

In summary, all 10x10 fuel assembly classes with the fuel enrichment of up to 5.0 wt% ^{235}U are qualified for loading into the MPC-89 basket using a partial credit for Gd rods with the following administrative requirements:

- The Gd rod loading is not less than 3.0 wt% Gd_2O_3;
- The Gd rods located in the peripheral row of the fuel lattice cannot be credited;
- At least one Gd rod is required for 10x10A, 10x10B and 10x10F fuel assembly classes;
- Not less than two Gd rods are required for 10x10C and 10x10G classes.

The maximum k_{eff} value, including all applicable biases and uncertainties, is below 0.95 with a substantial safety margin, sufficient to offset any potential uncertainties in the condition of the BWR fuel assembly with Gd rods.