UNITED STATES - ADVANCED PRESSURIZED WATER REACTOR SEISMIC ANALYSES AUDIT REPORT

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1.0 SUMMARY

An audit was conducted by the U.S. Nuclear Regulatory Commission (NRC) staff at the URS Corporation offices in Princeton, New Jersey between September 23 - 27, 2013, in accordance with the NRC Office of New Reactors (NRO) Office Instruction NRO-REG-108, "Regulatory Audits." The plan for this audit was documented and can be found in the Agencywide Document Access and Management System (ADAMS) under accession number ML13252A089, dated September 11, 2013. A list of attendees is provided as Enclosure 2. A list of documents made available to the NRC staff is provided as Enclosure 3.

2.0 PURPOSE

The purpose of the audit was to review the details regarding the seismic analysis and design of the nuclear island structures in support of the safety evaluation of the United States -Advanced Pressurized Water Reactor (US-APWR) Design Certification Document (DCD) Tier 2, Sections 3.7.1, 3.7.2, and 3.7.3. Calculations supporting the applicant's development of design time histories, soil profiles, structural models, and soil-structure interaction (SSI) models were reviewed. The seismic analysis of the nuclear island structures is described in the US-APWR DCD Tier 2, Section 3.7 and in several referenced technical reports.

3.0 BACKGROUND

In 2007, Mitsubishi Heavy Industries, Ltd. (MHI) submitted an application for a Standard Design Certification for the US-APWR. The US-APWR Reactor Building complex, which includes the Reactor Building, Pre-stressed Concrete Containment Vessel (PCCV), Containment Internal Structures, Fuel Handling Area, Auxiliary Building, East and West Power Source Buildings, and the Essential Service Water Pipe Chase, is supported on a common reinforced concrete mat foundation embedded approximately 42 ft below grade. The seismic analysis of the Reactor Building complex, which considers SSI effects, is described in DCD Tier 2, Section 3.7 and in several referenced technical reports. DCD Tier 2, Section 3.7 also describes the seismic analysis of the Turbine Building, which is adjacent to the Reactor Building complex. Structure-soil-structure interaction (SSSI) effects are also evaluated. The staff is currently performing a detailed review of the application, including several technical reports relating to seismic analysis.

The focus of this audit was on reviewing the calculations supporting the seismic analysis of the Reactor Building complex, including the SSSI effects on the Reactor Building Complex and the Turbine Building. The staff reviewed the implementation of DCD commitments in the detailed analysis models. Analysis code validation efforts, particularly as they relate to the SASSI Subtraction Method, were also reviewed.

4.0 OBSERVATIONS AND RESULTS

At the beginning of the audit, the applicant presented a summary of the seismic analysis methodology for the US-APWR and identified key design/modeling assumptions. The interface of seismic analysis and structural design and the applicant's approach for applying seismic demands to the various structural models were also discussed. During the audit, the staff engaged in extensive discussions with the applicant regarding the applicant's implementation of its seismic analysis methodology. The relevant sections of documents supporting the applicant's seismic analysis (i.e., technical reports and formal calculations) were reviewed by the staff. The staff's review of these documents focused on significant 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 follow-up RAIs so that the information discussed during the audit could be included on the docket. The more significant issues raised during the audit are described below.

Development of Structural Models of the Reactor Building Complex

The US-APWR Reactor Building complex is initially modeled using the ANSYS finite element (FE) analysis code. Two levels of model refinement are developed. The ANSYS detailed model defines the structures with a high degree of fidelity. A less refined ANSYS dynamic model is then developed. Static and modal analyses are performed with both models and compared to assess the adequacy of the dynamic model. As necessary, the ANSYS dynamic model is adjusted to simulate the ANSYS detailed model response. The ANSYS dynamic model is then translated into the SASSI structural model for the SSI analysis. This process is described in considerable detail in MHI Technical Report, MUAP-10006, Revision 3, "Soil-Structure Interaction Analyses and Results," dated November 2012, which the staff reviewed extensively prior to the audit. The staff identified several technical areas for follow-up during the audit, in order to verify that the SASSI structural model is a sufficiently accurate representation for the purpose of the SSI analysis.

During the audit, the staff performed a review of several ANSYS modeling assumptions, including consideration of beam-to-solid and shell-to-solid connections. The staff requested the applicant to perform a simple calculation to demonstrate that the beam-to-solid connection method achieves the desired rotational compatibility between the beam and solid elements. The staff found the applicant's approach to addressing rotational compatibility at beam-to-solid and shell-to-solid connections acceptable.

The staff performed a review of the treatment of flexible floors and walls (i.e., having out-of-plane fundamental frequencies potentially excited by the design-basis seismic loading). The staff reviewed in detail the applicant's methodology to adequately represent flexible floors in the ANSYS dynamic model, in order to match the ANSYS detailed model results. The staff found the applicant's approach to representing flexible floors in the ANSYS dynamic model to be acceptable. In response to the staff questions regarding the treatment of flexible walls, the applicant indicated that a comprehensive review had not been conducted. The applicant agreed to conduct a review of the walls and to develop an approach for addressing any local amplification of wall out-of-plane motion.

The staff also discussed with the applicant the adequacy of the number of solid elements through the thickness of the basemat, which in some areas of the basemat are fewer than the ANSYS recommendation of four to capture bending behavior. During the audit, the staff performed simplified hand calculations and plate FE analysis of the most flexible basemat slab, in order to estimate the fundamental plate out-of-plane frequency. Calculations assuming (1) only bending flexibility and (2) combined shear and bending flexibility were performed. In both cases, the fundamental frequency is higher than the maximum frequency of interest in the seismic analysis. The applicant indicated that no member forces for design of the basemat are taken from the SASSI SSI analysis. The staff concluded that modeling of the basemat in the SASSI structural model is adequate for the SSI analysis.

The staff reviewed details of the transfer from ANSYS dynamic model to SASSI structural model, to verify that the two models have essentially identical response characteristics. At the audit, the staff requested the applicant to compare SASSI transfer functions to ANSYS harmonic analysis results at representative locations in the Reactor Building Complex. The applicant performed the comparisons requested by the staff. The staff review found the comparisons to be very well correlated, providing quantitative verification that the ANSYS to SASSI transfer is accurate.

As necessary, the staff will issue follow-up RAIs on the issues discussed above, so that docketed RAI responses can be referenced in the staff's safety evaluation report.

SASSI SSI Analyses

The staff performed a review of SSI analysis calculations that support the technical information included in Part 3 of MUAP-10006 Revision 3. The applicant performed SSI calculations using the ACS SASSI analysis code. Several significant issues are highlighted below.

For the evaluation of the Reactor Building complex, the applicant used a SASSI modeling simplification known as the modified subtraction method (MSM). The MSM reduces the computational burden, compared to the more mathematically rigorous flexible volume method (FVM). However, the staff requires confirmation that each specific implementation of the MSM compares favorably with the FVM, and does not introduce any numerical anomalies in the SASSI solution. This technical issue was raised by the staff in RAI 812-5983, Question 3.7.2-109. During the audit, the staff reviewed the details of the applicant's response to RAI 812-5983, Question 3.7.2-109 with the applicant. As a result of these discussions, the staff will issue a follow-up RAI to RAI 812-5983, Question 3.7.2-109, requesting additional confirmatory calculations, the specifics of which the staff and applicant agreed to during the audit.

In its SSI analyses, the applicant assumes groundwater level and saturated soil conditions to be just below grade. To simulate saturated soil conditions, a value of Poisson's ratio approaching 0.5 is used. Specifically, the applicant has used 0.48. Recent SASSI sensitivity studies performed for DOE indicate the potential for erroneous results for Poisson's ratio above 0.42. This is highly case-dependent. The staff issued RAI 1025-7092, Question 3.7.2-226, requesting the applicant to address this for its specific SASSI application. During the audit, the staff and the applicant discussed the applicant's response to RAI 1025-7092, Question 3.7.2-226. The staff also performed a limited confirmatory analysis during the audit. Based on the staff's analysis, the applicant's SASSI results using Poisson's ratio of 0.48 are judged to be acceptable. The applicant agreed to make specific revisions to its initial response to RAI 1025-7092, Question 3.7.2-226, and to re-submit.

Technical Report MUAP-10006, Revision 3, Figure 03.3.4.1-3, "Excavated Soil Volume Elements," shows the finite element mesh used to model the excavated soil volume of the embedded Reactor Building complex. The staff noted that under the PCCV, there are regions where the mesh is irregular and the elements are highly distorted. During the audit, the staff discussed this with the applicant, and pointed out that this could potentially lead to inaccuracies in the ACS SASSI SSI solution. The staff will issue a follow-up RAI, requesting the applicant to demonstrate that their SASSI results are insensitive to the mesh irregularity. During the audit, the staff discussed with the applicant the specific information that will be requested.

Technical Report MUAP-10006, Revision 3, Table 03.3.5-1, "ACS SASSI Analysis Flow Chart," indicates that the cut-off frequency of the SSI analysis is 40 Hz for generic soil profiles 270-200 and 270-500, and 50 Hz for generic soil profiles 560-500, 900-100, 900-200 and 2032-100. The staff noted that, based on soil layer thickness, the S-wave passing frequency of the SSI model is lower than the analysis cut-off frequency. This is partially addressed in MUAP-10006 Revision 3. During the audit, the staff discussed this inconsistency with the applicant, and will issue a follow-up RAI requesting additional clarification and justification. During the audit, the staff discussed with the applicant the specific information that will be requested.

Basemat Uplift and Sliding

Extreme seismic demands, such as that assumed for the US-APWR design, can cause a large Reactor Building basemat to separate from supporting soil or rock material (i.e., basemat uplift). The nonlinear phenomenon of foundation uplift, while associated with soil separation, normally does not result in significant liftoff displacements and does not lead to overturning of the nuclear island. However, if the uplift occurs over a large enough foundation footprint, the seismic design response spectra developed from linear analysis models can be affected. Accordingly, the staff performs a review of foundation uplift and focuses on whether the uplift is sufficient to impact seismic demands. To address this issue, the staff issued RAI 1050-7218, Question 3.7.2-228 in August 2013.

During the audit, the staff performed a review of the applicant's calculations relating to foundation uplift and found that the calculation did not explicitly consider the coupled problem of uplift and sliding. To address this, the applicant performed a nonlinear calculation that was capable of both foundation uplift and sliding and showed that the contact area of the basemat remained greater than 75 percent at all times throughout the nonlinear response history. The staff's acceptance criterion (minimum of 80 percent contact) is based on performing a linear analysis, in which the soil-structure interface can transmit tensile loads, and the minimum percentage of basemat area in compression is calculated. The applicant did not complete a linear uplift analysis during the audit, but concluded that the linear analysis will show increased contact area because of the ability to transmit tension. The applicant agreed to include the results of both analyses (linear and nonlinear) in its response to RAI 1050-7218, Question 3.7.2-228.

Turbine Building Overturning Stability

The staff discussed with the applicant that in Technical Report MUAP-11002 Revision 2, "Turbine Building Model Properties, SSI Analyses, and Structural Integrity Evaluation," dated February 2013, Table 6.2-1, "Turbine Building and Electrical Room Minimum Overturning Factor of Safety for each Subsurface Profile," the minimum overturning factors of safety are identical in both the north south (N-S) and east-west (E-W) directions, except for a slight difference for soil profile 270-500. Considering that the plan dimensions of the Turbine Building differ substantially in the two horizontal directions, it is not clear to the staff why the factors of safety are the same. In addition, considering the geometry of the building and the vertical mass distribution, the reported factors of safety appear to be low. The applicant and its contractor agreed to check the calculation and to provide additional information in its response to a follow-up RAI to be developed by the staff.

5.0 CONCLUSION

At the audit exit meeting, NRC staff informed the applicant that the audit was productive and that support by MHI and contractors led to 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.