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MEMORANDUM TO: Shana Helton, Director
Division of Fuel Management
Office of Nuclear Material Safety
and Safeguards

FROM: Aida Rivera-Varona, Branch Chief
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Division of Fuel Management
Office of Nuclear Material Safety
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Signed by Rivera-Varona, Aida
on 01/31/24

SUBJECT: SAFETY DETERMINATION OF A POTENTIAL STRUCTURAL FAILURE OF THE FUEL BASKET DURING ACCIDENT CONDITIONS FOR THE HI-STORM 100 AND HI-STORM FLOOD/WIND DRY CASK STORAGE SYSTEMS

The U.S. Nuclear Regulatory Commission (NRC) staff performed a routine fabrication inspection that resulted in three apparent violations at the Holtec Advanced Manufacturing Division in Camden, New Jersey during December 12-15, 2022. The inspection assessed the adequacy of Holtec's fabrication activities for spent fuel storage casks with regard to the applicable requirements of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-level Radioactive Waste, and Reactor-related Greater Than Class C Waste," Holtec's NRC approved Certificate of Compliance (CoC) No. 1014 (HI-STORM 100) and CoC No. 1032 (HI-STORM Flood/Wind [FW]), Quality Assurance Program, and selected portions of 10 CFR Part 21, "Reporting of Defects and Noncompliance."

During the inspection (Agencywide Documents Access and Management System Accession No. ML23145A175) the staff identified that Holtec incorporated a design change regarding the honeycombed fuel basket for spent nuclear fuel storage for two dry cask storage systems (i.e., HI-STORM 100 and HI-STORM FW) per the 10 CFR 72.48 change implementation process.

Although the basket design variant has been incorporated by Holtec into the HI-STORM 100 and HI-STORM FW final safety analysis reports by revision and the 72.48 process, the 72.48 evaluations performed by Holtec for the design change made an incorrect determination, and the design change was required to be submitted to the NRC for review and approval by amendment pursuant to 10 CFR 72.244.

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Subsequently, the staff performed an Immediate Safety Determination and concluded that the safety significance of the improper 72.48 change was low, based on a preliminary review of tip-over analysis results provided by Holtec. The Holtec results showed that the structural integrity of the continuous basket shims (CBS) fuel baskets was essentially maintained. At that time, the staff relied on the CBS fuel baskets maintaining their structural integrity such that the criticality analysis would not be impacted. In addition, since the integrity of the casks containing the baskets was maintained and there is no moderator present, subcriticality was ensured.

During the concurrent licensing review of HI-STORM FW Amendment 7 that added the additional two basket designs, the staff preliminarily determined that the analysis results do not provide assurance that the fuel baskets maintain structural integrity during a non-mechanistic tip-over accident. Specifically, the stresses in areas of several fuel baskets appear to exceed 90 percent of the true ultimate strength of the basket material, and some areas appear to exceed the fracture stress, which may jeopardize the overall structural integrity of the fuel basket. Furthermore, the staff identified some anomalies in the analysis results that indicated potential nonconservative errors in the structural modeling, which further degraded staff confidence in the accuracy of the results. Some of the issues identified during the licensing review are applicable to the analyses of the four basket designs incorporated by the 72.48 process.

The structural technical review staff was not able to conclude that the fuel baskets maintain structural integrity during a non-mechanistic tip-over accident event based on Holtec’s submitted analysis results. As a result, the staff performed a multi-disciplinary safety assessment of a potential structural failure of the fuel basket during accident conditions for the HI-STORM 100 and HI-STORM FW dry cask storage systems.

The staff’s review during the inspection and during the CoC amendment did not identify any issues with other components of the storage system. Most importantly, Holtec demonstrated that the multi-purpose canister, which forms the confinement boundary, maintains its structural integrity during accident conditions.

The purpose of this memo was to determine whether there was any need to take an immediate action with respect to cask systems that are loaded. It also supports the severity and associated enforcement actions for three violations identified during the December 2022 Holtec fabrication inspection involving four separate design changes to four separate Multi-Purpose Canister (MPC) basket designs, which were all implemented without prior NRC approval.

The staff’s basis for its safety determination of very low safety significance with regard to fuel basket CBS variant designs in the HI-STORM FW and HI-STORM 100 dry cask storage systems is in the enclosure.

Docket Nos. 72-1014 and 72-1032

Enclosure:
Safety Determination

SUBJECT: SAFETY DETERMINATION OF A POTENTIAL STRUCTURAL FAILURE OF THE FUEL BASKET DURING ACCIDENT CONDITIONS FOR THE HI-STORM 100 AND HI-STORM FLOOD/WIND DRY CASK STORAGE SYSTEMS

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Safety Determination

A multi-disciplinary team of thermal, criticality, shielding, and structural staff assessed a potential structural failure of the fuel basket during accident conditions for the HI-STORM 100 and HI-STORM Flood/Wind (FW) dry cask storage systems and concluded that the consequences of a basket failure have a very low safety significance provided the confinement boundary is maintained and the fuel is kept in a dry storage condition. As these conditions are demonstrated to be met during a tip-over event, the staff determined that there was no need to take an immediate action with respect to loaded HI-STORM FW and HI-STORM 100 dry cask storage systems with the continuous basket shims (CBS) fuel basket designs. Further details of the staff's safety assessment are provided below.

1.1. Assumptions

The structural technical review staff was not able to conclude that the fuel baskets maintain structural integrity during a non-mechanistic tip-over accident event based on Holtec's submitted analysis results. As a result, the staff performed a multi-disciplinary safety assessment of a potential structural failure of the fuel basket during accident conditions for the HI-STORM 100 and HI-STORM FW dry cask storage systems using the assumptions below:

- The staff's assessment conservatively assumes that the fuel basket fails under the non-mechanistic tip-over load case, allowing the fuel to be reoriented from its original configuration, and resulting in a breach of the fuel cladding (and some fuel rods could be rubblized, becoming fuel debris). Note, the integrity of the fuel basket is required by 10 CFR 72.122(h)(1) which states that the spent fuel cladding must be protected during storage against degradation that leads to gross ruptures, or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage.

- The multi-purpose canister (MPC) confinement boundary is maintained during a non-mechanistic tip-over accident event; therefore, no fuel is released from the MPC, and no water is able to enter the interior of the MPC during accident conditions.

- The structural analysis of the non-mechanistic tip-over event is relied on to bound the consequences of other credible accident conditions (e.g., tornado missile strikes, seismic events, etc.), which is discussed further in the structural evaluation section below. Therefore, the staff's assessment assumes that the integrity of the fuel basket is lost during all credible accident conditions that result in a mechanical load on the fuel basket.

1.2. Thermal Evaluation

Based on the structural analysis review, the cask confinement boundary (MPC) function is maintained during the non-mechanistic tip-over accident event, and therefore the staff's thermal assessment assumes that there is no loss of confinement integrity. The staff assessed the thermal impact on the containment resulting from potential localized failures of the fuel rods.

Holtec has not thermally analyzed a postulated non-mechanistic accident (i.e., cask tip-over) resulting in a horizontal cask orientation. For this "unanalyzed" thermal condition, the fuel debris could be rubblized to cause hot spots near the lowest circumferential portions of the cylindrical side of the horizontally oriented MPC, which would also be in contact with the intact cask, that is in turn horizontally in contact with the ground. These hot spots could cause an increase in the temperatures of the remaining/surrounding intact fuel rods and MPC components, and an increase in the temperatures of the lowest circumferential portions of the cask concrete shielding material. Based on heat transfer phenomena, some of the heat transferred to the overpack concrete will be further transferred to the ground, therefore the temperature increase in concrete overpack will be limited. In addition, the staff notes that any hot spots inside the MPC will not degrade the MPC confinement because the MPC confinement shell is made of stainless steel, which is sustainable at a very high temperature.

Staff notes that Holtec analyzed completely rubblized fuel rods (debris) in the vertically oriented HI-STORM 100 cask with acceptable margins. Although a thermal analysis of the horizontal configuration has not been performed, the "average" MPC gas temperature will remain much the same as the conditions of normal storage, due to no change in decay heat. Therefore, the MPC internal pressure, as a function of the average MPC gas temperature, will remain the same and will not breach the MPC and the associated confinement welds. While the fuel rods might not be retrievable based on the unanalyzed fuel temperatures, the MPC confinement system will remain intact and will not be degraded. See section 1.5.2 for evaluation of retrievability and recovery.

Therefore, the staff concludes, per its thermal evaluation, that the containment will remain intact and therefore the non-mechanistic tip-over accident condition does not result in significant safety consequences for the HI-STORM FW and HI-STORM 100 storage systems.

1.3. Criticality Evaluation

The staff assessed the potential for an inadvertent criticality in the case of an unanalyzed geometry (e.g., complete structural failure of a fuel basket). A failure of the basket could result in the basket material and fuel debris rubblizing at the bottom or side of the MPC due to a postulated cask accident (e.g., tip-over). Nonetheless, as explained below, the staff does not expect any significant change to the prior criticality evaluation, where the basket geometry was known and included in a bounding criticality evaluation.

The staff reviewed previous studies of criticality analyses to determine the effects of failures of the basket. The minimum enrichment necessary to theoretically achieve criticality with an unmoderated, unreflected uranium metal sphere is 5.4 weight percent (wt.%) ^{235}U (Reference: Forsberg, C.W., C.M. Hopper, J.L. Richter, and H.C. Vantine. 1998. "Definition of Weapons-Usable Uranium-233." ORNL/TM-13517, Oak Ridge, TN: Oak Ridge National Laboratory. https://thoriumenergyalliance.com/wp-content/uploads/2020/02/weapons-usable-u-233-ORNL-TM-13517.pdf) In Figure 3.1 of that report, staff noted that the plot of minimum critical mass approaches this limit asymptotically, meaning this theoretical minimum mass would be absurdly large.

In its comparison of this theoretical limit to the postulated conditions, the staff considered the following: all else being equal, UO_2 is less reactive than uranium metal; the neutron absorbing material in the basket will still be present and mixed within the rubble and reduce reactivity; the spent nuclear fuel contents have been irradiated and the presence of fission products and depletion of ^{235}U lowers reactivity; even when fresh, the contents were enriched to less than 5 wt.% ^{235}U and the total mass is much less. Given those conservative considerations and that the degradation of the CBS basket will not impact the MPC confinement boundary during a non-mechanistic tip-over accident event; staff has determined water in-leakage to be highly unlikely, and staff finds reasonable assurance that a post-accident configuration will remain subcritical. Therefore, there is no criticality safety concern for the CBS basket variants for both the HI-STORM 100 and FW casks under the assumption of fuel basket failure.

Shielding Evaluation

A non-mechanistic tip-over accident condition is considered a hypothetical accident scenario and may affect the HI-STORM FW overpack by resulting in limited and localized damage to the outer shell and radial concrete shield. As the damage is localized and the vast majority of the shielding material remains intact, the effect on the dose at the site boundary is negligible. Therefore, the site boundary doses for the loaded HI-STORM FW overpack for accident conditions are equivalent to the normal condition doses, which meet the Title 10 of the *Code of Federal Regulations* (10 CFR) Section 72.106 radiation dose limits. However, the adjacent and one meter dose rates may be increased, which should be considered in any post-accident activities near the affected cask.

In terms of damaged fuel, and the potential change in dose rate as a result of fuel debris or a damaged fuel assembly collapse, the dose rate is not very significant for the storage of damaged fuel and/or fuel debris. Any potential damage to the fuel cladding resulting from the fuel basket failure would remain within the MPC and would not result in any safety consequences that affects the shielding capability.

Further, in the event of a tip-over, NRC staff anticipates that licensee's corrective actions would include a radiological and visual inspection to determine the extent of the damage to the overpack and the contained MPC and that special handling procedures, including the use of temporary shielding, would be implemented by the general licensee.

1.4. Structural Evaluation

The staff's review focused on the tip-over analysis of the CBS basket designs as the tip-over accident is the most significant challenge to the structural performance of the fuel baskets.

The primary safety function of the fuel basket is to prevent criticality, and the structural design criteria for the baskets are required to be met to support the criticality safety determination. The structural design criteria include demonstrating that the lateral deflections of the basket panels are less than those considered in the criticality analysis and that the basket maintains its structural integrity.

The non-mechanistic tip-over analyses submitted by Holtec as part of the licensing review of HI-STORM FW Amendment 7 demonstrated that the MPC maintains its structural integrity during and following the accident. The staff's review did not identify issues with the MPC enclosure vessels in the tip-over analyses. Thus, the staff concludes that the MPC confinement boundary maintains its structural integrity and no water is able to enter the interior of the MPC during accident conditions.

However, the non-mechanistic tip-over analysis did not reasonably assure that the CBS baskets maintain their deflection and stress requirements. The stress contour results for several of the basket analyses indicated localized stresses in the active fuel region that exceed the primary stress limits as well as the true fracture strength of the basket material. These results indicate that some areas will experience complete failure of the material for several of the HI-STORM FW fuel baskets currently submitted for Amendment 7.

Based on the results of Holtec's analysis, the staff cannot conclude that the fuel baskets maintain their geometry and structural integrity during accident conditions. Nonetheless, should the fuel basket fail to maintain its structural integrity, and, in a worst-case scenario, allow the fuel assemblies and cladding to fail, the fuel will be maintained in a subcritical condition, as discussed in the criticality evaluation. This is because the confinement remains intact and there is no moderator present. Therefore, the staff concludes that the non-mechanistic tip-over accident condition does not result in significant safety consequences for the HI-STORM FW and HI-STORM 100 storage systems.

1.5.1 Cladding Integrity

As discussed in section 3.5 of the HI-STORM FW final safety analysis report (FSAR), fuel rod cladding is not considered in the design criteria for confinement of radioactive material under normal, off-normal, or accident conditions. Since fuel cladding is not relied on for demonstrating safety, there is no requirement to demonstrate structural integrity of the cladding. Since the MPC maintains structural integrity, the staff concludes that any potentially damaged fuel resulting from the fuel basket failure would remain within the MPC.

1.5.2. Retrievability and Recovery

As discussed in NUREG-2215, retrievability is applicable only during normal and off-normal conditions and does not apply to accident conditions. The normal and off-normal conditions identified for the HI-STORM 100 and HI-STORM FW systems do not induce any significant loading on the fuel basket structure. Therefore, the staff concludes that the retrievability requirement for the systems with CBS fuel basket designs is satisfied.

Also as discussed in NUREG-2215, recovery is the capability of returning the stored radioactive materials from an accident condition to a safe condition without endangering public health and safety or causing significant or unnecessary exposure to workers. Holtec's evaluation of the non-mechanistic tip-over included a demonstration that the MPC remains inside the overpack and the overpack does not suffer any ovalization that would prevent the removal of the MPC. The staff's review did not identify issues with the overpack or MPC in the tip-over analysis.

Should the basket fail, and some fuel be rubblized, the fuel may not be easily recovered at the fuel assembly level. However, recoverability of the MPC with the encapsulated fuel is still possible.

1.5.3. Natural Phenomena Hazards (NPH)

While the non-mechanistic tip-over is a design basis accident condition for the HI-STORM FW and HI-STORM 100 systems, Holtec has performed stability analyses to demonstrate that other credible accident conditions do not cause the storage casks to tip-over. These include accident conditions caused by natural phenomena such as earthquakes, tornadoes, and flooding. Although Holtec has not specifically analyzed the structural response of the fuel baskets during these accidents, the results are considered to be bounded by those of the non-mechanistic tip-over analyses.

While the staff has concerns that the fuel baskets may not maintain their structural integrity during the bounding non-mechanistic tip-over, the staff notes that these NPH accidents would result in considerably lower structural demands on the fuel baskets. Based on the staff's review of the non-mechanistic tip-over results for the baskets and the lower structural demands for the

NPH accidents, the staff concludes that the structural failure of the fuel baskets during these NPH accident conditions is unlikely.

Nonetheless, a similar conclusion can be made for these NPH accident conditions as for the non-mechanistic tip-over. The MPC confinement boundary maintains its structural integrity and no water is able to enter the interior of the MPC. Should the fuel basket fail to maintain its structural integrity the fuel will be maintained in a subcritical condition since there is no moderator present. Therefore, the staff concludes that the NPH accident conditions do not result in significant safety consequences for the HI-STORM FW and HI-STORM 100 storage systems with the CBS fuel basket designs.

1.5.4. Handling Operations

Holtec has developed handling procedures for both storage systems that significantly reduce the likelihood of a tip-over during handling operations. In general, these scenarios are administratively controlled using the technical specifications (TS) for the HI-STORM FW and HI-STORM 100 systems.

The TS addressing the dry cask handling outside of the Fuel Handling Building require either the use of single-failure-proof lifting devices or the imposition of a lift height limit, which is supported by a drop analysis. As discussed in NUREG-0612, the staff considers the type of handling accident that could challenge the fuel basket structure to not be credible when using single-failure-proof lifting devices. A lift height limit is imposed when using non-single-failure-proof lifting devices to ensure that any potential drops remain bounded by the analyzed drop. The analyzed drop does not induce significant loads in the fuel basket structure that could lead to a loss of structural integrity. Thus, the staff concludes that the issues identified with the CBS fuel basket designs do not affect the safety analysis of dry cask handling operations described in the FSARs for the HI-STORM FW and HI-STORM 100 systems.

Site-specific dry cask handling configurations (e.g., stack-up) are addressed by licensees typically with the goal of demonstrating through analysis that the configuration will remain stable and a tip-over, or any load challenging the fuel basket structure, will not occur under accident conditions.

Therefore, a similar conclusion to that for the non-mechanistic tip-over can be made for dry cask handling accident conditions. The MPC confinement boundary maintains its structural integrity and no water can enter the interior of the MPC. Should the fuel basket fail to maintain its structural integrity during stack-up the fuel will be maintained in a subcritical condition.

It should be noted that the TSs do not address the loading and handling operations inside the licensee's Fuel Handling building, which are site-specific. Therefore, operations occurring inside the Fuel Handling Building, that involve loading and handling of the MPC and transfer cask in a wet condition are not covered by the dry cask non-mechanistic tip-over accident analysis. These wet loading operations require the fuel basket to maintain its geometry and structural integrity in order to prevent fuel criticality. The magnitude of load demands on the fuel basket during these wet loading/handling operations are not significant and not expected to challenge the geometry and structural integrity of the fuel baskets. Site-specific loading and handling configurations inside the Fuel Handling Building are addressed by licensees under 10 CFR Part 50, typically with the goal of demonstrating through analysis that the analyzed configuration will remain stable and that a tip-over, or any load challenging the fuel basket structure, will not occur under accident conditions.

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