8 CRITICALITY EVALUATION

8.1 Conduct of Review

The staff's review of the criticality evaluation included Chapter 3, "Principal Design Criteria" and Chapter 4, "ISFSI Design," of the Humboldt Bay Independent Spent Fuel Storage Installation (ISFSI) Safety Analysis Report (SAR) (Pacific Gas and Electric Company, 2004a), as well as other applicable sections of the SAR and the criticality evaluation calculations, as referenced in the SAR. The purpose of the criticality review is to ensure that the stored materials remain subcritical under normal, off-normal, and accident conditions during all operations, transfer, and storage activities at the proposed Humboldt Bay ISFSI.

The review considered how the SAR and related documents address the regulatory requirements of 10 CFR §72.40(a)(13) and §72.124(a–c). Complete citations of these regulations are provided in the Appendix of this Safety Evaluation Report (SER).

The applicant proposes to use the HI-STAR HB system, which is composed of the all-metal HI-STAR HB overpack and its integral multi-purpose canister (MPC-HB), which contains the fuel assemblies. Each of the five HI-STAR HB casks is designed to store up to 80 Humboldt Bay Power Plant (HBPP) fuel assemblies, with one additional cask storing Greater than Class C (GTCC) waste. The HI-STAR HB system is a variation of the HI-STAR 100 system, which has been certified by the U.S. Nuclear Regulatory Commission (NRC) for use by general licensees (U.S. Nuclear Regulatory Commission, 2001a).

Holtec International developed the modified MPC-HB for use at Humboldt Bay because of the smaller size (length and width) of the HBPP fuel assemblies. The HI-STAR HB system is modified from the certified HI-STAR 100 system in that it can store up to 80 HBPP fuel assemblies versus 68 standard boiling water reactor assemblies. The applicant proposes to use METAMIC® neutron absorber panels as an alternative to BORAL®. This is further discussed in Section 8.1.3.2 of this SER.

The modified HI-STAR HB system criticality analyses evaluated in this SER were performed in accordance with the methodologies previously reviewed and accepted by U.S. Nuclear Regulatory Commission (2001a,b) and documented in the Holtec HI-STAR 100 Final Safety Analysis Report (FSAR) (Holtec International, 2002). The Humboldt Bay ISFSI conditions for criticality safety are based on acceptance criteria outlined in NUREG-1567 (U.S. Nuclear Regulatory Commission, 2000). The staff's evaluation is summarized in the sections that follow.

8.1.1 Criticality Design Criteria and Features

This section evaluates whether the proposed criticality safety design criteria and features will maintain the stored materials in a subcritical configuration. The Humboldt Bay ISFSI design criteria and features related to criticality safety are described in Sections 3.3.1.4 and 3.3.1.7 of the SAR. Section 4.2.3.3.7 of the SAR addresses criticality design of the HI-STAR HB system. The applicant did not rely on the use of burnup credit or fuel-related burnable neutron absorbers for the criticality safety analysis. In the analysis, the applicant took no more than 75-percent credit for the minimum Boron-10 isotope content in the fixed neutron absorbers.

8.1.1.1 Criticality Design Criteria

The design criterion for criticality safety in Section 3.3.1.4 of the SAR is clearly identified and adequately described. For criticality safety, the design criterion is that the effective k_{eff}, including statistical biases and uncertainties, shall not exceed 0.95 during all credible normal, off-normal, and accident conditions and events.

The proposed HI-STAR HB cask system provides a subcritical configuration of stored materials independent of any other ISFSI structures or components. The design criterion for criticality safety is consistent with the 10 CFR §72.124(a) requirement that at least two unlikely, independent, and concurrent or sequential changes to the conditions essential to criticality safety under normal, off-normal, and accident conditions must occur before an accidental criticality is possible (American National Standards Institute/American Nuclear Society, 1998). Adequate protection against accidental criticality is defined as maintaining k_{eff} below 0.95 at a 95-percent confidence level. Criticality safety of the design is based on favorable geometry of the MPC-HB basket and permanently fixed neutron absorbing materials.

The staff finds that the proposed design criterion will meet the double contingency requirements of 10 CFR §72.124(a) and, therefore, will be protective of public health and safety in accordance with the requirements of 10 CFR §72.40(a)(13).

8.1.1.2 Features

The criticality safety design features for the HI-STAR HB system are described in Section 4.2.3.3.7 of the Humboldt Bay ISFSI SAR. This cask system maintains the stored materials in a subcritical configuration independent of the ISFSI design under normal, off-normal, and credible accident conditions during spent nuclear fuel transfer and storage operations. For criticality prevention, the cask system relies on the MPC-HB, which provides the confinement system for the stored fuel. At the Humboldt Bay ISFSI, the fuel will be dry and sealed within a welded MPC-HB. The confinement review is discussed in detail in Chapter 9 of this SER. The primary design features and control methods used to prevent criticality for MPC-HB configurations include (I) the favorable geometry provided by the MPC-HB fuel basket with a minimum pitch of the fuel cells {14.8 cm [5.83 in]}, (ii) the incorporation of permanent neutron absorbing material attached to the fuel basket walls with a minimum required loading of the Boron-10 isotope (0.01 g/cm^2), (iii) use of a damaged fuel container (DFC) to store damaged fuel to ensure there is no significant relocation of fuel material in the MPC-HB, and (iv) use of peripheral cells or a checkerboard pattern as required loading configurations for damaged fuel/fuel debris in DFCs.

The MPC-HB may contain up to 80 intact fuel assemblies with or without channels. Up to 24 damaged fuel assemblies/fuel debris may be stored in DFCs in the peripheral cells of the basket (Figure 2.1-1 of the Technical Specifications) (Pacific Gas and Electric Company, 2004b, Attachment C). Furthermore, up to 40 damaged fuel assemblies/fuel debris may be stored in DFCs in a checkerboard pattern (Figure 2.1-2 of the Technical Specifications). Both figures are referenced in Table 2.1-1 of the Technical Specifications. Intact fuel assemblies may also be stored in DFCs according to Table 2.1-1.

The criticality monitoring system requirements of 10 CFR §72.124(c) have been addressed by the applicant in Section 4.2.3.3.7 of the SAR. The monitoring features described by the applicant apply to cask loading and unloading activities performed in the Refueling Building (RFB). These features include a combination of installed and portable radiation monitoring instrumentation to detect conditions that may result in excessive radiation levels, which will trigger the initiation of appropriate safety actions. The radiation monitoring generally conforms to the guidance in Regulatory Guide 3.71 (U.S. Nuclear Regulatory Commission, 1998) and American National Standards Institute/American Nuclear Society (1997).

The HI-STAR HB system design, associated procedural controls, Humboldt Bay ISFSI Technical Specification requirements, and Section 10.2 of the SAR operating controls and limits ensure that a criticality event during SNF cask loading operations in the RFB is highly unlikely. Based on these features and controls and the radiation monitoring features provided, the staff finds that the applicant meets the requirements of 10 CFR §72.124(c). In accordance with 10 CFR §72.124(c), criticality monitoring of dry cask storage areas where the special nuclear material is packaged in its stored configuration is not required.

The staff finds that (i) the design features important to nuclear criticality safety are clearly identified and adequately described; (ii) the stored material will be maintained in a subcritical configuration during SNF transfer, placement, and storage; and (iii) the design basis, off-normal, and postulated accident events will not have an adverse effect on the design features important to criticality safety. The staff, therefore, concludes that the design features meet the requirements of 10 CFR §72.124(b) and §72.40(a)(13).

8.1.2 Stored Material Specifications

The proposed stored materials specifications are described in Section 3.1.1, Tables 3.1-1, 3.1-2, and 3.4-2 of the SAR. The fuel assembly limits and characteristics for the material to be stored are described in Sections 10.2.1.1, 10.2.1.2, and 10.2.1.3 of the SAR, and provided in Tables 10.2-1 and 10.2-2, respectively. Section 2.0 of the proposed Technical Specifications (Pacific Gas and Electric Company, 2004c, Attachment C) describes technical specifications for the stored materials.

The materials to be stored include intact HBPP fuel assemblies, damaged fuel assemblies/fuel debris, and GTCC waste. In the HBPP inventory, there are 390 fuel assemblies and a quantity of loose debris that is described in Section 3.1.1 of the SAR as constituting the equivalent of one additional assembly. The SNF assemblies to be stored consist of General Electric Type II (7 × 7 array of fuel rods), General Electric Type III, Exxon Type III, and Exxon Type IV (6 × 6 array) boiling water reactor (BWR) fuel assemblies. A summary of the physical characteristics of each type is presented in Table 3.1-2 of the SAR. In the review of this table, the fuel specifications important to criticality safety are:

- Maximum planar average initial enrichment
- Number of fuel rods
- Minimum clad outer diameter
- Maximum clad inner diameter
- Maximum pellet diameter
- Fuel rod pitch
- Maximum active fuel length
- Number of water rods

- Minimum water rod thickness
- Maximum channel thickness

These parameters represent the bounding parameters for BWR fuel assemblies (i.e., most reactive). The staff finds that the criticality analysis performed for the HI-STAR HB system (SAR Section 4.2.3.3.7) used the bounding fuel specifications discussed here and conservatively assumed fresh fuel with no credit for burnup, no credit for fuel-related burnable neutron absorbers, and a Boron-10 neutron absorber content of 75 percent of the minimum specified content. The justification provided in Section 4.2.3.3.7 of the SAR provides reasonable assurance of the continued efficacy of the neutron absorber material in the HI-STAR HB design and thus meets the requirements of 10 CFR §72.124(b).

The applicant stated that intact fuel assemblies may be stored in DFCs per Table 2.1-1 of the proposed Technical Specifications (Pacific Gas and Electric Company, 2004b, Attachment C). Because the applicant is relying on administrative controls to ensure that damaged fuel/debris is placed in appropriate locations within the MPC-HB, which is not easily verifiable because of the potential use of DFCs for both damaged and intact fuel, the applicant has committed to revise Technical Specification Section 5.1.3 to add the following administrative control to prevent misloading events (Pacific Gas and Electric Company, 2005):

> 5.1.3 MPC-HB and SFSC Loading, Unloading, and Preparation Program
>
> > f. Loading is to be independently verified by a cognizant engineer to ensure that the fuel assemblies in the MPCs are placed in accordance with the original loading plan.

Based on the administrative controls provided in Section 5.1.3 of the Technical Specifications and the loading procedures for approved contents provided in Section 2.1, incorrect loading of an MPC-HB is not considered a credible accident. Section 10.2.1.4 of the SAR addresses the requirements of Section 2.2 of the Technical Specification should any of the fuel specifications or loading conditions be violated. This requires placing the affected fuel assemblies in a safe condition and reporting the event and proposed corrective actions to NRC. These requirements and stored material specifications provide reasonable assurance that the requirements of 10 CFR §72.40(a)(13) and §72.124(a) are met.

8.1.3 Analytical Means

The staff reviewed the analytical means used by the applicant to demonstrate that the materials stored in the ISFSI will remain subcritical. Section 4.2.3.3.7 of the SAR and supporting calculations contain the relevant information reviewed by the staff.

8.1.3.1 Model Configuration

The applicant used three-dimensional models in its criticality analyses. The fuel assemblies were modeled explicitly with all intact assemblies, including water channels, as is appropriate for BWR fuel assemblies using a conservative model assumption that increases reactivity. The models for damaged fuel assemblies considered fuel in the DFC as arrays of bare fuel rods or fuel fragments in both the periphery and checkerboard loading patterns shown in

Figures 10.2-1 and 10.2-2 of the SAR, respectively. This approach conservatively neglects the presence of fuel cladding and other structural materials and replaces them with a moderator (water) to provide reasonable assurance that the requirements of 10 CFR §72.124(a) are met. The staff reviewed the models described in the supporting calculations. Based on the information presented, the staff agrees that the models reviewed are consistent with the description of the cask and contents given in Chapters 3 and 4 of the SAR and that the most reactive combination of cask parameters and dimensional tolerances were incorporated into the calculation models.

8.1.3.2 Material Properties

The compositions and densities of the materials considered in the calculational models are provided in Tables 5.1, 5.2, and 5.3 in the applicant's criticality evaluation (Holtec International, 2004, HI-2033010). The models make a number of conservative assumptions on the material properties consistent with the guidance provided in Section 8 of NUREG-1567 (U.S. Nuclear Regulatory Commission, 2000). These include

- Fresh fuel isotopics (i.e., no burnup credit)
- No credit is taken for fuel-related burnable neutron absorbers
- 75-percent credit for the Boron-10 loading in fixed neutron absorber panels
- Fuel stack density of 96 percent of theoretical density (10.522 g/cm^3)
- The fuel rod pellet-to-gap regions are flooded with pure water at the highest reactivity density (1 g/cm^3) within the expected operating temperature range
- Manufacturing tolerances are assumed in the worst hypothetical combination (i.e., most reactive)
- Maximum planar-average initial enrichment is assumed for BWR fuel
- Neutron absorption in structural members is neglected, and those minor structural members are conservatively modeled as water moderator
- Configurations of the assemblies in the MPC-HB basket with centered and eccentric positions are considered

One of the most important materials concerning the criticality safety analysis is the fixed neutron absorber. The minimum Boron-10 content will be verified through the acceptance testing program described by the applicant (Pacific Gas and Electric Company, 2004c). The staff acceptance of the tests described is partly based on the use of only 75-percent credit of the minimum required Boron-10 content to be verified in the test procedure. The applicant has proposed and the staff has accepted the tests described as follows as a license condition. Prior to loading SNF into any dry storage cask, the following testing must be successfully completed:

For all fixed neutron absorbers

(i) Each plate of neutron absorbers shall be visually inspected for damage (e.g., scratches, cracks, burrs, peeled cladding, foreign materials embedded in the surface, voids, delamination, and surface finish) as applicable.

(ii) The required Boron-10 content (areal density) of the neutron absorber panels for the MPC-HB shall be verified to be greater than or equal to 0.01 gm/cm^2.

For BORAL®

After manufacturing, a statistical sample of each lot of BORAL® neutron absorber shall be tested using wet chemistry and/or neutron attenuation testing to verify the minimum Boron-10 content (areal density) in samples taken from the ends of the panel.

For METAMIC®

(i) Verification that the boron carbide (B_4C) content in the METAMIC® is not more than 33.0 weight percent

(ii) Verification that all lots of B_4C powder shall meet particle size distribution requirements

(iii) Qualification testing shall be performed on the first production run of METAMIC® panels to be used in a Holtec MPC to validate the acceptability and consistency of the manufacturing process and verify the acceptability of the METAMIC® panels for neutron absorbing capability.

1. The B_4C powder weight percent shall be verified by testing a sample from 40 different mixed batches. (A mixed batch is defined as a single mixture of aluminum powder and B_4C powder used to make one or more billets. Each billet will produce several panels.) The samples shall be drawn from the mixing containers after mixing operations have been completed. Testing shall be performed using the wet chemistry method.

2. The Boron-10 areal density shall be verified by testing a sample from one panel from each of 40 different mixed batches. The samples shall be drawn from areas contiguous to the manufactured panels of METAMIC® and shall be tested using the wet chemistry method. Alternatively, neutron attenuation tests on the samples may be performed to quantify the actual Boron-10 areal density.

3. To verify the local uniformity of the boron particle dispersal, neutron attenuation measurements of random test coupons shall be performed. These test coupons may come from the production run or from pre-production trial runs.

4. To verify the macroscopic uniformity of the boron particle distribution, test samples shall be taken from the sides of one panel from five different mixed batches before the panels are cut to their final sizes. The sample locations shall be chosen to be representative of the final product. Wet chemistry or neutron attenuation shall be performed on each of the samples.

(iv) For production runs of the panels to be used in the MPC-HB canisters, the following tests shall be performed:

1. Testing of mixed batches shall be performed on a statistical basis to verify that the correct B_4C weight percent is being mixed.

2. Samples from random METAMIC® panels taken from areas contiguous to the manufactured panels shall be tested via wet chemistry and/or neutron attenuation testing to verify the Boron-10 areal density. This testing shall be performed to verify the continued acceptability of the manufacturing process.

As stated previously, the justification provided in Section 4.2.3.3.7 of the SAR provides reasonable assurance of the continued efficacy of the neutron absorber material in the HI-STAR HB design and, thus, the requirements of 10 CFR §72.124(b) are met. The model configuration and material properties used in the criticality analyses provide reasonable assurance that the requirements of 10 CFR §72.40(a)(13) are met.

8.1.4 Applicant Criticality Analysis

The staff finds that the applicant addressed the most reactive configurations and conditions in the cask system analysis. The criticality analysis results are described and presented in Section 4.2.3.3.7 of the SAR and in the supporting calculation report, HI-2033010 (Holtec International, 2004). The applicant's criticality analysis references the previously reviewed and approved analysis described in Chapter 6 of the HI-STAR 100 FSAR (Holtec International, 2002) used in the licensing of the HI-STAR 100 system. The modified HI-STAR HB system analyses evaluated in this SER were performed in accordance with the methodologies previously reviewed and accepted by NRC (U.S. Nuclear Regulatory Commission, 2001a,b) and documented in the Holtec HI-STAR 100 FSAR (Holtec International, 2002). The staff finds that these methodologies are appropriate for the HI-STAR HB criticality analysis, and are therefore acceptable.

8.1.4.1 Computer Program

The applicant's principal criticality analysis code was Monte Carlo N-Particle (MCNP) Version 4A (Briesmeister, 1993), a three-dimensional, continuous-energy, MCNP code. The applicant's MCNP4A calculations used continuous energy cross-section data based on ENDF/B-V files provided with the MCNP4A code. The staff finds the use of MCNP acceptable, as discussed in NUREG-1567 (U.S. Nuclear Regulatory Commission, 2000), and agrees that the code and cross-section data used in the applicant's criticality analyses are appropriate for this application.

8.1.4.2 Multiplication Factor

Then results of the applicant's analyses for all proposed fuel loadings yielded values for k_{eff}, including all biases and uncertainties, below 0.95 for normal, off-normal, and accident conditions, thus meeting the staff's acceptance criterion. These results are presented in Section 4.2.3.3.7 of the SAR and are described in the supporting calculations of HI-2033010 (Holtec International, 2004). The limiting reactivity condition occurs in the spent fuel pool during fuel loading where assemblies are loaded into the MPC-HB in unborated water. The bounding analysis for this condition with intact fuel assemblies provides a maximum k_{eff} of 0.8410. The limiting reactivity condition analyzed with 40 DFCs containing damaged fuel and fuel debris loaded in the checkerboard pattern of Figure 10.2-2 of the SAR results in the applicant's maximum calculated k_{eff} of 0.9003. In the storage condition, the HI-STAR HB system is helium-filled, and therefore, has no water moderator; thus, the reactivity of the system is very low (k_{eff} less than 0.40). The staff reviewed the applicant's calculated multiplication factor values and agrees that they have been appropriately adjusted to include all biases and uncertainties at the 95-percent confidence level.

Based on the applicant's criticality evaluation, the staff concludes that the HI-STAR HB system will remain subcritical, with an adequate safety margin, under all credible normal, off-normal, and accident conditions, and thus meets the requirements of 10 CFR §72.124(a).

8.1.4.3 Benchmark Comparisons

The applicant relied on the benchmark analysis discussed in Chapter 6, Appendix 6.A of the HI-STAR 100 System FSAR (Holtec International, 2002). The same analysis method and modeling assumptions are used in the supporting criticality calculations provided in HI-2033010 (Holtec International, 2004). The value of the bias correction used for k_{eff} was 0.0021 with an uncertainty of 0.0006. The benchmark analysis was previously reviewed by the staff and found to use critical experiments relevant to cask design; only biases that increase k_{eff} have been applied. The use of this benchmark analysis is, therefore, appropriate for the HI-STAR HB criticality analysis and provides reasonable assurance that the requirements of 10 CFR §72.124(a) are met.

8.1.4.4 Independent Criticality Analysis

The staff performed independent criticality analyses for the HI-STAR HB system using the CSAS/KENO-Va code modules in the SCALE5 suite of analytical codes. The staff's modeling assumptions were similar to those used by the applicant. The staff's model considered the most reactive conditions in modeling each of the intact and damaged spent fuel configurations identified by the applicant. The results of the staff's analyses were in close agreement with the applicant's results.

8.2 Evaluation Findings

Based on a review of the SAR and the presentations and information supplied by the applicant, the staff finds that:

- The design, procedures, and materials to be stored at the proposed Humboldt Bay ISFSI provide reasonable assurance that the activities authorized by the license can be conducted without endangering the health and safety of the public in compliance with 10 CFR §72.40(a)(13).

- The design and proposed use of the Humboldt Bay ISFSI handling, packaging, transfer, and storage systems for the radioactive materials to be stored provide reasonable assurance that the materials will remain subcritical and that, before a nuclear criticality accident is possible, at least two unlikely, independent, and concurrent or sequential changes must occur in the conditions essential to nuclear criticality safety, in compliance with 10 CFR §72.124(a).

C The SAR analyses adequately show that acceptable margins of safety will be maintained in the nuclear criticality parameters commensurate with uncertainties in the data and methods used in calculations and demonstrate safety for the handling, packaging, transfer, and storage of SNF during normal, off-normal, and accident conditions in compliance with 10 CFR §72.124(a) and §72.124(b).

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