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. 19-67

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. Revise the design control document (DCD) as necessary.

a. APR1400 DCD Rev. 0, Section 19.2.3.3.3.2, provides a list of phenomena for which CORQUENCH models were used to tune MAAP model parameters for analyzing molten core concrete interactions in the reactor cavity. Describe how these phenomena were captured in modeling with MAAP.

b. Provide molten core-concrete interaction (MCCI) results for a case with no overlying water present in the cavity.

c. APR1400 DCD Rev. 0, Figure 19.2.3-7 has a caption “Ablation Depth in Floor and Sidewall for the PRA Sequence of Loss of Essential Service Water.” However, the figure also has a title “Loss of AC power with short battery life.”

Response – (Rev.2)

a. MAAP 4.0.8 only considers two main phenomena related to ex-vessel corium coolability, initial jet breakup and water ingression.

Initial jet breakup is the phenomenon occurring when a corium jet flows from the vessel into a deep water pool. Corium particles are stripped off from the corium jet due to the Kelvin-Helmholtz instability at the vapor/liquid interface. These particles can eventually settle on top of the upper crust of corium pool, forming a layer referred to as the particle bed. As a result of this process, the mass of the molten corium pool can be significantly reduced, making the MCCI less severe.

Water ingression is the phenomenon occurring once corium is fully settled on the cavity floor. As the corium is covered by water, the large heat removal from the top surface can produce a thick upper crust. According to experimental data, the heat removal rate by water in this configuration far exceeds the maximum conduction heat transfer rate through the upper crust layer, if the layer were assumed to be continuous and impermeable. The upper crust is not a continuous, impermeable layer; instead, numerous deep cracks develop, as the solidified corium in the upper crust is subjected to a large temperature gradient. Water can ingress (infiltrate) into the corium through these cracks, contacting the hotter region of the corium. As the solidification progresses, both the temperature gradient and the cracks extend deeper into the corium pool.

The model in MAAP 4.0.8 evaluates the heat transfer and oxidation of metal during the process of the initial jet breakup. However, it does not simulate the formation of the particle bed on top of the upper crust. MAAP 4.0.8 assumes that the particles formed during the initial jet breakup are promptly merged into the corium pool. The rate of mass stripping from a jet is calculated using a formulation similar to the Ricou-Spalding model:

$$\frac{dr_{dj}}{dt} = \mathrm{ENT0C} \cdot \left(\frac{\rho_w}{\rho_{dj}} \right)^{1/2} u_{dj}$$

where r_{dj} is the radius of the corium jet, ρ_w is the density of water, ρ_{dj} is the density of corium jet, and u_{dj} is the velocity of the corium jet. Model parameter ENT0C is a coefficient multiplier to the total mass of stripped particles (the higher the coefficient, the larger the fraction is).

MAAP 4.0.8 models water ingression by assuming the heat flux from a corium pool to its overlying water is prescribed by the critical heat flux, or higher, because water always ingress into the hot region in the corium. The heat flux formulation is given by:

$$q''_{cr-wt} = \mathrm{FCHF} \cdot \left[\frac{g\sigma(\rho_l - \rho_g)}{\rho_g^{\,2}} \right]^{1/4} \rho_g (h_g - h_l)$$

where g is the gravity constant, ρ_l and ρ_g are densities of saturated water and steam, and h_l and h_g are enthalpies of saturated water and steam. Modeling parameter FCHF is the Kutateladze number for corium to water heat transfer, which controls the magnitude of the heat flux.

The results of the CORQUENCH 3.03 calculations were used to tune the MAAP model parameters ENT0C and FCHF for the purposes of MCCI analysis. ENT0C was set to a low value in order to effectively disable heat transfer between corium and water as corium is relocating out of the vessel and into the pool of water in the reactor cavity. This results in more corium reaching the concrete at high temperature, which increases the calculated ablation depth. FCHF was tuned so that the reactor cavity ablation depth predicted by MAAP 4.0.8 is approximately the same as the reactor cavity ablation depth predicted by

CORQUENCH 3.03 for a conservative Large LOCA sequence with full core relocation into the reactor cavity. The models used in APR1400 MCCI analysis will be addressed in DCD section 19.2.3.3.3.2 as shown in Attachment2.

b. The scenario used to represent the Basemat Melt-Through fission product release category in Section 6.2.11 of APR1400-K-P-NR-013603-P “Full Power Level 2 PRA – Source Term Category Analysis Notebook Rev.0 (1-035-N463-603)” provides a conservative, but reasonable representation of MCCI results for a case with a dry cavity. The sequence presented in section 6.2.11 demonstrates that fission product release will occur due to breach of the containment liner if no systems are available to mitigate MCCI.

c. This figure will be replaced with the correct figure. See Attachment 1. Description on ablation depth for the selected sequences in DCD Rev.0 Section 19.2.3.3.3.3.3 is revised as shown in Attachment 3.

Impact on DCD

The DCD Tier 2 Figure 19.2.3-7 will be revised as shown in Attachment 1.

The DCD Tier 2 section 19.2.3.3.3.2 will be revised as shown in Attachment 2.

The DCD Tier 2 section 19.2.3.3.3.3.3 will be revised as shown in Attachment 3.

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 Environment Report.

Security-Related Information – Withhold Under 10 CFR 2.390

Figure 19.2.3-7 Ablation Depth in Floor and Sidewall for the PRA Sequence of Loss of Essential Service Water

Page intentionally blank

It is understood that steam explosions may pose a non-negligible threat to the cavity and containment integrity. Thus, there may be an incentive to delay actuation of the CFS until vessel breach (VB) is imminent or when the reactor vessel lower head has failed. While actuation of the CFS before VB is presently deemed desirable, the consequences of delayed CFS actuation (prior to extensive concrete erosion) may also achieve similar results. Flooding of the HVT progresses until the water levels in IRWST, HVT, and reactor cavity equalize at 6.4 m (21 ft) from the reactor cavity floor (EL. 69 ft 0 in).

Thus, it is currently believed that an acceptable stable state can be achieved ex-vessel as long as the CFS has been actuated prior to VB. Although providing water to the reactor cavity may not immediately terminate the concrete erosion, having a water-filled reactor cavity initially reduces and ultimately terminates the erosion, while simultaneously providing scrubbing of fission products released in the molten core-concrete interaction process.

19.2.3.3.3.2 Analysis Methodology

The MCCI analysis for the reactor cavity is performed with MAAP using model parameters tuned based on the results of the more sophisticated debris coolability code CORQUENCH (Reference 16). CORQUENCH models a broad range of MCCI and debris coolability phenomena, including:

a. Stress-induced cracking of the upper crust and water ingression

b. Melt eruption due to debris entrainment by offgas produced from the decomposition of concrete

c. Particle bed formation due to melt eruption and jet breakup during debris relocation after vessel failure

d. Formation of stable crust bridges that prevent water contact with molten debris

~~Analysis of MCCI in a flooded reactor cavity and reactor cavity sump is first performed using CORQUENCH for a conservative LBLOCA sequence with early relocation of 100 percent of the core inventory into the reactor vessel cavity. The results of this analysis are then used to tune the model parameters in the MAAP.~~ MAAP is then used to analyze the progression of MCCI in the reactor cavity for several of the most likely core damage

Replace this text with the text “A” in the next page

A

Initial jet breakup is the phenomenon occurring when a corium jet flows from the vessel into a deep water pool. Corium particles are stripped off from the corium jet due to the Kelvin-Helmholtz instability at the vapor/liquid interface. These particles can eventually settle on top of the upper crust of corium pool, forming a layer referred to as the particle bed. As a result of this process, the mass of the molten corium pool can be significantly reduced, making the MCCI less severe.

The model in MAAP 4.0.8 evaluates the heat transfer and oxidation of metal during the process of the initial jet breakup. However, it does not simulate the formation of the particle bed on top of the upper crust. MAAP 4.0.8 assumes that the particles formed during the initial jet breakup are promptly merged into the corium pool. The rate of mass stripping from a jet is calculated using a formulation similar to the Ricou-Spalding model with model parameter ENT0C. ENT0C is a coefficient multiplier to the total mass of stripped particles (the higher the coefficient, the larger the fraction is).

Water ingression is the phenomenon occurring once corium is fully settled on the cavity floor. As the corium is covered by water, the large heat removal from the top surface can produce a thick upper crust. The heat removal rate by water in this configuration far exceeds the maximum conduction heat transfer rate through the upper crust layer, if the layer were assumed to be continuous and impermeable. The upper crust is not a continuous, impermeable layer; instead, numerous deep cracks develop, as the solidified corium in the upper crust is subjected to a large temperature gradient. Water can ingress (infiltrate) into the corium through these cracks, contacting the hotter region of the corium. As the solidification progresses, both the temperature gradient and the cracks extend deeper into the corium pool.

MAAP 4.08 does not simulate the water ingression, mechanically. Instead, MAAP 4.0.8 models water ingression by assuming the heat flux from a corium pool to its overlying water is prescribed by the critical heat flux, or higher, because water always ingress into the hot region in the corium. The heat flux formulation is affected by model parameter FCHF. Parameter FCHF is the Kutateladze number for corium to water heat transfer, which controls the magnitude of the heat flux.

The results of the CORQUENCH calculations were used to tune the MAAP model parameters ENT0C and FCHF for the purposes of MCCI analysis. ENT0C was set to a low value in order to effectively disable heat transfer between corium and water as corium is relocating out of the vessel and into the pool of water in the reactor cavity. This results in more corium reaching the concrete at high temperature, which increases the calculated ablation depth. FCHF was tuned so that the reactor cavity ablation depth predicted by MAAP 4.0.8 is approximately the same as the reactor cavity ablation depth predicted by CORQUENCH for a conservative Large LOCA sequence with full core relocation into the reactor cavity.

sequences as well as a LBLOCA sequence. Each sequence is run with a flooded reactor cavity.

Debris coolability in the sump is evaluated using CORQUENCH for a conservative LBLOCA sequence.

19.2.3.3.3.3 Analysis Result

The corium in the APR1400 reactor cavity is quenched, and the integrity of containment liners is maintained when the CFS is available, based on the analyses presented in this subsection. This is due to the ample corium spreading area in the reactor cavity, which allows for sufficient heat transfer from the corium pool into the overlying pool of water and thus prevents the ablation front from reaching the containment liner plate.

19.2.3.3.3.3.1 CORQUENCH Result for MCCI in the Reactor Cavity

For the MCCI analysis in the reactor cavity, the conservative large-break LOCA (LBLOCA) scenario is calculated by CORQUENCH. This sequence conservatively assumes early relocation of 100 percent of the core inventory into the containment and that no jet breakup occurs when the core debris relocates into the flooded reactor cavity. The depth of concrete ablation in the reactor cavity for the conservative LBLOCA scenario was predicted to be 0.27 m (0.86 ft) by CORQUENCH.

19.2.3.3.3.3.2 CORQUENCH Results for MCCI in the Reactor Cavity Sump

The limiting case for MCCI analysis is large-break LOCA with 100 percent core relocation into the reactor cavity. For the large-break LOCA scenario, corium is predicted to be quenched in the reactor cavity sump before the depth of concrete ablation reaches the buried containment liner. This sequence conservatively assumes early relocation of 100 percent of the core inventory into the containment.

19.2.3.3.3.3.3 MAAP Results for MCCI in the Reactor Cavity

~~The largest amount of concrete erosion in the reactor cavity is predicted to occur for the large-break LOCA scenario. This scenario models a large-break LOCA with MAAP~~

~~predicting early vessel failure and some debris retained in the reactor vessel lower plenum. Figures 19.2.3-7 through 19.2.3-11 show the ablation depth in the floor and sidewall. MAAP predicts an ablation depth of 0.24 m (0.79 ft). The final ablation depth is well short of the 0.91 m depth of the containment liner embedded in the reactor cavity.~~ Figure 19.2.3-12 shows the containment pressure. The containment pressure remains below the 8.7 kg/cm^2 (123.7 psia) for 24 hours following the onset of core damage. The basis of pressure 8.7 kg/cm^2 (123.7 psia) is described in Subsection 19.2.4.2.1.

19.2.3.3.4 High-Pressure Melt Ejection and Direct Containment Heating

Accident initiators such as station blackout, loss of feedwater, and small-break LOCA can result in core melt and reactor vessel failure at high pressures. If the reactor vessel fails while the reactor coolant system is still pressurized, particulate core debris can be entrained from the reactor cavity by gas flows and transported directly into the upper containment atmosphere. This can result in a rapid temperature and pressure increase in containment by directly transferring the heat from the core debris into the containment gas space. This process is referred to as direct containment heating (DCH), and the core debris ejection process following reactor vessel failure at high pressure is called high-pressure melt ejection (HPME).

The DCH phenomenon is investigated by looking at three distinct areas: debris entrainment in the reactor cavity, debris de-entrainment in the lower containment compartments, and impacts of debris that reaches the upper containment compartments. Once the reactor vessel fails, core debris is discharged into the reactor cavity. As the reactor vessel depressurizes, high-velocity gas flows fragment and entrain debris from the corium pool. The fragmented debris particles can be dispersed into different areas of containment. During this transport process, a large portion of the entrained debris particles are de-entrained during sharp turns in the flow and are contained in the lower containment compartments. The fraction of core debris that is transported into the upper compartments can interact with the containment atmosphere, resulting in rapid temperature and pressure increases by rapid heat transfer. In addition, metallic constituents of the ejected material, principally zirconium and steel, can exothermically react with oxygen and steam to generate chemical energy and (in reactions with steam) hydrogen. Together with hydrogen combustion, this process can impose additional loads on the containment.

Figures 19.2.3-7 through 19.2.3-11 show the ablation depth in the floor and sidewall according to the selected sequences. MAAP predicts the largest amount of concrete erosion in the reactor cavity of 0.24 m (0.79 ft) for the large-break LOCA scenario, as shown in Figure 19.2.3-11. This scenario models a large-break LOCA with MAAP predicting early vessel failure and some debris retained in the reactor vessel lower plenum. The final ablation depth is well short of the 0.91 m depth of the containment liner embedded in the reactor cavity.