September 17, 2004

Mr. Evan Rosenbaum
Licensing Manager
Holtec International
555 Lincoln Drive West
Marlton, NJ 08053

SUBJECT: HI-STORM 100, AMENDMENT 2, HIGH HEAT LOAD THERMAL EVALUATION (TAC NO. L23657)

Dear Mr. Rosenbaum:

On March 4, 2002, Holtec International (Holtec) submitted an application in accordance with 10 CFR Part 72 for an amendment to Certificate of Compliance (CoC) No. 1014 for the HI-STORM 100 Cask System to: (a) revise the contents in accordance with various new thermal, confinement, criticality, and shielding review methodologies; (b) permit the inclusion of damaged fuel contents to the Multi-Purpose Canister (MPC) -32; and ©) permit the inclusion of intact, damaged fuel, and fuel debris contents to a new MPC-32F.

The Nuclear Regulatory Commission (NRC) staff, hereafter referred to as the staff, performed a technical review of your application and issued Holtec two Requests for Additional Information to which Holtec responded. Holtec submitted two significant, comprehensive revisions to the application during the course of this review primarily in response to staff questions. The staff performed confirmatory calculations in the thermal area and presented the preliminary results to Holtec in letters dated March 23, 2004, and May 4, 2004. Over the course of the staff's review of the complex methodologies associated with Holtec's approach to the thermal analysis, the staff was unable to confirm or verify Holtec's calculated results. Subsequently, the NRC staff met with Holtec on August 4, 2004, to inform Holtec that significant issues remained outstanding regarding the thermal evaluation in support of the request for an increase in the maximum heat load that could be loaded into the HI-STORM 100 Cask System. At this meeting, the NRC staff informed Holtec of the decision to discontinue the review of this application.

Holtec has since withdrawn that portion of the amendment submittal pertaining to the request for a higher heat load and associated new analyses and methodologies in a letter dated August 13, 2004, in order to facilitate continuing the review with the goal of obtaining approval of the remaining changes requested in the Amendment 2 submittal. Commensurate with the withdrawal of the request for the higher heat load, included with the letter, Holtec submitted a revised Final Safety Analysis Report (FSAR) and proposed CoC changes. The staff is currently reviewing this most recent submittal.

The NRC staff agreed to provide Holtec with an evaluation of the thermal analyses and methodology Holtec submitted in support of the higher heat load request that was withdrawn by your August 13, 2004, letter. This evaluation describes those areas where the staff was unable to verify Holtec's results in the thermal discipline and therefore draw any conclusive findings that would have resulted in an approval of the proposed design changes. The staff's findings were inconclusive based on the information you provided. The attached evaluation will be of use to you in the formulation of a sound technical basis should you wish to resubmit a request for a higher heat load HI-STORM 100 Cask System design in the future. This letter will close our technical review of these thermal analyses and methodology until resubmitted by Holtec for staff review at a later date.

It should be noted that the attached evaluation is based on Holtec's August 6, 2003, comprehensive revision to the FSAR (HI-STORM 100 Cask System LAR 1014-2, Revision 2) as supplemented through July 30, 2004, and any additional technical information that you have provided to the staff through July 30, 2004.

Please continue to reference docket number 72-1014 and TAC No. L23657 in future correspondence related to this action. You may contact me at (301) 415-1179, if you have any questions regarding our review of the amendment request.

Sincerely,

/RA/

Christopher M. Regan, Project Manager
Licensing Section
Spent Fuel Project Office
Office of Nuclear Material Safety
and Safeguards

Docket No. 72-1014
TAC No. L23657

Enclosure: Thermal Evaluation

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Docket No. 72-1014
TAC No. L23657

Enclosure: Thermal Evaluation

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Enclosure

HI-STORM 100 Cask System
Docket Number 72-1014
Amendment Request 2
Thermal Evaluation of Proposed High Decay Heat Load

THERMAL EVALUATION

The Nuclear Regulatory Commission (NRC) staff, hereafter referred to as the staff, reviewed the HI-STORM 100 Cask System proposed License Amendment Request (LAR) 2 thermal design for high heat load for conformance to 10 CFR Part 72 requirements (Ref. 1). This review was based on the HI-STORM 100 Cask System LAR 1014-2, Revision 2, submitted August 6, 2003, as supplemented, and supplemental technical information provided to the staff through July 30, 2004. The staff performed independent confirmatory calculations to affirm that the cask, canister and fuel material temperatures are maintained within accepted allowable values under normal, off-normal, and accident conditions, per 10 CFR Part 72 criteria. Given the thermal conditions proposed by the applicant, the staff's independent analyses identified modeling issues that required additional justification/validation. The staff's analyses resulted in temperatures that were in excess of the accepted guidelines provided in Interim Staff Guidance (ISG) 11, Revision 3. The staff's review followed the guidance outlined in Sections 4 and 11 of NUREG-1536, "Standard Review Plan for Dry Cask Storage Systems," (Ref. 2) as well as associated ISG documents.

The staff has concluded that the applicant's thermal models and analysis methods, described in Chapter 4 of the Safety Analysis Report (SAR) and other applicable references, have not been demonstrated to provide realistic or conservative estimates of the peak cladding temperature (Ref. 3). In order for the staff to find the applicant's analyses acceptable, the applicant would either have to model the geometric configurations in greater detail, or provide applicable experimental validations that are consistent with the heat load and helium conditions proposed in the Amendment 2 application.

1.0 DESCRIPTION OF PROPOSED CHANGES

The principle changes proposed by the applicant in the LAR that affect the thermal performance of the HI-STORM 100 Cask System are listed as follows:

1. The thermal analysis is revised to comply with recently issued NRC staff guidance ("Cladding considerations for the Transportation and Storage of Spent Fuel," ISG-11, Rev. 3);

2. The aluminum heat conduction elements (AHCEs), optional under Amendment 1 of Certificate of Compliance (CoC) 1014, are removed from the design. Removing the AHCEs from the Multi-Purpose Canister (MPC) eliminates the constriction of the downcomer flow (see Figure 4.0.1 of the SAR) and thus further enhances the thermal performance of the MPC;

3. The whole spectrum of regionalized storage of Spent Nuclear Fuel (SNF) for each MPC type has been analyzed to allow flexibility in Region 1 (the core region of the basket) and Region 2 (the outer region of the basket) heat loads. The heat load flexibility afforded to the Independent Spent Fuel Storage Installation (ISFSI) owner by the analysis documented in the FSAR permits MPCs to be loaded in the most effective manner to minimize dose;

4. Certain elements of excessive conservatism in the mathematical model have been relaxed to retain a moderate level of conservatism. SAR Subsection 4.4.6 documents conservatisms that apply to the thermal solution. A quantitative estimate of the consequences of the elements of conservatism is provided in SAR Appendix 4.B;

5. The Helium backfill pressure is increased (SAR Table 4.4.38) to facilitate increased heat dissipation from the MPC through the classical thermosiphon action (SAR Figure 4.0.1); and

6. The design maximum decay heat load for the HI-STORM Cask System is revised (SAR Table 4.4.39).

2.0 Spent Fuel Cladding

The applicant adopted certain guidelines of NUREG-1536 (Ref. 2) and ISG-11, Rev. 3 (Ref. 3) to demonstrate the safe storage of the material contents described in Chapter 2 of the SAR and in the CoC for the HI-STORM 100 Cask System. The applicant intends to design the HI-STORM 100 Cask System to comply with the following eight criteria:

1. The fuel cladding temperature at the beginning of dry cask storage should generally be below the anticipated damage-threshold temperatures for the licensed life of the system.

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

3. The maximum internal pressure of the cask should remain within its design pressures for normal (1% rod rupture), off-normal (10% rod rupture), and accident (100% rod rupture) conditions.

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

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

6. For long term normal and short term operations (defined in Chapter 2 of the SAR), the maximum commercial spent fuel (CSF) cladding temperature shall be limited to 752°F (400°C).

7. The cask system should be passively cooled.

8. The thermal performance of the cask should be within the allowable design criteria specified in Chapter 2 and 3 of the SAR for normal, off-normal, and accident conditions.

A summary of the applicant's thermal results, which are based on the analysis methods and calculations described in the SAR, is presented in the following paragraph.

The HI-STORM 100 Cask System maximum temperatures for normal storage are presented in Tables 4.4.9, 4.4.10, and 4.4.26 of the SAR for the MPC-24, MPC-24E, MPC-68 and MPC-32, respectively and in Table 4.4.36 of the SAR for the overpack temperatures. Maximum MPC pressures for normal storage are presented in Table 4.4.14 of the SAR. Table 4.5.11 of the SAR provides the value of the threshold heat loads for which vacuum drying is permitted. Table 4.5.12 of the SAR provides the threshold heat loads (steady state) and time limits on the on-site transport evaluation if the threshold is exceeded. For a limiting case for on-site transfer of an MPC loaded with high burnup fuel (Condition 3 in Table 4.5.12 of the SAR), the maximum fuel clad temperatures are presented in Table 4.5.2 of the SAR, which also summarizes maximum calculated temperatures in different parts of the HI-TRAC transfer cask and MPC. Maximum internal pressures for accident conditions are provided in Tables 11.2.4 and 11.2.10 of the SAR.

3.0 Cask System Thermal Design

The HI-STORM 100 Cask System accommodates a wide variety of spent nuclear fuel (SNF) assemblies in a single overpack design by utilizing different MPCs. The MPC-24, MPC-24E, and MPC-24EF contain a maximum of 24 Pressurized Water Reactor (PWR) fuel assemblies. The MPC-32 and MPC-32F contain a maximum of 32 PWR fuel assemblies. The MPC-68, MPC-68F, and MPC-68FF, contain a maximum of 68 Boiling Water Reactor (BWR) fuel assemblies. The assembly average burnup, initial enrichment and cooling time is described in Table 2.1.17 through Table 2.1.24 of the SAR. The HI-STORM 100 overpack is equipped with large penetrations near its lower and upper extremities to permit natural circulation of air to provide for passive cooling of the MPC and the contained radioactive material. The air inlets and outlets are covered by a fine mesh screen to reduce the potential blockage. The HI-STORM 100 cask is stored in a vertical orientation that leads to an effective natural convection cooling flow around the MPC. The complete cell-to-cell connectivity inherent in the honeycomb basket structure provides an uninterrupted heat transmission path, making the MPC an effective heat rejection device.

The HI-TRAC transfer cask is a rugged, heavy-walled cylindrical vessel. The transfer cask is a steel, lead, steel layered cylinder with a water jacket attached to the exterior. The transfer cask provides an internal cylindrical cavity of sufficient size for housing an MPC. Two standard design HI-TRAC transfer casks of different weights are provided to house the MPCs. The 125 ton HI-TRAC weight does not exceed 125 tons during any loading or transfer operation. The 100 ton HI-TRAC weight does not exceed 100 tons during any loading or transfer operation. The two HI-TRACs are identical except for a reduced thickness of lead and water of the 100 ton cask. Therefore, the 125 ton HI-TRAC has a larger thermal resistance than the 100 ton HI-TRAC. For normal conditions, the 125 ton HI-TRAC thermal analysis bounds that of the 100 ton HI-TRAC.

4.0 Thermal Load Specifications

The applicant proposed a maximum total decay heat load per MPC of 38 Kilowatt (kW) for MPC-24, MPC-24E, MPC-24EF, MPC-32, and MPC-32F, with a maximum per assembly heat load as specified in Table 2.1.26 of the SAR for uniform heat load distribution. The applicant proposed a maximum total decay heat load per MPC of 35.5 kW for MPC-68, and MPC-68FF, with a maximum per assembly heat load as specified in Table 2.1.26 of the SAR for uniform heat load distribution. When zoning (preferential loading) is used to distribute the heat load in a nonuniform manner, the procedure described in Section 2.1.9.1.1 of the SAR is applied to obtain the decay heat limits.

5.0 Model Specifications

5.1 Thermal Properties of Materials

Material property tables for the HI-STORM 100 Cask System components are included in Section 4.2 of the SAR. The temperature range for the material properties covers the range of temperatures encountered during the thermal analysis with some exceptions that were properly justified by the applicant.

5.2 Use of Effective Thermal Conductivity Models

The applicant applied the concept of effective thermal conductivity to model a highly heterogeneous geometry. In other words, the basket region of the MPC and the fuel assembly are homogenized to calculate an effective thermal conductivity. According to Section 4.V.4.a of NUREG-1536, use of effective thermal conductivity coefficients for regions within the confinement cask, other than the fuel (e.g., gaps), may overestimate heat transfer. If effective thermal conductivity is used in this manner, the applicant should verify that the same values have been determined from test data that are representative of similar geometry, materials, temperatures, and heat fluxes used in current application. The applicant has not provided any justification for deviating from the staff's review guidelines or an evaluation of the impact on calculated thermal results presented in the SAR.

5.2.1 Spent Fuel Effective Thermal Conductivity

Effective thermal conductivity values for the most heat transfer resistive PWR and BWR fuel assembly types are obtained by the applicant to represent the fuel region. The Westinghouse Electric (WE) 17x17 OFA PWR and General Electric (GE)11-9x9 BWR fuel assemblies were determined by the applicant to be the bounding configurations for analysis of zircaloy clad fuel at design basis maximum heat load. Detailed conduction-radiation finite-volume calculations of the bounding PWR and BWR fuel assemblies were performed by the applicant by using the FLUENT® computational fluid dynamics code. Temperature-dependent effective conductivities of PWR and BWR bounding fuel assemblies are shown in Figure 4.4.5 of the SAR.

5.2.2 Effective Thermal Conductivity of Neutron Absorber/Sheating/Box Wall Sandwich

Directional effective thermal conductivity values of the composite basket wall-neutron absorber-sheating sandwich are obtained by the applicant considering a series (out-of-plane) and parallel (in-plane) approach. In the lateral out-of-plane direction heat is transported across layers of sheating, helium gap, neutron absorber and basket wall series resistances. Heat conduction in the longitudinal in-plane direction is through an array of parallel resistances of the layers listed above. These non-isotropic thermal conductivities are determined by the use of two-dimensional (2-D) ANSYS finite element temperature results combined with a one-dimensional heat conduction equation applied for each direction (in-plane and out-of-plane).

5.2.3 Effective Thermal Conductivity of Fuel Basket Support

An effective basket cross-sectional thermal conductivity is obtained by the applicant by applying an equivalence between an ANSYS finite element model of the basket and an analytical expression obtained by treating the MPC as a cylindrical conducting region with uniform heat generation and constant thermal conductivity. Temperature-dependent effective thermal conductivities of the fuel regions and composite basket walls are applied to the ANSYS model. The effective thermal conductivity values are lower bound values because the effective conductivity of the most resistive fuel assembly types is used in the MPC finite element simulations. According to the SAR, the internal basket panels are modeled as orthotropic material with along-panel and through-panel defined thermal conductivities. As it is specified in the applicant's ANSYS thermal model, a material oriented in the X-direction would be using the correct associated thermal conductivity values (along the panel for the X-direction and through-panel in the Y-direction). However, the same material oriented in the Y-direction would incorrectly use these conductivities (i.e., along the panel thermal conductivity would be used instead of through-panel thermal conductivity and through-panel thermal conductivity would be used instead of along the panel thermal conductivity). Based on the applicant's ANSYS thermal model defined coordinate system, different materials should be used for the internal panels oriented in the horizontal (X) direction and vertical (Y) direction to correctly capture the orthotropic nature of this material. Figure 1 schematically shows a fuel assembly cell and associated basket walls. Figure 1 (a) shows the applicant's material definition used in the ANSYS model of the fuel assembly basket. Figure 1 (b) illustrates how the staff believes the materials used to model this part of the basket using different material identification numbers to represent the basket walls should be defined.

Reviewing the applicant's ANSYS thermal models, the staff found that some of the fuel basket thermal conductivity values are inconsistent with the values used by the applicant in the FLUENT® model. Specifically, for the MPC-32 fuel basket effective conductivity calculated at 700°F (371°C), a value of 1.486 BTU/hr-ft-°F (2.572 W/m-K) is used in the FLUENT® model while the ANSYS result corresponds to 1.4323 BTU/hr-ft-°F (2.4788 W/m-K). Similarly, for the MPC-68, a value of 1.5 BTU/hr-ft-°F (2.596 W/m-K) is used in the FLUENT® model while the ANSYS result corresponds to 1.4323 BTU/hr-ft-°F (2.4788 W/m-K). An increase in some of the fuel basket effective thermal conductivity calculated values has not been properly justified by the applicant. Also, as it was stated before in Section 5.2 of this evaluation, the use of effective thermal conductivity models for regions other than the fuel has not been justified nor has the impact from deviating from the NUREG-1536 guidelines been evaluated.

Axial effective thermal conductivity of the basket is determined by calculating the area occupied by each material in a fuel basket cross-section, multiplying by the corresponding material thermal conductivity, summing the products, and dividing by the total fuel basket cross-sectional area. The only portion of fuel assemblies credited in these calculations is the fuel rod cladding.

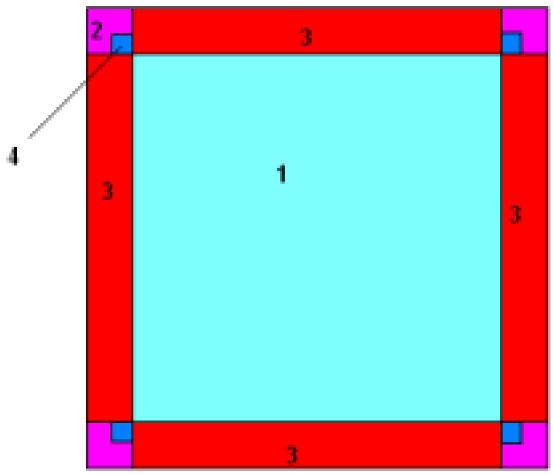

Figure 1 (a)

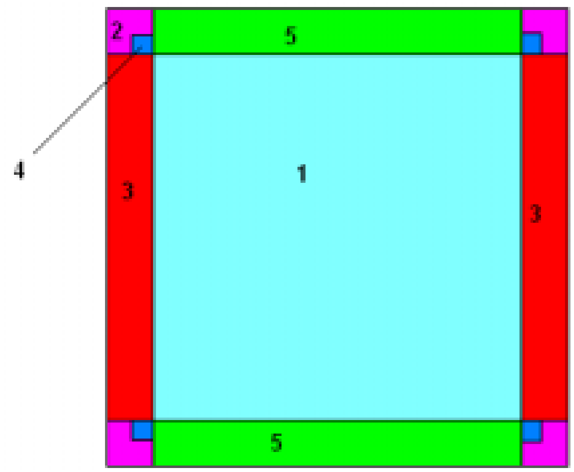

Figure 1(b)

5.2.4 Effective Thermal Conductivity of HI-TRAC Water Jacket

The applicant obtained effective radial thermal conductivity for the water jacket region by combining the heat transfer resistance of the water jacket individual components (radial steel ribs and water spaces) in a parallel network. The applicant stated that a bounding calculation is assured by using a minimum available metal thickness for radial heat transfer.

5.3 Boundary Conditions

The HI-STORM 100 Cask System thermal analyses were performed for normal conditions involving normal ambient temperature of 80°F (26.7°C) with insolation and partial radiation blockage due to the presence of neighboring casks. This normal ambient temperature represents the bounding annual average. Off-normal conditions considered by the applicant in the analysis include:

1. Three-day average ambient temperature of -40°F (-40°C) without insolation; and
2. Three-day average ambient temperature of 100°F (37.8°C) with insolation

Extreme accident level conditions utilized in the analysis include: three-day average ambient temperature of 125°F (51.7°C) with insolation starting at steady-state off-normal high environment temperature

The HI-TRAC transfer cask thermal analyses were performed for normal conditions involving normal ambient temperature of 100°F (37.8°C) with insolation. This normal ambient temperature represents the bounding annual average. Off-normal conditions considered by the applicant in the analysis include:

1. Three-day averaged ambient temperature of 0°F (-17.8°C) without insolation; and
2. Three-day averaged ambient temperature of 100°F (37.8°C) with insolation

Handling operations with the loaded HI-STORM 100 overpack and HI-TRAC transfer cask are limited to working area ambient temperatures greater than or equal to 0°F (-17.8°C) as specified in the Design Features of Appendix B of the CoC.

5.4 Model Configuration

The applicant credits convection heat transfer in the canister internals. Applicants seeking NRC approval of specific internal convection models where peak material temperature limits may be exceeded, may propose a comprehensive test program as a means to demonstrate the adequacy of the cask design and validation of the convection models. Actual spent fuel properties and uncertainties (e.g., friction factors, crud and oxide buildup, eccentricities, non-uniform axial and radial decay heat profiles) should be addressed. The applicant, in this instance, has not fully addressed these issues. Also, the thermal model described in the SAR may not include the minimum necessary features that would accurately capture the heat transfer and flow characteristics assumed in the cask design. Potential modeling problems and non-conservative assumptions identified by the staff in the applicant's thermal evaluation of the HI-STORM 100 storage cask are described in the following Sections.

The applicant used an axisymmetrical two-dimensional (2-D) computational fluid dynamics (CFD) model to analyze the thermohydraulic response of the HI-STORM 100 storage cask. This axisymmetric model considers only radial and axial directions. The MPC with associated internals (fuel assemblies, fuel basket, top and lower fuel spacers, downcomer region with non-uniform peripheral cross-section, lower and upper plenum with non-uniform cross-section) was represented by two discrete regions: (1) basket region assuming uniform-cross section from bottom to top, and (2) helium-filled downcomer peripheral region also assuming uniform-cross section from bottom to top.

FLUENT® porous media models were used to model the fuel region, top and bottom inactive regions, and top and bottom plenums of the MPC. Constant flow resistance parameters calculated for each MPC type (MPC-24, MPC-24E, MPC-32, etc.) were applied to the porous media model.

The applicant's 2-D porous media model used to perform the analysis of the storage cask may have potential modeling deficiencies due to the irregularities encountered in the real geometry of the MPC internals. Discontinuities of the real geometry, simplified to an equivalent perfect axisymmetrical polar coordinate system, may have limitations when this approach is applied to capture the physics of an otherwise three-dimensional (3-D) flow and heat transfer problem. Flow phenomena, such as flow separation and secondary flows in area expansions and contractions, may not be easily detected when area discontinuities and blockages are represented by the equivalent flow resistance, as applied in the applicant's analysis. The flow slows down in area expansions and accelerates in contractions, consequently affecting the local heat transfer rates. The assumptions and approaches used in the applicant's analysis model may present some limitations for predicting this behavior. The staff believes a 3-D representation of each MPC type (MPC-24, MPC-32,MPC-68) of the HI-STORM 100 storage cask geometry will better capture the flow and heat transfer characteristics of the storage system. Use of porous media should be limited to represent the fuel assembly heated regions (e.g., fuel pins only). Other regions of the MPC internals should be modeled explicitly because these regions may exhibit different thermal-hydraulic characteristics.

5.4.1 HI-STORM 100 Cask System

5.4.1.1 Thermal-Hydraulic Model

The HI-STORM 100 overpack is modeled as a FLUENT® CFD two-dimensional axisymmetric body. The hydraulic resistances of the inlet and outlet ducts are represented by equivalent axisymmetric porous media. The axial resistance to airflow in the MPC/overpack annulus is replaced by a hydraulically equivalent annulus. The HI-STORM module is assumed to be confined in a large cylindrical “tank” whose wall surface boundaries are modeled as zero heat flux boundaries. The air in the tank is the source of “feed air” to the overpack. This air is replenished by ambient air from above the top of the overpack. Two sources of heat input to the exposed surface overpack are considered: internal heat generation within the MPC and insolation. Summarized essential features of this model include a canister pressure of 7 atm. Solar heat input is applied to the top surface and the cylindrical surface of the overpack with an absorptivity equal to 1.0. The heat generation is assumed to be uniform in each region in a horizontal plane with axially varying heat generation with specified distribution according to Table 2.1.11 of the SAR. A cask with the maximum radiative blockage is modeled. The bottom surface of the overpack rejects heat through the pad to a constant temperature of 77°F (25°C). For some scenarios, the bottom surface of the overpack is assumed to be adiabatic.

5.4.1.2 HI-STORM 100 Air Annulus Flow Regime

5.4.1.2.1 Laminar versus Turbulent Flow

To determine the flow regime, the applicant calculated a Rayleigh (Ra) number based on the height of the MPC overpack annulus. The applicant assumes that the MPC outer shell can be treated as an isolated vertical heated plate. This approach may have modeling limitations because the HI-STORM 100 air annulus is not a true vertical heated plate, but more so an enclosure. Based on the actual geometry of the enclosure and data from technical papers when calculating the Ra number, the staff believes the applicable characteristic length should be the gap thickness. Staff’s calculated Ra numbers, based on the thickness of the annulus (which is about 2 inches thick), suggest that the air annulus may be operating in a laminar flow regime. Staff’s preliminary 3-D calculations based on laminar flow conditions for the air annular gap have resulted in maximum cladding temperatures that are at least 125°F (52°C) higher than the applicant’s 2-D analysis that assumed turbulent flow in the air annular region.

In a letter submitted to the NRC on May 14, 2004, the applicant expressed the intent to validate the above assumption on the basis of using experimental data obtained from a different geometry. The geometry referenced by the applicant corresponded to a vertical isolated heated plate as compared to the actual HI-STORM 100 annular geometry. According to the applicant, the maximum thickness of the vertical isolated heated plate (thermal) boundary layer is approximately 12 mm (about 0.5 inches). The applicant indicated that since the HI-STORM 100 thermal-hydraulic model of the air annulus predicts a thermal boundary layer thickness of about 10 mm, it would be appropriate to consider the HI-STORM 100 annulus as an (isolated) vertical plate. Based on the above findings and on calculated MPC height-based Ra number, the applicant concluded the flow conditions inside the air annular gap are turbulent.

In a letter submitted to the NRC on June 18, 2004, the applicant provided a calculation of the HI-STORM 100 annulus thermal boundary layer thickness. From a FLUENT® calculation the applicant obtained a temperature profile for the annulus as a function of the cask system radius from the top corner of the MPC to the overpack inner shell. According to the applicant, this temperature profile can then be used to calculate the thermal boundary layer as a function of the slope and a temperature difference between the minimum air temperature from the extracted profile and the temperature of each surface (MPC outer shell and overpack inner shell). This calculation assumes a linear relationship of the thermal boundary layer thickness regarding the slope (which is defined as the ratio between the radius difference between the first two data points for each surface and a temperature difference between these two points). Based on Figure O.1 (see page O-5 of Appendix O of Holtec Report HI-2033054) and assuming that a thermal boundary layer could be defined for this geometry, it appears the thickness of this boundary layer could potentially cover the whole annular gap and not the 10mm as the applicant has indicated.

In addition to the above approach, the applicant calculated an air annulus hydraulic diameter-based Ra number which implies that the air annulus operates in a laminar flow regime. The applicant did not provide conclusions from this calculation and only indicated that the approach used to calculate the Ra number for this type of geometry would depend on the reference being used.

The staff believes that in order to justify the assumption of conditions of fully developed turbulent flow in the air annular gap, it would be necessary to validate the assumption by comparing it with experimental data obtained from a geometry that closely resembles the HI-STORM 100 overpack to MPC outer shell annular geometry. The staff's findings are based on limited available theory for characterizing buoyancy driven flows for the geometry and flow characteristics of the HI-STORM 100 air annular gap. In the absence of specific data from technical literature the staff is not able to confirm or deny the applicant's assumptions and methods.

5.4.1.2.2 Staff Investigation on Applicant's Annulus Airflow Turbulent Model

The applicant applied the FLUENT®' s Renormalization Group (RNG) Theory k-ε model (Ref. 4) to the air flow region in the MPC HI-STORM annulus along with non-equilibrium wall functions for near-wall treatment. However, according to Ref. 4, "the wall function approach becomes less reliable when the flow conditions depart too much from the ideal conditions underlying the wall functions." Ref. 4 provides examples of departure from ideal conditions. Specific examples of departure from ideal conditions which are applicable to the HI-STORM geometry are:

1. Low-Reynolds-number or near-wall effects (e.g., flow through a small gap or highly viscous, low velocity fluid-flow)

2. Strong body forces (e.g., buoyancy driven flows)

Based on the applicant's 2-D axisymmetric model, the staff increased the number of nodes in the radial direction of the air annulus to use a more detailed approach to deal with the near-wall treatment. This model is referred to as the enhanced wall treatment in the FLUENT® literature (Ref. 4). The staff followed the near-wall mesh guidelines provided in the FLUENT® literature to assure this model was used correctly. Based on the applicant's licensing basis model and using the enhanced wall treatment option, the staff's calculated peak cladding temperature was 50° F higher than the applicant's licensing basis calculated results and exceeds the ISG-11, Rev. 3 allowable temperature limit.

5.4.1.3 MPC Loading Approach

The HI-STORM 100 Cask System is evaluated by the applicant for two fuel storage scenarios: uniform loading and regionalized loading. In the uniform loading, every basket cell is assumed to be occupied with fuel producing heat at the maximum rate. In the regionalized fuel loading shown in Figure 4.4.25 of the SAR, a two region fuel loading configuration is stipulated.

5.4.2 HI-TRAC Transfer Cask

The HI-TRAC transfer cask is used to load and unload the HI-STORM overpack including onsite transport of the MPCs. Within a loaded HI-TRAC, heat generated by the radioactive materials inside the MPC is transferred from the outer surface of the MPC shell to the ambient by conduction, thermal radiation, and natural convection modes of heat transfer. Two HI-TRAC transfer casks are available for onsite handling and transport: the 125-ton and the 100-ton versions which differ in terms of lead thickness (gamma shielding) and the thickness and number of radial connectors in the water jacket (neutron shielding) region. The rate of heat transfer in the radial direction is principally characterized by the available metal thickness in the water jacket, defined as the product of the number of radial connectors and their thickness. From the outer surface of the MPC to the ambient atmosphere, heat is transferred through six concentric layers which are the air gap between the outer MPC surface and the HI-TRAC inner shell, the HI-TRAC inner shell, the lead shielding, the HI-TRAC outer shell, the water jacket, and the enclosure shell. Heat is rejected from the outer surface of the enclosure shell by natural convection and radiation heat transfer. Heat is transferred across the air gap by conduction and thermal radiation. Heat is transferred though the cylindrical wall of HI-TRAC by conduction through successive layers of steel, lead and steel. In the water jacket region, heat is transferred by conduction through the water and the radial connectors. In the vertical position, the bottom face is modeled as an insulated surface. The HI-TRAC top lid is modeled as a surface with convection, radiative heat exchange with air and a constant maximum incident solar heat flux load.

6.0 Staff's Confirmatory Analysis of the HI-STORM 100 Cask System

Confirmatory analyses of the HI-STORM 100 thermal design, using COBRA-SFS finite volume thermal code for the MPC-24 and MPC-32 and FLUENT® finite volume code for the MPC-68 (the thermally limiting MPC), were performed by the staff as an independent evaluation of the thermal analysis presented in the applicant's SAR. Preliminary calculations have indicated the applicant's approach may involve potential modeling issues. The staff performed more detailed analysis of the MPC-68, limiting case. The staff's analysis focused on determining realistic flow resistance parameters of the internals of the canister. These parameters appear to play a very important role on the predicted peak cladding temperatures. The following section describes the applicant's and the staff's flow resistance evaluations.

6.1 MPC-68 Hydraulic Resistance Calculation

6.1.1 Analytic Approach

In Appendix C of Holtec Report HI-2033054, the applicant considered a friction factor f=64/Re that is applicable for fully developed flow inside a pipe. According to applicable literature (Ref. 7), numerical solutions and experimental data identified a friction factor f=96/Re or more (for example, f=100/Re). For the reasons discussed in later paragraphs, the staff finds the use of a friction factor f=64/Re unjustified.

According to the applicant, Appendix M of Holtec Report HI-2033054, Revision 2, presents a realistic porous media hydraulic resistance calculation for the MPC-68. The applicant determined the General Electric (GE) 12/14 10x10 fuel assembly is the most resistive Boiling Water Reactor (BWR) fuel assembly type. When calculating the flow resistance, the applicant made the following assumptions:

1. The area between the fuel assembly and the MPC-68 fuel cell is incorporated into the calculation;

2. The actual number of fuel rods present in the fuel assembly is used in this analysis (92 rods);

3. The open area within the water rods is incorporated in the analysis (two water rods);

4. A conservative formula for friction factor (f=80/Re, where Re is the Reynolds Number) is used in the calculation; and

5. The expansion-contraction inertial loss factors in the grid strap region is calculated based on actual contraction and expansion parameters.

The staff's findings on this analytic method and associated assumptions are as follows. From Holtec Drawings 1495, Rev. 11, 3928, Rev. 1, 3923, Rev. 8 (Ref. 5), and from limited publicly available description of GE fuel design, it is apparent that incorporating the area between the fuel assembly and the MPC-68 fuel cell into the calculation may underestimate the flow resistance for the in-channel region by averaging the resistance throughout the MPC fuel cell cross sectional area. This modeling technique is not realistic and has not been justified through experimental data nor through detailed analyses that incorporate the proper geometry.
The applicant has not demonstrated how the helium flow is distributed through the in-channel region and outside that region. It is apparent from the design of the MPC internals that most of the helium will flow through the in-channel region and any flow outside that region would be negligible.

Furthermore, since buoyancy is produced through density variations, helium will be preferentially flowing upwards through the in-channel heated region. These two regions (in-channel area and area between the fuel assembly and the MPC-68 fuel cell) will exhibit different thermal-hydraulic characteristics and, therefore, cannot be averaged, unless such averaging has been demonstrated to be conservative. The applicant's 2-D porous media model cannot predict the thermo-hydraulic characteristics of the flow in the annular area around the channel.

The staff believes these phenomena can only be evaluated using a 3-D thermal-hydraulic analysis of the storage cask and modeling these regions or components explicitly.

Incorporating the total open area within the water rods in the analysis may be non-conservative. At the time the review was discontinued the staff had not been provided with adequate information to evaluate this assumption. Per GE proprietary information (Ref. 6), it appears that not all of the water rod cross-sectional area may be available for helium flow. Therefore, only a fraction of this area should be credited in the analysis. Additional justification to support this claim is needed.

In a letter submitted to NRC on June 18, 2004, the applicant revised its methodology described in Ref. 8, to justify the friction factor correlation applied in both appendices C and M of Holtec Report HI-2033054. Detailed calculations are provided in Appendix O of the above report. However, the methodology described in Ref. 8 is applicable to turbulent flow conditions only. It is stated that "the only condition on which the method can be applied is the required knowledge of the geometry factor of laminar flow. However, geometry factors for laminar flow are known for a variety of non-circular channels or else can be determined quickly and rather accurately by numerical procedures." The author of the Ref. 8 technical paper initially assumed that for non circular channels, the well known correlation for laminar flow inside a pipe (i.e., friction factor f=64/Re) is also applicable to, for example, rod bundles. Therefore, it appears that the methodology described in Ref. 8 cannot be applied to laminar flow through an array of rod bundles. To obtain a friction factor correlation for rod bundles of infinite extension, the author of the Ref. 8 technical paper cites Ref. 9.

Ref. 9 provides a rigorous analytic solution for the spent fuel geometry and type of flow prevailing in the internal natural circulation of the HI-STORM 100 MPC storage canister. This analytic solution assumes the flow is laminar and fully developed. Because basic law of momentum conservation is applied, the solution approach is very accurate because it is based on basic principles. In Ref. 9, the resulting differential equation was solved in an approximate, but almost exact manner by the use of truncated trigonometric series. Only a few series coefficients (six or seven) were used by the authors to obtain the solution. The authors showed by calculation that adding more terms to the series did not significantly change the numerical values of the first coefficients. Also, the authors found that only the first coefficients were important in the computation of the shear stresses and velocity distribution.

In order to verify these findings, based on the analytic solution proposed in Ref. 9, the staff performed additional calculations by considering a larger number of coefficients (up to 10 coefficients were used) in the infinite series. The staff's calculation confirmed the results of Ref. 9. Based on the staff's calculation, which considers 10 coefficients in the infinite series, and using Equation (16b) of Ref. 9, the staff calculated a friction factor-Re number relationship of approximately 89 for the pitch-to-diameter ratio of the GE-12/14 10x10 fuel assembly. Absent experimental data, this is the value the staff would consider most appropriate for use in the applicants calculation of the porous media flow resistence coefficients. Considering a friction factor f=89/Re, the porous media permeability parameters that would most appropriately be used in the applicant's 2-D axisymmetric model are:

$K_r = 1.262 \times 10^6$ Rods Region

$K_s = 11.728 \times 10^6$ Grids Region

K_c=1.8112x10^6 Combined Rods and Grid Straps (based on a grid strap axial length of 0.9 inches)

If the above flow resistance parameters calculated by the staff are used to perform the thermal analysis of the HI-STORM 100 storage cask, peak cladding temperature would exceed the limits specified in ISG-11, Rev. 3.

It should be noted that empirically derived parameters, like the friction factor used in the HI-STORM 100 thermal-hydraulic analysis, may exhibit large uncertainties. The applicant has not addressed the uncertainties associated with this parameter and, in general, the applicant has not addressed the code biases and uncertainties included in calculating the peak cladding temperature.

6.1.2 CFD-Based Fuel Bundle Pressure Drop

The applicant developed a detailed CFD model of a quarter of assembly which corresponds to the GE-12/14 10x10 fuel assembly design. The applicant referred to this model as an enhanced model. According to the applicant, in this refined model the fuel rods and the water rods are represented as dimensionally accurate circular rods as in the real geometry, including the orificing of the water rods. However, the staff believes the above discussion to be not totally accurate because the CFD fuel assembly model does not represent the water rods and orifices explicitly. The porous media model is used to represent the top and bottom segments of the water rod where the orifices are located. A review of the FLUENT® input and output files of this model reveals velocity distributions which appear to be non-physical considering the fuel design. Due to lack of further information on the fuel assembly details, the staff finds these results inconclusive.

The applicant used the FLUENT® CFD model described above to perform the following analyses:

1. Benchmarking of the CFD analysis with experimental data;

2. Determination of the porous media properties for helium flow through the fuel bundle; and

3. Determination of the peak cladding temperature using the porous media properties determined above.

The staff finds the comparison against experimental data to be inconclusive because of the modeling issues mentioned earlier and also because of lack of information on the experimental data used by the applicant. Further information regarding the measured pressure drop data would indicate whether or not an adequate comparison of the calculated results versus the measured data was performed. Any modeling deviation from the actual hardware used to obtain the measured data would need to be evaluated and justified.

In order to determine flow through the fuel bundle, the applicant used the FLUENT® CFD model described previously applying an axial pressure drop of 2.5 Pa. In previous submittals (Appendix I of Holtec Report HI-2033054, Rev. 1), the applicant stated that this value is selected to ensure the calculated velocity is in the range of the MPC's helium thermosiphon flow

(0.01 to 0.04 m/s). However, this parameter is unknown and highly depends on the flow resistance specified on the fuel assembly porous media model. A given specified pressure drop value would dictate the magnitude of the flow resistance coefficients. It might not be unreasonable to use a higher or a lower value of pressure drop because the operating range is not known. The applicant's approach of assuming an unknown pressure drop is not justified. This approach may produce flow resistance parameters that may be non-conservative.

The applicant applied the above coefficients without performing any additional weighting based on the applicable weighting parameter. These parameters have to be converted to either pitch area-based (for the Holtec's 2-D model) or fuel basket cell opening-based (staff's 3-D developed model). Properly weighted parameters would result in an increase of about 52% in temperature for the 2-D model and about 32% for the 3-D model.

The staff demonstrated earlier that assuming the applicant's licensing-based flow resistance parameters are correct, peak cladding temperature would be higher than the allowable limit (ISG-11, Rev. 3). Because the CFD-based flow resistance parameters are higher than the applicant's licensing-based values, this will increase the peak cladding temperature beyond ISG-11, Rev. 3 acceptance limit even further.

Additional staff review of the FLUENT® CFD fuel assembly models reveals that most of the pressure drop occurs in the axial segment of the fuel bundle rodded region which indicates that, when calculating the viscous resistance, only the length of the axial segment covered by rods should be used in the calculation. This will result in an additional increase of the viscous resistance parameters. The staff also conducted sensitivity calculations on the applicant's specified pressure drop by either increasing or decreasing the imposed value. From these sensitivity calculations the staff concluded that an increase in pressure drop does not result in a linear increase of the in-channel superficial velocity. This would indicate that the resultant viscous coefficient will be highly dependent on the specified pressure drop which is an unknown parameter for the operating conditions of the MPC.

In summary, additional justification and explanation on the developed fuel assembly CFD model (for example, use of porous media to model parts of the water rods), assumed pressure drop, and application of CFD analysis results to calculate flow resistance parameters is necessary.

7.0 Applicant's Assessment of Thermal Margin

In a letter submitted to the NRC on July 23, 2004, the applicant stated that all HI-STORM 100 Cask System thermal models, as updated per License Amendment Request No. 2, have been based on an emissivity of 0.36 for stainless steel. According to the applicant, this value is far too conservative for the pickled annealed stainless steel used in the fabrication of Holtec's MPCs. The applicant indicated that, based on National Advisory Committee for Aeronautics (NACA) test data (Ref. 10), the emissivity of this type of stainless steel could be in excess of 0.7 at the elevated temperatures that exist in an MPC. Previous thermal analysis considered an emissivity of 0.36 for the Alloy "X" (which is defined in the SAR to be any of the following types: 316, 316LN, 304, 304LN). Based on NACA measured data the applicant stated that a value of 0.587 can be applied which is lower than the reported measured data.

NACA Technical Note 4206 (Ref. 10) states that the measured data was obtained for metals including stainless steel (ANSI 303) and mild steel (ANSI C1020). The report states that "the variation of the total hemispherical emissivity due to oxidation of the metal was determined for the highest temperature which would produce an adherent oxide coating of stable emissivity."

In terms of behavior to produce the same oxidation coating, the applicant then assumes that the Alloy X defined above will show the same characteristics and therefore will exhibit the same emissivity. It is not clear to the staff how different the Alloy X is as compared to the metals used in NACA experiments.

If credit is to be taken for this increase in emissivity, then Alloy X would need to be treated in the same exact conditions as the metals of the NACA experiments. In addition, measured data to justify this claim would need to be provided.

Based on the available information, the staff concludes that the stainless steel used in the fabrication of Holtec's MPC is not treated for conditions that will provide an emissivity higher than the value used currently by the applicant to perform the thermal analysis. In addition, the operating conditions do not resemble those of the NACA experiments. The applicant's claim for additional thermal margin due to the use of higher emissivity of stainless seel has not been justified.

8.0 Applicant's use of FLUENT CFD Code

The applicant needs to fully justify the FLUENT CFD models used in the thermal evaluation, particularly those shown by analysis to have a large impact on the overall thermal response of the storage cask and on the calculated peak cladding temperature as addressed above. In order for the staff to make a positive finding as to the acceptability of the design and analysis methods, it should be shown that the calculated results are mesh-independent for any fluid region, solid region, and porous media region considered in the analysis.

9.0 Conclusions

1. The applicant has not justified the use of an effective thermal conductivity for regions other than the fuel. According to Section 4.V.4.a of NUREG-1536, use of effective thermal conductivity coefficients for regions within the confinement cask, other than the fuel (e.g., gaps), may overestimate heat transfer. Justification and evaluation for deviating from the staff's review guidelines have not been provided in the SAR.

2. The applicant's ANSYS fuel basket FEA model used to calculate the fuel basket effective thermal conductivity incorrectly represent the basket walls. The applicant's FLUENT® CFD analysis model includes effective thermal conductivity values. However, some of the values differ from calculated results obtained from the fuel basket ANSYS FEA model. This increase in the fuel basket effective thermal conductivity calculated values has not been justified.

3. The applicant has not fully justified the models and assumptions used to calculate the MPC internal natural convection.

4. The applicant has not demonstrated that a 2-D axi-symmetric porous media thermal model can be used to represent the complicated internal flow and heat transfer paths encountered in the HI-STORM 100 system geometry.

5. The applicant has not justified the use of fully developed turbulent flow to represent the operating conditions of the MPC overpack air annular region.

6. Assuming that the air annulus flow is operating in the turbulent flow regime (which has not been justified), the applicant has not justified the use of non-equilibrium wall functions for near-wall treatment.

7. The applicant has not justified the derived flow resistance parameters used to characterize the internal circulation of helium inside the MPC.

8. The applicant has not justified that an enhanced FLUENT® model can be validated using pressure drop measured data. Also, the flow resistance parameters for helium flow through the fuel rod bundle were obtained assuming an unknown pressure drop.

9. The applicant's claim of additional thermal margin due to the use of higher emissivity of stainless seel has not been justified.

10.0 Evaluation Findings

F.1 Based on the analysis methods and models described in the HI-STORM 100 Cask System SAR, dated August 3, 2003, as supplemented through July 30, 2004, associated references, applicant's calculation packages submitted up to July 30, 2004, and staff's confirmatory 3-D analyses, the staff finds that the applicant has not demonstrated that the peak clad temperature can be maintained below acceptable limits (Ref. 3) for the operating conditions described in the SAR throughout the planned storage period.

F.2 The staff also finds that the applicant has not justified or evaluated the impact on the calculated thermal results of deviating from NUREG-1536 review guidance.

F.3 The staff also finds that the applicant has not demonstrated compliance with the design conditions and acceptance criteria described in 10 CFR Part 72 and, therefore, the staff finds the thermal evaluation of "Licensing Amendment Request No. 2 to CoC 1014" unacceptable.

11.0 References

1. U.S. Code of Federal Regulations, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste," Title 10, Part 72.

2. U.S. Nuclear Regulatory Commission, "Standard Review Plan for Dry Cask Storage Systems," NUREG-1536, January 1997.

3. U.S. Nuclear Regulatory Commission, Interim Staff Guidance No. 11, Revision 3, "Cladding Considerations for the Transportation and Storage of Spent Fuel," November 17, 2003.

4. FLUENT® 6.1 User's Manual.

5. “Final Safety Analysis Report for the Holtec International Storage and Transfer Operation Reinforced Module Cask System (HI-STORM 100 Cask System),” Revision 1, September 2002.

6. “General Electric Fuel Bundle Designs,” Global Nuclear Fuel (SNF), NEDE-31152P, Revision 7 Class III, June 2000. SNF Proprietary Information.

7. N. E. Todreas , M. S. Kazimi, Nuclear Systems I: “Thermal-Hydraulic Fundamentals,” Hemisphere Publishing Corporation, 1990.

8. K. Rehme, “Simple method of Predicting Friction Factors of Turbulent Flow in Non-Circular Channels,” International Journal of Heat and Mass Transfer, Vol. 16, pp. 933-950, Pergamino Press 1973.

9. E. M. Sparrow and A. L. Loeffler, “Longitudinal Laminar Flow Regime Between Cylinders Arranged in Regular Array,” A.I.Ch.E Journal, Vol. 5 No. 3, pp 325-330, September 1959.

10. R. W. William, “Measurements of Total Hemispherical Emissivity of Various Oxidized Metals at High Temperature,” National Advisory Committee for Aeronautics. Technical Note 4206. March 1958.