RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

APR1400 Design Certification

Korea Electric Power Corporation / Korea Hydro & Nuclear Power Co., LTD

Docket No. 52-046

RAI No.:	**432-8377**
SRP Section:	**19 – Probabilistic Risk Assessment and Severe Accident Evaluation Section: 19**
Application Section:	**19**
Date of RAI Issue:	**03/08/2016**

Question No. 19-62

10 CFR 52.47(a)(23) states that a design certification (DC) application for light-water reactor designs must contain an FSAR that includes a description and analysis of design features for the prevention and mitigation of severe accidents, e.g., challenges to containment integrity caused by core-concrete interaction, steam explosion, high-pressure core melt ejection, hydrogen combustion, and containment bypass.

APR1400 design control document (DCD) Rev. 0, Section 19.2.3.3.5.1.1, states that in-vessel steam explosion analysis is performed to confirm the applicability of the NRC Fuel-Coolant Interactions (FCI) expert review group OECD/NEA FCI specialist conclusions to the APR1400 design. The applicant provided this in-vessel steam explosion analysis in APR1400-E-P-NR-14003-P, “Severe Accident Analysis Report.” Rev. 0, Appendix D, “Severe Accident Analysis Report for FCI.” Add text to the DCD to describe the in-vessel steam explosion analysis performed including key assumptions, methodology, and key results.

Response

As addressed in Section 3 of APR1400-E-P-NR-14003-P, “Severe Accident Analysis Report”, Rev. 0, Appendix D, In-Vessel Steam Explosion (IVSE) analysis has been done to confirm IVSE does not lead to the reactor vessel failure. Methodology for IVSE study is categorized as follows:

- Setup the initial and boundary condition (Section 3.2 in Appendix D)
- Evaluate the enegertic load due to IVSE by using TEXAS-V (Section 3.3 and 3.4 in Appendix D)
- Assess the reactor vessel lower head integrity against the load given by TEXAS-V (Section 3.5 and 3.6 in Appendix D)

To incorporate the requested information in DCD the text including key assumptions, methodology, and key results are added in DCD Section 19.2.3.3.5.1.1 and 19.2.3.3.5.2.1 as shown in the Attachment.

Impact on DCD

DCD Tier 2, Subsection 19.2.3.3.5.1.1 and 19.2.3.3.5.2.1 is revised, as indicated in the Attachment.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

There is no impact on any Technical, Topical, or Environmental Report.

19.2.3.3.5.1 Analysis Methodology

19.2.3.3.5.1.1 In-Vessel Steam Explosion (IVSE)

The alpha-mode failure caused by IVSE has been considered as a threat to containment integrity for many years. The FCI expert review group sponsored by the NRC concluded in NUREG-1116 (Reference 21) and NUREG-1524 (Reference 22) that probability of this failure was vanishingly small or physically unreasonable. The OECD/NEA FCI specialist meeting (Reference 23) confirmed this conclusion. Therefore, the IVSE analysis is performed to confirm the applicability of the experts' conclusions to the APR1400 design.

The analysis consists of determination of initial and boundary conditions for the IVSE including corium and coolant characteristics, evaluation of pressure loads with TEXAS-V (Reference 24), and evaluation of reactor vessel lower head structural integrity against the pressure loads.

19.2.3.3.5.1.2 Ex-Vessel Steam Explosion (EVSE)

EVSE has been considered as one of the important threats to containment integrity for many years although no specific requirements are stated in the CFRs. Therefore, the EVSE analysis aims analytically to confirm the maintainability of containment integrity by employing a mechanistic FCI code to calculate EVSE pressure loads. The APR1400 specific analysis consists of four steps:

a. Selection of the initial and boundary conditions for the base case analysis based on MAAP analysis results

b. Evaluation of pressure loads with TEXAS-V (Reference 24) for the base case analysis

c. Assessment of uncertainties associated with the pressure load evaluation

d. Evaluation of containment structural integrity against the pressure loads

The base case of the EVSE analysis is assumed to be a case where the vessel failed at the bottom center of the RPV due to the in-core instrument guide tube ejection resulting in the ejection of oxidic core debris into a subcooled pool of water in the reactor cavity.

19.2.3.3.5.2 Analysis Result

19.2.3.3.5.2.1 In-Vessel Steam Explosion

The key physical processes that can influence in-vessel steam explosions for PWRs are (a) melt relocation into the lower plenum, (b) corium jet breakup and coarse mixing formation in the lower plenum, (c) triggering of coarse mixing, (d) energetic FCIs, and (e) pressure loads to the upper and lower vessel heads and their responses.

Both NUREG-1116 and NUREG-1524, written by the NRC-sponsored Steam Explosion Review Group, concluded that the potential for alpha-mode failure is vanishingly small or physically unreasonable. The OECD/Committee on the Safety of Nuclear Installations (CSNI) also confirmed the conclusion of NUREG-1524 and concluded that the alpha-mode failure issue was resolved from a risk perspective.

Because the APR1400 design is not significantly different from current PWRs, the NUREG-1524 conclusions are applicable to the APR1400 design, thus no mitigation features are provided to prevent or mitigate IVSE.

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19.2.3.3.5.2.2 Ex-Vessel Steam Explosion

The initial and boundary conditions for EVSE are largely dependent upon the in-vessel severe accident progression, severe accident management procedure, and vessel failure modes. Thirteen severe accident sequences were chosen to cover the spectrum of key variable parameters and thus characterize the initial and boundary conditions for EVSE analysis. The key parameters considered include corium discharge rates, corium thermal conditions, cavity conditions, and related parameters.

The result of analysis using the MAAP code provided the initial conditions for the TEXAS-V code. TEXAS-V was then used to calculate the peak pressure due to EVSE. The pressure at the nearest cavity wall was then estimated by the TNT method (Reference 25).

The reactor cavity and RPV column support have to maintain structural integrity in events such as an ex-vessel steam explosion. The reactor cavity and RPV column support is

"A"

Initial and boundary conditions for the IVSE are constructed under the conservative assumptions such as the jet falling at the center of the vessel and the ignoring of the complex internal structure disruption. The key parameters considered include corium temperature, jet diameter, jet velocity, water level, and water temperature. To reflect the uncertainty pertinent to the relocation, multi-jet configuration is also examined. TEXAS-V was then employed to evaluate the peak pressure due to IVSE.

The stress analysis for the reactor vessel lower head against the dynamic loads given by IVSE event was performed with the conservative failure criteria of the pressure vessel. The stress analysis indicates that no thread of the APR1400 lower head due to the IVSE is expected.

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Question No. 19-63

10 CFR 52.47(a)(23) states that a design certification (DC) application for light-water reactor designs must contain an FSAR that includes a description and analysis of design features for the prevention and mitigation of severe accidents, e.g., challenges to containment integrity caused by core-concrete interaction, steam explosion, high-pressure core melt ejection, hydrogen combustion, and containment bypass.

Provide the following regarding the discussion on *in-vessel* steam explosion as provided in APR1400-E-P-NR-14003-P, "Severe Accident Analysis Report," Rev. 0, Appendix D, "Severe Accident Analysis Report for FCI" and revise the design control document (DCD) to incorporate them:

a. Figure 3-1 shows one-dimensional nodalization of TEXAS-V for the in-vessel steam explosion in the APR1400 RPV. Explain and justify using one-dimensional analysis.

b. Section 3.4.1 states that "The penetration velocity profile [in Figure 3-2(a)] shows the typical corium penetration behavior in TEXAS where the corium jet is injected with the initial velocity and rapidly decelerated where the initial jet break-up occurs and start accelerating again." Explain the reasons for a second deceleration and subsequent acceleration of the jet.

c. Provide the initial void fraction assumed for the melt jet.

d. Explosion energy generated depends on melt fraction and void fraction before triggering an explosion, which are functions of time after the initiation of premixing. Provide the timing and justify the time at which triggering was assumed.

Response

a. The TEXAS-V code is a transient, one-dimensional model capable of simulating fuel-coolant interactions. And to maximize the fuel mass participates in the explosion, the external trigger when the jet touches the bottom of the lower head. Thus the constant cross-sectional area nodes system for the lower head zone is employed in IVSE analysis rather than considering the hemi-spherical shape of the lower head. TEXAS-V, therefore, can provide more conservative estimation of IVSE loading at the given initial conditions by adjusting the radial mixing zone.

b. TEXAS-V models LaGrangian particle filed for the melt as discrete material volumes or ‘master particles’ within Eulerian control volume for coolant vapor and liquid. The LaGrangian treatment for the fuel makes it quite straightforward to track the fuel particle movement and thus eliminates the numerical diffusion difficulties encountered in pure Eulerian codes.

   For a given initial velocity and radius of melt jet, how much of the fuel first enters the water pool as discrete fuel masses can be specified. In TEXAS-V code only discrete fuel masses and the leading edge may undergo hydrodynamic fragmentation. In addition, the TEXAS-V models the fuel jet as a collection of master particles and the jet breakup is attributed to Rayleigh-Taylor instabilities at the jet leading edge. As an approximation of the actual coherent jet, this jet is taken to be composed of a series of discrete ‘blobs’ or master particles that enter the coolant sequentially with the jet leading edge found by the relative position of the first unfragmented master particle ‘blob’ compared to the position of the master particles preceding it.

   Therefore, for the velocity profile given in Figure 3-2(a), the deceleration zone represents the influence of the fragmentation of the first leading master particle. After the completion of the first master particle fragmentation, the preceding (or the second) master particle then has a leading position and will have the hydrodynamic fragmentation which leads to the second deceleration.

c. For melt jet, the initial void fraction is set to be zero.

d. The steam explosion energetics depends largely upon the corium mass participated in the interaction. Therefore, it is assumed that the artificial trigger is provided by the corium jet contact at the bottom of RPV. The less conservative results will be obtained if the corium jet is triggered before or after the bottom contact of corium leading edge to the RPV wall.

Impact on DCD

There is no impact on the DCD.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

There is no impact on any Technical, Topical, or Environmental Report.

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Question No. 19-64

10 CFR 52.47(a)(23) states that a design certification (DC) application for light-water reactor designs must contain an FSAR that includes a description and analysis of design features for the prevention and mitigation of severe accidents, e.g., challenges to containment integrity caused by core-concrete interaction, steam explosion, high-pressure core melt ejection, hydrogen combustion, and containment bypass.

Provide the following regarding the discussion on ex-vessel steam explosion as provided in APR1400-E-P-NR-14003-P, “Severe Accident Analysis Report,” Rev. 0, Appendix D, “Severe Accident Analysis Report for FCI” and revise the design control document (DCD) as necessary

a. Figure 4-2 shows one dimensional nodalization of TEXAS-V for the ex-vessel steam explosion in the APR1400 RPV. Explain and justify using one-dimensional analysis for the cavity which has a large cross sectional area.

b. TEXAS-V code being one dimensional, assumed diameter for the mixing region would significantly affect the premixing results as shown in Figures 4-3 and 4-4. As stated in Section 4.5.3, mixing has an area of 7 m^2, which is significantly larger than the cross-sectional area of the melt jet of 0.2 m^2. Justify using one-dimensional analysis.

c. Provide the initial void fraction of the melt jet.

d. Explosion energy generated depends on melt fraction and void fraction before triggering an explosion, which are functions of time after the initiation of premixing. Provide the timing and justify the time at which triggering was assumed.

e. Table 4-17 showing cavity structural analysis results lists number of cracks as “47,073 EA” and a maximum crack width of 0.027 in. with a remark of considerable concrete damage. However, Table 5-1 remarks that ex-vessel steam explosion has no threat to APR1400 design. Explain what is meant by EA in listing number of cracks and why a possible concrete damage with 47,073 cracks would not cause a threat to the APR1400 cavity design.

Response

a. TEXAS-V code is a one-dimensional code and the user is expected to input the area of the node as a user-defined parameter, ARIY, which corresponds to the cross-sectional area of the cavity. This user parameter is used to specify the amount of coolant at given node and its cooling capacity, in consequently. ARIY plays an important role in determining the vapor fraction during the mixing phase as well as the numerical convergence.

   Instead of the actual cavity cross-sectional area (approximately 80 m^2), ARIY is set to give a maximum energetic load based on the energy index concept, i.e. when the ratio of the given melt's initial thermal energy and the coolant energy places in the optimal range the explosion pressure can be maximized. In other words, if a user introduces the actual cavity floor area of APR1400 as ARIY, the excess of cooling capacity can produce the higher void fraction and eventually it can lead to the limited energetic load due to one-dimensional characteristics of TEXAS-V code. In contrary for the case with too small ARIY, the certain amount of the melt thermal energy may remain inside the melt and it can restrict the higher load.

   The influence of the large cross-sectional area of the cavity is eliminated in TEXAS-V study in this way from the conservatism standpoint.

b. As discussed in Response a., ARIY represents the node area not the mixing area. The editorial error will be revised as Attachment ("mixing" replaced with "node").

c. For melt jet, the initial void fraction is set to be zero.

d. The steam explosion energetics depends largely upon the corium mass participated in the interaction. Therefore, it is assumed that the artificial trigger is provided by the corium jet contact at the bottom of the reactor cavity. The less conservative results will be obtained if the corium jet is triggered before or after the bottom contact of corium leading edge to the cavity floor.

e. The numbers of cracks described in Table 4-17 include all cracks having from a very small crack width to maximum 0.027 in crack width. In addition, there are no through cracks in concrete. It means that the possible concrete damage did not cause a threat to the cavity design even though cracks seem quantitatively much. In the scope of leakage, the damage of liner plate rather than concrete crack is more important. By ex-vessel steam explosion, the maximum stress in the liner plate is 54.9 ksi which is less than the ultimate tensile strength (75 ksi). In addition, the maximum effective plastic strain is around 1.1% which is less than the failure strain criteria of liner plate (5%). Therefore, it can be concluded that the APR1400 cavity structure remains intact from the ex-vessel steam explosion.

Impact on DCD

There is no impact on the DCD.

Impact on PRA

There is no impact on the PRA.

Impact on Technical Specifications

There is no impact on the Technical Specifications.

Impact on Technical/Topical/Environmental Reports

Technical Report APR1400-E-P-NR-14003-P/NP, “Severe Accident Analysis Report,” Rev. 0, Appendix D, “Severe Accident Analysis Report for FCI” Section 4.5.3 is revised as shown in Attachment.

The analysis shows that the peak pressure and corresponding impulse of 60.35 MPa and 194.07 kPa-s, as shown in Table 4-12, are estimated. The results are similar to those from the base case. As described in Table 4-8, the initial conditions for the SVF case assume that the corium is 100% metallic composition with high superheat of corium but lower temperature. In addition, the corium injection velocity at the vessel breach location is low due to the small gravitational head of corium in the reactor vessel. Comparing to the base case, the peak pressure due to steam explosion is similar but the impulse generated by the steam explosion is higher. The steam explosion loadings to the cavity wall will be higher than that of the base case due to the location of the vessel failure.

4.5.2 SAMG Related Issues: In-Vessel Corium Melt Retention (IVR)

For the case of IVR/ERVC, the RPV is in a stage of submersion in the fully flooded cavity water up to EL114'-4" from the plant ground level, or 13.8 m from the plant cavity floor (see Figure 4-2), to provide the external cooling when the core meltdown and relocation to the bottom of the reactor vessel occurs. In this situation, there is two potential vessel failure modes; bottom and side vessel failures at the locations assumed to be 6.5 and 8.05 m, respectively.

Table 4-12 shows that the peak pressures and maximum impulses for both bottom and side vessel failures with IVR-ERVC are 69.79 MPa, 217.33 kPa-s and 48.84 MPa, 226.16 kPa-s. It is noted that for the bottom vessel failure in the case of fully-flooded (FF) case, the explosion peak pressure is slightly higher but the impulse becomes about 20% higher. For the side vessel failure, however, it was observed that the tendency of explosion pressure profile was opposite to one for the bottom vessel failure, resulting in about 20% lower peak pressure but 26% higher impulse. The result indicates that the energetics of the side vessel failure is slightly higher than one of the bottom vessel failure.

4.5.3 Effects of Key Physical Parameters on EVSE Energetics

In this sensitivity analysis, some of key parameters pertaining to the thermal and dynamic properties of corium and the conditions of cavity water are examined to investigate their uncertainties on the energetics of EVSE in the APR1400 design. In this sensitivity analysis, it is worth to note that the mixing area defined by the model parameter, ARYI value of 7 m^2, is maintained in most of cases (except corium jet diameter effects).

node

4.5.3.1 Corium Temperature Effects

The effect of the initial corium temperatures on the EVSE energetics with the minimum and the maximum temperatures of 2900 and 3150 K is analyzed as shown in Table 4-13. Those temperatures correspond to the corium superheats of 50 and 300 K respectively. The results show that the energetics of EVSE in terms of pressure impulse increases with the corium temperature; 168.27 and 216.69 kPa-s for 50 K and 300 K superheat of corium, respectively. However, it also shows that the peak pressures for three cases; minimum, base, and maximum, are in a similar range of approximately 57-67 MPa. It indicates that the increase of thermal contents of corium enhances the explosion pressure peaks and profiles.

4.5.3.2 Corium Ejection Velocity Effects

The corium ejection velocity influences directly to the mixing phase of steam explosion process, mainly to corium jet breakup. In general, jet breakup length depends on the Froude number, and the ratio of density ratios between jet and coolant as shown in Eq. (4-2) below, showing the linear increase of the jet breakup length with the jet velocity,

$$\frac{\mathrm{L}}{D_j} \propto \left(\frac{\rho_j}{\rho_c}\right)^{0.5} (Fr)^{0.5} \qquad \text{(Eq. 4.2)}$$

where,