UNITED STATES - ADVANCED PRESSURIZED WATER REACTOR CONTAINMENT INTERNAL STRUCTURES AND STRUCTURAL ANALYSIS AND DESIGN AUDIT REPORT

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1.0 SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) staff conducted an audit at Mitsubishi Nuclear Energy Systems office in Arlington, Virginia between November 4 and 8, 2013, in accordance with the NRC Office of New Reactors (NRO) Office Instruction NRO-REG-108, "Regulatory Audits." The audit plan for Design Certification Document (DCD) Section 3.8.3 can be found in the Agencywide Document Access and Management System (ADAMS) under accession number ML13255A051, dated October 8, 2013. The audit plan for the DCD Sections 3.8.1, 3.8.4, and 3.8.5 can be found in ADAMS under accession number ML13295A304, dated October 25, 2013.

2.0 PURPOSE

The purpose of the DCD Section 3.8.3 audit was to review the design reports and calculations for the design of the containment internal structures (CIS). The purpose of the DCD Sections 3.8.1, 3.8.4, and 3.8.5 audit was to review the design reports for the Reactor Building (R/B) Complex which consists of the Prestressed Concrete Containment Vessel (PCCV), the R/B, the East Power Source Building (PS/B), the West PS/B, the Auxiliary Building (A/B), and the Essential Service Water Pipe Chase (ESWPC); the common basemat for the nuclear island; and the related documentation and supporting calculations for the structural design of those structures.

3.0 BACKGROUND

In 2007, Mitsubishi Heavy Industries, Ltd. (MHI) submitted an application for a Standard Design Certification for the United States – Advanced Pressurized Water Reactor (US-APWR). The US-APWR R/B Complex is supported on a common reinforced concrete mat foundation embedded approximately 42 ft. below grade. The structural analysis and design of the R/B Complex, which considers soil-structure interaction (SSI) effects, is described in DCD Tier 2, Section 3.8. The staff is currently performing a detailed review of the application.

Enclosure

The focus of this audit was to review the design reports and calculations supporting the structural analysis and design of the R/B complex, including the SSI effects on the R/B Complex.

4.0 OBSERVATIONS AND RESULTS RELATED TO CONTAINMENT INTERNAL STRUCTURES

At the beginning of the audit, the applicant presented a summary of the analysis and design procedures for the US-APWR CIS. This presentation included an overview of the design documents, audit scope, and an overview of the design of the CIS. During the audit, the staff engaged in discussions with the applicant regarding the applicant's implementation of its analysis and design approach as described in the US-APWR technical reports and DCD Revision 4, Section 3.8.3 and Appendix 3L. Relevant sections of documents supporting the applicant's analysis and design (i.e., technical reports and calculations) were reviewed by the staff. The staff's review of these documents focused on significant issues identified in prior reviews of the US-APWR technical reports and design assumptions, and did not constitute a comprehensive review of each document. At the conclusion of the audit, the staff and the applicant agreed on a list of audit action items. The applicant committed to issue revised request for additional information (RAI) responses on a number of technical issues, and the staff committed to issue a new RAI. The more significant issues raised during the audit are described below.

Review of Containment Internal Structures

The overall design and analysis approach used for the CIS is based on ACI 349-06, supplemented by additional design requirements for aspects unique to steel-concrete (SC) walls of the CIS. It is also supported by historical experimental tests for SC walls, as well as large-scale confirmatory tests of typical US-APWR SC walls and SC wall connections.

The staff reviewed a number of outstanding issues identified during the review of the applicant's US-APWR technical reports and associated RAIs. Additional questions were identified during the review of the calculations and reports that were made available during the audit. Most of these issues and questions were closed during the audit with a summary of the key issues and several outstanding items described below.

1. Response spectrum analysis (RSA) of the CIS: RSA of the CIS was performed to determine the member forces for use in design of the SC and reinforced concrete (RC) members. The use of a separate detailed finite element model (FEM) of the CIS, fixed at its base, performing the RSA was determined to be acceptable. This was acceptable because a CIS model was included in the seismic SSI analysis of the entire R/B Complex, as such the overall analysis accounted for the stiffness and mass effects of the CIS and direct comparison and verification can be made with the CIS sub-model. A question arose as to why the rotational input motions from the SSI analysis response at the CIS base were not included in the RSA of the CIS. The applicant explained that this was addressed by comparing the story shear forces from the CIS RSA with those from the SSI analysis, and the CIS RSA forces were amplified by a factor so that the CIS RSA would envelop the SSI analysis responses. This approach led to amplification factors of

1.18 and 1.12 in the two perpendicular horizontal directions. Therefore, this approach addresses the issue raised in the RSA analysis.

2. CIS stiffness value used in the Linear Elastic Finite Element (LEFE) model: During the audit the staff found that, for the accident thermal and seismic loading condition, the stiffness value of the CIS predicted by the Nonlinear Finite Element (NIFE) model is lower than the stiffness value used in the LEFE model which was utilized for the analysis and design of the CIS. The applicant indicated that the reduced stiffness value for the NIFE occurs only for the primary shield wall (PSW). To assess the impact of this reduced stiffness on the design of the CIS, the applicant performed a modal analysis with reduced stiffness for the PSW. Analysis results showed that the use of the reduced stiffness for the PSW would have a very small effect on seismic loads, and any small increases would be covered by the broadening of the seismic response spectra used for seismic input. Because the modal analysis results demonstrated that the reduced stiffness for the PSW only has a negligible effect on the design forces, the staff determined this issue to be closed.

3. Design of SC wall critical sections: During the audit, the staff performed a review of the applicant's calculations relating to the design of SC wall critical sections. The staff found that initial analyses indicated localized steel faceplate yielding in several locations of the refueling cavity wall and the SG compartment wall, and there is no localized yielding after the applicant utilized a distance of two times the wall thickness to distribute the localized forces. The staff also found that steel faceplate yielding occurred at the base of the refueling water storage pit (RWSP) wall under accident thermal condition. The applicant explained that the use of a distance of two times the wall thickness is a common industry practice; however, no code, standard, published paper, or other reference could be identified during the audit for using this approach. The applicant also explained that the RWSP wall is not a primary lateral load path, the localized yielding of the SC faceplate will partially relieve the restraint of the thermal demand, and therefore, the localized yielding is acceptable because calculations showed that a full plastic hinge would not develop at the base of the wall. To address this issue, the applicant agreed to provide more definitive information to justify the use of two times the wall thickness for distributing the member forces in a revised response to an existing related RAI.

4. Design of the PSW: During the audit, the staff performed a review of the applicant's calculations relating to the design of the PSW. The staff found that only shear forces versus strength were considered in the design of the PSW, and it appears that in-plane membrane forces from overall bending and vertical seismic forces were not included. Since the ACI 349 Code requires consideration of all of these forces, they should be included in the design. As a result of discussions during the audit, the applicant agreed to address this issue in a revised response to an existing related RAI.

5. SC wall fabrication, construction and inspection: During the audit, the staff presented and discussed with the applicant, five draft questions related to the review of Technical Report MUAP-12006-P, Revision 0, regarding SC wall fabrication, construction and inspection. The questions mainly request additional information on mockup testing, non-destructive evaluation methods, construction tolerances, and applicable codes and standards for the construction of the SC walls. Through discussions, the applicant understood the questions and it was agreed upon by the applicant that the questions

would be addressed in a response to a new RAI to be issued by the NRC. The staff will issue a new RAI for the questions related to MUAP-12006-P, Revision 0.

6. <u>HVAC penetration detail design</u>: During the audit, the staff performed a review of the applicant's calculations and design drawings relating to the design of HVAC penetrations through the SC walls. It wasn't clear to the staff as to why the specific penetration presented in the calculations was selected for design since there are other larger penetrations that would be expected to be more critical for design. In addition, it was not clear to the staff how high temperatures from hot lines are reduced for SC wall penetrations in order to meet ACI code requirements. Through discussions, the applicant understood the questions and agreed to provide a revised response to a related existing RAI.

In addition to the above, the staff provided its initial feedback on the review of Section 3.8.3 of DCD Revision 4, and the markups to Section 3.8.3 and associated Appendix 3L, related to the CIS. In some cases, the applicant provided clarifications to the staff's questions. In other cases, the applicant noted the feedback and agreed to address these items in a future revision to the DCD.

In summary, as a result of the staff's audit, various issues identified during the prior review of the US-APWR technical reports and additional questions raised during the review of the design documents were closed with several outstanding items identified as discussed above.

5.0 <u>OBSERVATIONS AND RESULTS RELATED TO STRUCTURAL ANALYSIS AND DESIGN OF THE R/B COMPLEX</u>

At the beginning of the audit, the applicant presented a summary of the analysis and design procedures for the US-APWR R/B Complex, including the containment and basemat. This included an overview of the design documents, the audit scope and the design of the structures comprising the R/B Complex. During the audit, the staff engaged in discussions with the applicant regarding the applicant's implementation of its analysis and design approach as described in the DCD Revision 4, Sections 3.8.1, 3.8.4, 3.8.5, and Appendix 3L. Relevant sections of documents supporting the applicant's analysis and design (i.e., design reports and calculations) were reviewed by the staff. The staff's review of these documents focused on significant issues identified in prior reviews of the technical reports and design assumptions, and did not constitute a comprehensive review of each document. At the conclusion of the audit, the staff and the applicant agreed on a list of audit action items. The applicant committed to issue revised RAI responses on a number of technical issues, and the staff committed to issue new RAIs. The more significant issues raised during the audit are described below.

<u>Review of Prestressed Concrete Containment Vessel (PCCV)</u>

The staff reviewed the reinforcement design for the PCCV for factored load cases in accordance with Article CC-3510 of ASME Section III, Division 2, "Code for Concrete Containments" – the ASME Code. The staff wanted to know the stress distribution assumed for concrete and the relationship assumed for concrete stress and the strain. The applicant indicated that the concrete stress distribution was assumed to be a triangle, and a linear relationship was assumed for the concrete stress and strain. So, in effect, the methodology used by the applicant for the factored load design was that specified in the ASME Code for the service load design. The applicant showed that by using the same methodology for both the service load design and factored load design, the design met the stress and strain requirements specified in the ASME code for both the service loads and factored loads. The staff will issue an RAI requesting more details and confirmations of the adequacy of the design implementation approach.

The staff reviewed how concrete cracking is considered in the PCCV design due to thermal loading; including the liner plate spike load. The applicant indicated that four cases of concrete cracking were considered in the PCCV design (Case 1: no cracking in the cross section; Case 2: cross section has a partial crack formed from the interior PCCV surface; Case 3: cross section has a partial crack formed from the exterior PCCV surface; Case 4: PCCV cross section is fully cracked). The applicant presented the methodology used in calculating concrete and rebar stresses in a cracked cross section. The applicant also showed how the concrete limiting strain criteria (0.002 per ASME Table CC-3421-1) is satisfied. Base on the information provided by the applicant, cracking of concrete is properly considered in the PCCV design.

The following applicant and NRC staff actions were identified related to the review of the PCCV:

- The applicant indicated that it would revise the response to RAI 1040-7139, Question 03.08.01-17, to include the equivalent static force in Table 3.8.1-4 of the DCD.

- The NRC staff will issue an RAI regarding the ultimate capacity of the PCCV being consistent with regulatory position C1 in RG 1.216, “Containment Structural Integrity Evaluation for Internal Pressure Loadings Above Design-Basis Pressure,” issued August 2010.

- The NRC staff will issue an RAI concerning the appropriateness of assuming a straight line stress-strain relationship for factored load design conducted in accordance with the ASME Code.

Review of Other Seismic Category I Structures

The staff reviewed the design report and calculations associated with the preliminary design of the R/B Complex. As part of this review, the staff verified that the load combinations used in the analysis and design were consistent with Appendix C to ACI 349-06, “Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-06) and Commentary” – the ACI Code, ANSI/AISC N690-1994, “American National Standard Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures” – the AISC Code, and Regulatory Guide (RG) 1.142 as applicable. The staff reviewed the preliminary design of the steel structure supporting the Fuel Handling Crane to verify that an acceptable lateral force-resisting system had been provided in the Fuel Handling (F/H) Area and the design of the steel girders and columns was carried out in accordance with the AISC Code. During the review of the design of the reinforced concrete shearwalls in the R/B Complex, the staff determined that lateral ties to restrain buckling of the vertical wall reinforcement had not been provided in all reinforced concrete shearwalls with vertical reinforcing area greater than 0.01 times the gross concrete area.

The staff reviewed how the polar crane induced seismic force is considered in the PCCV design. The applicant stated that the polar crane is included in the PCCV global seismic model based on a typical polar crane. Localized PCCV design is carried out after the seismic forces are determined.

The following applicant and NRC actions were identified related to the review of the other seismic Category I structures:

- The NRC staff will issue an RAI concerning the need for lateral ties in shear walls and whether this issue was evaluated in accordance with Section 14.3.6 of the ACI 349 Code.

- The NRC staff will issue an RAI regarding the applicant revising the DCD to specify COL parameters for the polar crane.

Review of Foundations

The staff reviewed the design report, calculations and drawings associated with the preliminary design of the combined basemat supporting the R/B Complex. As part of this review, the staff verified that the load combinations and allowable stresses used in the analysis and design were consistent with the ASME Code. The staff reviewed shear and moment diagrams for the critical section cuts identified in the DCD and the methodology and theory the licensee was using for implementing the requirements of the ASME Code for the design of the combined basemat.

During the review, the staff determined that the licensee was assuming the straight line theory of stress and strain to be applicable for factored load design performed in accordance with Article CC-3500, “Containment Design Details” of the ASME Code. Based on this assumption, the strain in the concrete corresponding to the maximum allowable primary-plus-secondary membrane and bending compressive stress of 0.85f’c does not correspond to a limiting strain of 0.002 in./in. as stated in Note (3) of Table CC-3421-1, “Allowable Compression Stresses for Factored Loads” of the ASME Code. The staff identified the need for a RAI for the applicant to provide additional information concerning the appropriateness of the assumed stress-strain relationship for factored loads and the accuracy of the corresponding analytical results when concrete compressive stress levels exceed the elastic limit, as well as conformance of this assumption with the applicable provisions of the ASME Code.

The staff reviewed the response spectrum method used in the ANSYS analysis of the R/B complex structures. The applicant explained the process used in its analyses and that different approaches are applied to different portions of the R/B Complex.

The following applicant and NRC actions were identified related to the review of foundations:

- The applicant indicated that it will address the assumed concrete linear stress-strain relationship under factored load design in accordance with the ASME Code in a revised response to RAI 490-3732, Question 03.08.01-9.

- The applicant indicated that it would revise the response to RAI 1045-7141, Question 03.08.05-54, to clarify the differences between the table in the RAI response and MUAP-10006, Revision 3.

- The NRC staff will issue RAIs requesting the applicant to address the following:

    - Provide a clear description in the DCD of each of the Step 2 models (R/B Complex, CIS, PCCV), and describe the approach to ensure that conservative seismic demands are used in the design of these structures.

    - Clarify whether the RSA models utilized broadened or un-broadened input and provide justification for not using broadened input, if applicable.

    - Demonstrate that conservative estimates of demand are obtained using such an approach (the combination of linear and nonlinear analysis) as compared to a fully linear or a fully non-linear analysis.

    - It is the staff's understanding that this analysis was based on linear material properties for the structural and soil elements and that the only nonlinearity was due to the use of nonlinear gap elements used as compression-only springs. As the DCD is unclear in this regard, the applicant is requested to confirm the staff's understanding and update the DCD to describe the analysis approach more adequately.

    - Provide the results of the parametric study using the time history analyses to demonstrate that consideration of the R/B complex basemat uplift results in a contact area between the basemat and the supporting soil of approximately 80 percent. Provide a description of the study in the DCD indicating the consistency of the approach with Standard Review Plan, Rev. 4. If not consistent with SRP, Rev 4.; explain why the approach used is adequate.

    - Explain the rational for asserting that the seismic analysis results obtained from the SASSI SSI analysis are adequate despite the fact that the SASSI analysis is a linear analysis and does not account for uplift.

    - Describe the basemat design approach to ensure that the seismic demands used in the design of the basemat are conservative and have sufficient margin to account for the approximations made in the stepped analysis approach and in modeling the flexibility of the basemat. The applicant is requested to include this description in DCD Section 3.8.5.

    - Provide the technical rational to support the assertion that the demands calculated for the two profiles (2032-100 and 270-500) envelope the demands for the remaining four profiles.

    - Assess the effect of variable soil modulus (i.e, the dishing effect) on the seismic demands calculated for the basemat on soft soil.

<u>Review of Critical Sections</u>

The staff reviewed the design report, calculations and drawings associated with the design of the critical sections included in DCD Tier 2, Appendix 3L. The following applicant and NRC staff actions were identified related to the review of the design of the critical sections:

- The applicant indicated that it would delete the phrase “summed with the absolute value of the response” in the fifth paragraph of DCD Tier 2, Subsection 3L.4.1.3.

  > “After the R/B complex is analyzed for each load case and soil profile, the total seismic response in each direction is calculated using the square root of the sum of the squares (SRSS) of the dynamic fluid response, dynamic earth pressure response, and in-phase and out-of-phase components of seismic response. The three directional responses are combined using SRSS in accordance with American Society of Civil Engineers (ASCE) 4-98, Section 3.2.7.1.2 (Reference 3L-11), <u>then summed with the absolute value of the response</u>.”

- The applicant indicated that it would clarify the phrase “reinforcing steel being in the Y (vertical) direction” in the second to last paragraph of DCD Tier 2, Subsection 3L.4.2.4, “Other R/B Complex Structures.”

  > “The required <u>reinforcing steel area for top and bottom faces in the X (horizontal) and Y (vertical) directions</u> for each element is calculated. Refer to Section 3L.4.1.3 for orientation of shell elements for reinforced concrete design.”

- The applicant indicated that it would correct in the next revision of the DCD Table 3L-12, “Demand Capacity Ratios for Buttress Evaluations,” to use consistent designations for the load cases in the portion of the table on Sheet 2 of 2 and the notes.

6.0 CONCLUSION

At the audit exit meeting, the NRC staff informed the applicant that the audit was productive and that the support of the applicant and contractors led to a quick resolution of technical questions. The audit tasks identified in the audit plan were all accomplished. The significant audit actions, as discussed above, are (1) the applicant will submit revised RAI responses, and (2) the staff will issue new RAIs, as appropriate to address the technical areas discussed during the audit.