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MDEP Technical Report TR-APR1400-03

APR1400 Working Group activities

Technical Report on the findings of the review of the Molten Core Concrete Interaction (MCCI) phenomena for the APR1400

Participation

Regulators involved in the MDEP working group discussions:	KINS (South Korea), FANR (United Arab Emirates) and US NRC (United States)
Regulators which support the present report:	KINS (South Korea), FANR (United Arab Emirates) and US NRC (United States)
Regulators with no objection:	-
Regulators which disagree:	-
Compatible with existing IAEA related documents:	Yes

Table of Contents

List Of Figures

List of Tables

1. Introduction

Molten core-concrete interaction (MCCI) is a severe accident phenomenon which may occur after melted core material (corium) is released from the Reactor Vessel (RV) into the reactor cavity. The interaction involves melting and decomposition of concrete, chemical reaction between concrete and corium, and heat transfer from corium to its surroundings. MCCI can potentially cause significant concrete erosion which may threaten the ability of the containment to retain fission products.

MCCI can potentially cause:

a) a large amount of non-condensable and flammable gas to be released by concrete decomposition;
b) a large amount of heat due to the chemical reactions between the corium and materials and/or off-gases released from the concrete;
c) fission product release from the corium to the containment atmosphere; and
d) significant concrete erosion.

If there is sufficient water in the reactor cavity, the water pool can cool the underlying corium and also scrub (remove a portion of) the released fission products. MCCI in a flooded reactor cavity is therefore generally less severe than MCCI in a dry cavity. However, heat transfer from corium to water can potentially generate a large amount of steam, which represents another source of containment pressurization in addition to non-condensable gas. In order to ensure that the necessary regulatory criteria are satisfied, it is crucial to assess the potential consequences of MCCI and any associated threats to containment integrity.

Two important mechanisms associated with water cooling of corium in a reactor cavity are water ingression and melt eruption. These mechanisms influence the coolability (quenching) of the core debris, and thus by extension impact the extent of concrete ablation. Water ingression relates to the ability of water to penetrate into cracks in the corium crust. Melt eruption refers to the entrainment of corium particles as off-gas bubbles up through a corium pool. The accumulated particulate debris is much easier to cool than a continuous corium bed.

2. APR1400 Reactor Cavity Design

The APR1400 reactor cavity has been designed to maximize the unobstructed floor area available for the corium debris to flow and spread out. The reactor cavity floor is free from obstructions and provides an area for corium debris spreading (see Figure 1). Uniform distribution of 100% of the corium debris within the reactor cavity results in a relatively shallow debris bed of approximately 30 cm. The containment steel liner is adequately embedded in concrete in the reactor cavity area to preclude direct contact of core debris with the containment basemat. The steel liner is embedded 0.914 m (3 feet) below the cavity floor. An additional 3.353 m (11 feet) of concrete is provided below the liner with the exception of the area under the reactor cavity sump where 2.134 m (7 feet) of concrete is provided below the liner.

The reactor cavity is designed to satisfy the Korean User Requirements Document (KURD) requirement related to the minimum distance between the floor elevation and the embedded portion of the containment steel liner of 0.914 m (3 ft.). In addition, the cavity floor area of 80,36 m^2 (866 ft^2) results in a floor area/reactor thermal power ratio of 0.0201 m^2/MWt which is slightly larger than the KURD requirement of 0.02 m^2/MWt.

The containment steel liner is adequately embedded in concrete in the reactor cavity area to preclude direct contact of core debris with the containment shell. While both U.A.E and U.S. designs have a minimum of 0.914 m (3 ft) thick limestone or limestone-common sand concrete layer above the containment liner, the Korean design has a minimum of 1.22 m (4 ft) thick concrete layer (1 ft thick limestone concrete layer over a 3-foot-thick basaltic concrete layer).

The CFS passively supplies water from the IRWST after the manual opening of motor-operated valves installed between the IRWST and HVT and between the HVT and the reactor cavity. Actuation of the CFS can provide flooding up to 6.4 m (21 ft) above the reactor cavity floor (elevation 69 ft. 0 in) thus enabling cooling of core debris if it is spread on the reactor cavity floor and scrubbing of fission products released to the containment atmosphere.

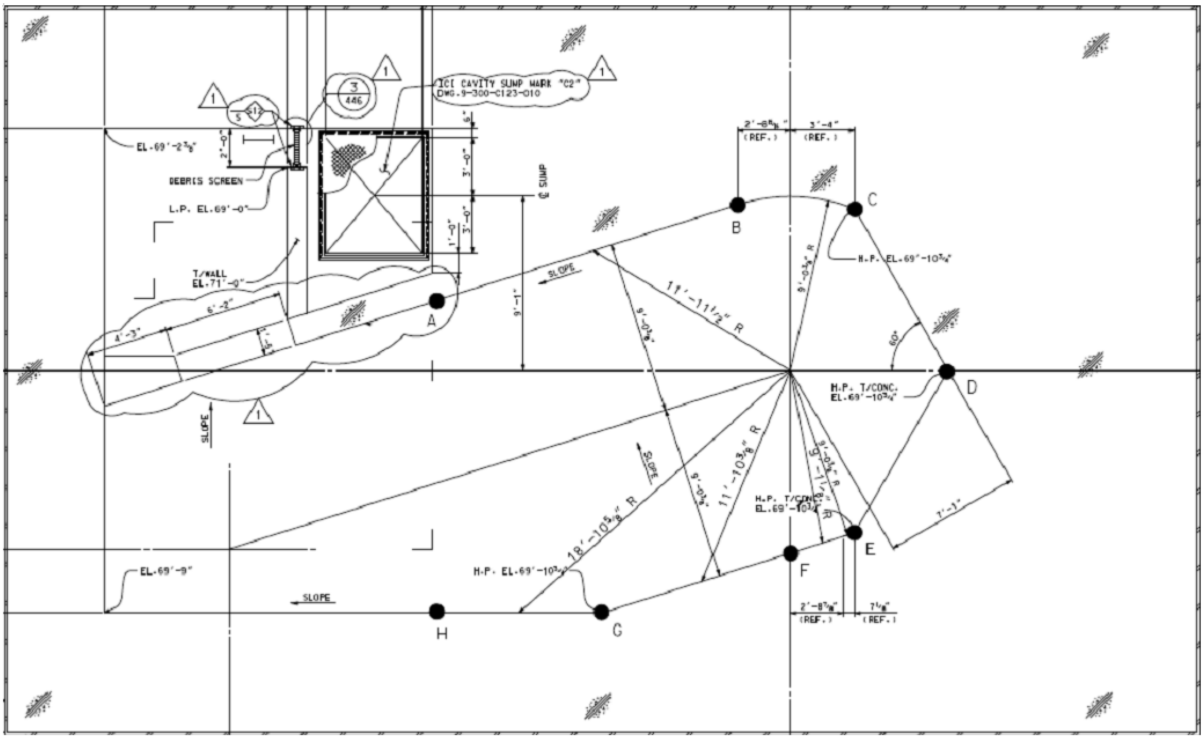

Figure 1: Plan View of the APR1400 Reactor Cavity

3. Regulatory review of APR1400 MCCI Submissions

3.1 FANR review of ENEC submission

The Construction License Application (CLA) for Barakah Nuclear Power Plant (BNPP) Units 1 and 2 was provided for FANR review on 27 December 2010. The application contained a Preliminary Safety Analysis Report (PSAR), Section 19.2 of which included a brief introduction to the severe accident evaluation. Severe accident aspects were addressed in more detail in a Severe Accident Analysis Report (SAAR) submitted six (6) months after submittal of the PSAR. This information was supplemented by information in the SAAR Rev 2 which was submitted in March 2013, in SAAR Rev 5 that was submitted in November 2013 and a document containing the MCCI analysis performed using the MAAP 5.02 code in August 2014.

The SAAR describes design features for prevention of severe accidents that include, but are not limited to, anticipated transients without scram (ATWS), mid-loop operation events, station blackout (SBO), fire, and intersystem loss-of-coolant accidents (ISLOCA). Examples of the documented design features include, but are not limited to, a diverse protection system for initiation of reactor trip and auxiliary feedwater during an ATWS, redundant shutdown cooling system (SCS) trains and redundant instrumentation to monitor reactor coolant water inventory for prevention of mid-loop operation events. Additionally, provisions include two emergency diesel generators and an AAC power source, as well as battery backup capable of supporting essential safety system loads for sixteen hours.

The SAAR documents plant mitigation features that include containment design, cavity flooding system, hydrogen mitigation system, safety depressurization and vent system, cavity design, and an emergency containment spray backup system. In addition, the SAAR provides severe accident analyses in support of the adopted severe accident management strategy.

The SAAR makes the claim that the USNRC SECY-93-087 document is used as a key basis for severe accident mitigation design features and evaluations and it also meets FANR regulatory requirements.

With regard to the review of the MCCI analysis, a significant finding of the review of the SAAR Rev 0 indicated that the applicant had used a modified version of the MELCOR code for the performance of the analysis for which there was inadequate validation information. In addition, the material intended for use in the containment basemat of the Barakah units differed to that assumed in the analysis. FANR performed a confirmatory analysis for the base event identified by the applicant using a validated code and the proposed containment material to demonstrate that FANR regulatory requirements would be met for at least the first 24 hours. The results of this analysis and the commitment of the applicant to perform a complete re-analysis of the severe accident phenomena using the Barakah specific material properties within six months after the issue of the construction license provided a reasonable assurance that FANR regulatory requirements would be met, and supported the commencement of construction activities for BNPP Units 1 and 2. At that time 15 conditional acceptance items, 9 of which were related to MCCI or its effects, remained to be addressed in the revision to the SAAR. The FANR review of the SAAR Rev 0 indicated that should siliceous concrete be used for the reactor cavity basemat construction, the

MCCI phenomena would in all likelihood result in failure of the containment integrity at some period during the progression of those severe accidents presented. In some cases the containment liner was breached within a 72 hour period, in the majority of all other cases, the basemat ablation due to MCCI continued unabated at the end of the analysis period. The confirmatory analyses performed by FANR, with the limestone based concrete proposed for the Barakah units, indicated that containment integrity could be maintained with basemat ablation terminating prior to contact with the containment liner. The lower rates of ablation of limestone based concretes is attributed to the combined effects of the higher heat of decomposition and higher decomposition temperature of limestone based concretes when compared to siliceous concretes.

During the course of the revision to the SAAR the applicant requested an extension to the delivery date of the document in order to address the identified issues. This extension was granted by FANR and SAAR Rev 2 was provided in March 2013. The review indicated that in response to FANR review comments the applicant had revised the methodology related to analysis of MCCI. The review also indicated that 9 of the 15 conditional acceptance items had not been addressed in the submission, 6 of these 9 were related to MCCI or its effects. It was observed that the revised report contained numerous other quality and consistency issues. In June 2013 the FANR review of the SAAR Rev 2 was suspended to allow the applicant the opportunity to address the outstanding conditional acceptance items. At the time of suspension an additional 24 requests for additional information had been raised on the revised submission.

The technical review of the updated submission containing the SAAR Rev 5 was commenced in January 2014. The review was started after confirming that all previously identified commitments had been incorporated in the submission. The review indicated further revisions to the methodology employed in the analysis, these changes initiated primarily in response to FANR review comments. Review comments on the SAAR Rev 5 included inconsistencies in input assumptions, inadequate justification of the analytical tools used, and incorrect validation calculations, and further requests for additional information were initiated. The review of the information supplied indicated that the code used in the analysis under-predicted the MCCI effect by approximately 50% and that in the base case selected by the applicant, the containment integrity is compromised within 62 hours of the event initiation. Approximately 60% of the cases presented in the uncertainty analysis indicated a threat to the containment integrity in the longer term i.e. after 24 hours. The analysis presented by the applicant indicated that FANR requirements related to containment performance were not met.

The Molten Core Concrete Interaction (MCCI) and its effect on the performance of the containment had been an unresolved issue since it was first identified during the review of ENECs submission of the Severe Accident Analysis Report (SAAR) in support of the BNPP Unit 1 and 2 Construction License Application in June 2011. Subsequent reviews of revisions of the SAAR submitted in March 2013 and December 2013, and supporting information supplied in response to Requests for Additional Information (RAIs) developed during these reviews, had failed to resolve the outstanding issues related to the MCCI analysis. These submissions had been performed using various versions of the MELCOR code. MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light-water reactors. On 23 July 2014 FANR were informed that ENEC had some difficulty meeting FANR regulatory requirements using the MELCOR code and that a new safety case using the Modular Accident Analysis Program (MAAP) code, version 5.02 was to be submitted to FANR. MAAP has been used as a tool for severe accident analysis and associated severe accident phenomena, which includes molten core concrete interactions for over 20 years.

On 20 August 2014 ENEC submitted a MCCI analysis using the MAAP5.02 code to support closure of the MCCI issue for BNPP Unit 3 and 4 Construction License Application. FANR review of this analysis is described below.

3.1.1 FANR Regulatory Basis

FANR Regulations (REG) establish requirements that the applicant/licensee must comply with. Regulatory Guides (RGs) are issued to describe methods and/ or criteria acceptable to FANR for meeting and implementing specific requirements in FANR regulations. Regulatory Guides are not substitutes for regulations, as compliance with Regulatory Guides is not mandatory. Methods of complying with the requirements in regulations that differ from the guidance set forth by the Regulatory Guide may be acceptable if assurance is provided that the requirements are met. The following FANR regulatory requirements were considered to be directly applicable to the review of the submission:

FANR-REG-03, Article (24) 1.d)

States that the NPP design shall take into account "*provisions for mitigation of molten core debris concrete interaction*" (MCCI).

FANR-REG-03, Article (44) 2

Requires that "*The computer programmes, analytical methods and plant models used in the Safety analysis shall be verified and validated, and consideration shall be given to uncertainties*."

FANR-REG-03, Article (60) 2

Requires that "*provisions for maintaining the integrity of the containment in the event of a possible severe accident shall be considered.*"

FANR-RG-004 Article (12) 3.d) and Article (12) 3.f)

Article (12) provides additional guidance on the criteria acceptable to FANR for implementing the regulations as follows.

3.d) Core Debris-Concrete Interaction
In the event of a Severe Accident in which the core has melted through the reactor vessel, it is possible that Containment integrity could be breached if the molten core is not sufficiently cooled. In addition, interactions between the core debris and concrete could

generate large quantities of additional hydrogen and other non-condensable gases, which could contribute to the eventual overpressure failure of the Containment. Downward erosion of the basemat concrete could also lead to basemat penetration with the potential for ground water contamination and subsequent discharge of radionuclides to the surface environment. Thermal attack by molten corium on retaining sidewalls could produce structural failure within the Containment causing damage to vital systems and perhaps to failure of Containment boundary. Therefore, the applicant/licensee should assess a) reactor cavity floor space to ensure adequate area for debris spreading; b)means to flood the reactor cavity to assist in the cooling process; and c) impact of core concrete interaction with cavity walls on the Containment integrity.

3.f) Containment Performance under Severe Accident Conditions
The Containment should be designed to have a high probability of withstanding the loads associated with Severe Accident phenomena. This should be done by demonstrating that the Containment will maintain its role as a reliable, low leakage barrier for approximately 24 hours following the onset of core melt accident. After 24 hours, releases from the containment should be controlled or ensure that a containment failure probability of 0.1 is achieved.

3.1.2 ENEC Submission

The submission of the August 2014 MCCI analysis contained a report of 5 sections and 5 Appendices.
Appendices A to D contained explanations of the models and benchmarks for MAAP5.02 models.
Appendix E contained plots of the MAAP output data for all analysed sequences.
The following is a summary of the content of the various sections:

Section 1.0

> The section contained a description of the FANR regulations related to severe accident applicable to the analysis. The section also included a description of USNRC guidance related to severe accidents, general methodology of the MCCI analysis and a brief overview of the MAAP code.

Section 2.0

> This section contained the summary of all 13 cases considered in the analysis and indicated that the maximum concrete erosion in the cavity was 19.7 cm, and in the cavity sump 68 cm. The conclusion made was that the integrity of the containment liner would not be challenged by core concrete attack and it would remain intact under severe accident conditions and the result was in compliance with FANR Regulations.

Section 3.0

This section contained a review of the MAAP MCCI model including; an evaluation of the corium thermal properties, concrete-corium chemical reactions, corium structure and thermal hydraulics and concrete ablation. The coolability model included the treatment of water ingression and particle bed formation caused by both jet break-up and melt eruption. The section concluded with a chapter on the benchmarking of the MCCI and coolability models.

Section 4.0

This section contained a justification for the selection of the best estimate/realistic scenario and the assumptions used in the analysis. The key modelling assumptions were described and the selection and range of the parameters used in the uncertainty analysis were provided.

Section 5.0

This section contained the discussion on the results of the analyses and provided detailed figures related to what was considered the more likely sensitivity case. In addition, the section contained a brief discussion on the results of the other sensitivity cases.

3.1.3 FANR Review Comments

Section 1.0

The regulatory requirements related to the performance of the containment in severe accident conditions were appropriately identified. The general methodology related to the MCCI analysis and the discussion related to the incorporation of the water ingression and melt eruption models in the MAAP code were clear and adequately described the application of the code to the analysis in the sections that followed.

Section 2.0

Information in this section indicated that:

For the Cavity Floor - Core debris on the cavity floor is quenched and solidified without challenging the containment boundary. Ablation of the cavity floor terminates with little concrete having been eroded.

For the Cavity Sump - The calculations with BNPP-specific concrete predicted that concrete erosion is stopped well before reaching the containment liner.

These conclusions were supported by a summary of the calculation results which demonstrated that the maximum concrete erosion in the cavity is 19.7 cm, and in the cavity sump 68 cm. In all but one cases analysed, the concrete ablation in the reactor cavity sump is significantly greater than that in the reactor cavity. This is to be expected given that the relative mass of corium to floor surface area in the reactor cavity sump is approximately six times greater than that of the reactor cavity. This ratio is important in the calculation of concrete ablation. The only case where the reactor cavity concrete erosion was greater than the reactor cavity sump concrete erosion was the sensitivity case where the effective corium spreading area is reduced, in this case no corium reaches the reactor cavity sump. These results tended to indicate that the analysis related to the reactor cavity sump is the most significant when assessing compliance to FANR regulatory requirements.

Since the leak tight containment liner is embedded in 90 cm of concrete, the results indicated that there is a minimum of 25 % margin of un-eroded concrete to the depth of the liner, and to the point where containment integrity would be challenged, and thus the results of the analysis met the FANR regulatory requirements.

Section 3.0

Information contained in this section and Appendix A, MCCI Model in MAAP5.02, adequately described the assumptions made in the MCCI model to simplify the complexity of the processes within the code. These assumptions were consistent with assumptions previously reviewed by FANR.

The discussion in this section, supplemented by that in Appendix B – Coolability Model in MAAP5.02, described the enhancements made to the MAAP code to reflect the latest information on the melt ingression and particle bed formation phenomena. These phenomena had been observed in the numerous experiments related to ex-vessel severe accident progression and numerical models have been developed to reflect these phenomena. The discussion was comprehensive and included appropriate references to support the numerical solutions proposed.

This section discussed the benchmarking of the code against both wet and dry MCCI tests.

Section 4.0

The best estimate/realistic scenario selected for analysis was the station blackout (SBO). The selection was based on the event with the highest contribution to the core damage frequency (CDF). The Level 1 internal events at power PRA available at the time was reviewed and this assumption was considered acceptable.

In the SBO scenario the a.c. power is not recovered and heat removal from the primary circuit is via the turbine driven auxiliary feedwater pumps (TDAFPs) and the main steam safety valves (MSSV). At 16 hours the d.c. battery power supplying the TDAFPs is exhausted and the pumps would stop supplying feedwater. Prior to d.c. battery exhaustion the primary pilot-operated safety relief valves (POSRVs) are opened. The opening of the POSRVs results in a loss of primary inventory, core uncovery, core melt with eventual corium relocation into the lower plenum of the reactor pressure vessel (RPV). The RPV is expected to fail when the weld material of one of the penetrations in the bottom of the RPV is melted and the penetration is ejected into the reactor cavity. Corium material is then released into a flooded cavity. This sequence of events was considered acceptable as the best estimate/realistic response of the plant to this accident. Table 1 provides some description of the accident progression and associated assumptions.

Table 1. Accident progression and description of Accident Scenario Analysed

No.	Accident Progression	Descriptions
1	Multi-unit SBO initiator	Multi-unit SBO is initiated by a multi-unit loss of offsite power coupled with the concurrent failure of both EDGs to supply power to their associated Class 1E 4.16 kV buses. • Success criteria in PRA: One of the EDGs successfully operates in all of the other units • Assumption in SA Analysis: AC power is not available
2	No SBO in any other units except plant under analysis	
3	Failure of Alternative a.c.(AAC) Diesel Generator (DG)	If AAC DG is not used by any other plant after multiple-unit LOOP, the AAC DG can be loaded onto class 1E 4.16 kV buses so that the safety equipment can be supplied with power. • Success criteria in PRA: Successful connection of AAC DG to any Class 1E 4.16kV division • Assumption in SA Analysis: AC power is not available. DC batteries are available
4	Success of initial secondary heat removal using TDAFP	In order to remove decay heat from the RCS, secondary heat removal will be established by feeding the SGs (Steam Generators) using the AFW system and relieving steam with one ADV or MSSV. • Success criteria: At least one TDAFP delivers flow to a SG and at least one (1) ADV or MSSV removes steam • Assumption in SA Analysis: One TDAFP is available
5	Success of RCP seal integrity	During a SBO, RCP seal LOCA (Loss of Coolant Accident) may occur if both seal injection and seal cooling are unavailable due to AAC failure. • Success criteria: Probability of RCP seal LOCA • Assumption in SA Analysis: No RCP seal LOCA
6	Success of DC load shedding to extend battery life up to 16 hours	Although mobile DG and EDG crosstie fail to provide AC power to the class 1E 4.16kV buses, the secondary heat removal using one TDAFP can be maintained with successful DC load shedding. Since DC power (from battery) is available for a design basis 2 hours without DC load shedding, successful DC battery load shedding makes it possible to extend the battery lifetime from 8 hours up to 16 hours. • Success criteria: Load shedding for Class 1E batteries C and (or) D within 2 hours to extend its life time up to 16 hours. • Assumption in SA Analysis: One TDAFP is available only for 16 hours

The molten jet of corium may partially or completely break-up and turn into small particles as it travels through the cavity water pool. The quantity of particles generated depends on the jet velocity, the pool depth, and the MAAP input parameter for the jet entrainment coefficient. When the best estimate/realistic value of the jet entrainment coefficient is used in the analysis, most of the molten jet is entrained into the water pool and converted into small particles. This configuration allows for enhanced heat transfer between the debris jet and the water pool due to the increase in surface area. Because of this, the initial corium pool temperature will be low and there will be approximately 1.4 cm of erosion in the cavity and no erosion in the cavity sump. The arguments provided are reasonable but there are uncertainties associated with this best estimate/realistic case. To cater for these uncertainties, additional cases are analysed with combinations of assumptions:

- Assuming no heat removal from jet break-up (increases the temperature of the corium in the cavity),
- Assuming total RPV failure rather than penetration failure (increases the mass of corium initially released),
- Assuming thermal conductivity related to the average corium composition rather than that of oxides (reduces the heat transfer to the overlying pool),
- Assuming the corium surface area is increasing (increases surface area in contact with overlying pool),
- Assuming the melt eruption coefficient decreases (decrease the amount of corium erupted into overlying pool),
- Assuming a reduced erupted particle size (smaller particles result in a reduced critical heat flux),
- Assuming a reduced melting temperature of concrete (reduction in temperature should result in greater MCCI),
- Assuming a reduced heat transfer coefficient (reduces heat transfer into the crusts),
- Assuming a lower energy required to decompose concrete (should result in greater MCCI),
- Assuming a reduced corium spreading area (concentrates the corium in a confined area).

The assumptions and variability in the sensitivity parameters was explained and considered adequate to cater for the uncertainties.

Section 5.0

The results for the 13 cases analysed were presented in this section, the figures associated with the results, with the exception of the most likely sensitivity case which was presented in this section, were presented in Appendix E. The explanation of the results was considered adequate. Table 2 presents a summary of the analysis results and assumptions.

For the best estimate case cavity erosion was approximately 1.4 cm and no erosion occurred in the cavity sump because the intensive cooling by jet breakup and particle bed generation lowered the average corium temperature in the reactor cavity below the concrete melting temperature very quickly.

The maximum erosion calculated in the cavity for all the sequences was 0.197 m. This was associated with the case with the limited corium spreading area.

The maximum erosion calculated in the cavity sump for all the sequences was 0.68 m. This was associated with the case where the reactor pressure vessel fails extensively resulting in rapid release of corium into the cavity. The entrainment coefficient for melt eruption is at its lower sensitivity value, resulting in less heat removal by melt eruption, and, assuming the average thermal conductivity for the corium which reduces the heat transfer to the overlying pool.

The variation in the ablation depths for the cavity and cavity sump were considered reasonable given the description of the various models in the MAAP5.02 code.

Table 2. Summary of Results for BNPP MCCI Studies

Case No.	Jet Breakup at Vessel Failure (V.F.)	Particle Bed Formation due to Jet Breakup	Thermal Conductivity Used for Water Ingress.	Corium Top Surface Area in Sump	Entrainment Coefficient for Melt Eruption	Particle Diameter due to Melt Eruption (mm)	Melting Temp. of Concrete (K)	Forced Extensive Vessel Failure	Heat Transfer Coefficient (melt pool to crusts)	Energy required to melt concrete	Note	Cavity Ablation Depth (m)	Cavity Sump Ablation Depth (m)
1	Yes	Yes	Oxide	Increasing	0.08	4	1813	No	Default[1]	Default[2]	Best Estimate (B.E.) Case	0.0137	0
2	No	No	Average	Constant	0.08	4	1813	No	Default	Default	B.E + No J.B. + Avg. thermal conduct + Const. top area.	0.0175	0.564
3	No	No	Oxide	Constant	0.08	4	1813	No	Default	Default	Case 2 + Oxide thermal Cond.	0.0393	0.512
4	No	No	Oxide	Constant	0.08	2	1813	No	Default	Default	Case 3 + 2 mm particle diameter	0.0395	0.512
5	No	No	Oxide	Constant	0.08	4	1632 (10% Reduction)	No	Default	Default	Case 3 + 10% less Melting Temp.	0.0249	0.518
6	No	No	Oxide	Constant	0.08	4	1813	Yes	Default	Default	Case 3 + Forced Extensive V.F.	0.0672	0.511
7	No	No	Oxide	Constant	0.08	4	1813	No	Constant h=300	Default	Case 3 + Const. h=300 (w/m^2K)	0.0412	0.465
8	No	No	Oxide	Constant	0.064 (20% reduction)	4	1813	No	Default	Default	Case 3 + 20% Less Entrain. Coeff.	0.043	0.619
9	No	No	Oxide	Constant	0.064	4	1813	Yes	Default	Default	Case 8 + Forced Extensive V.F.	0.0726	0.619
10	No	No	Oxide	Constant	0.08	4	1813	No	Default	10% reduction	Case 3 + 10% Less Conc. Melt. Energ.	0.0255	0.503
11	No	No	Average	Constant	0.064	4	1813	Yes	Default	Default	Case 9 + Avg. Thermal Conduc.	0.0225	0.68
12	No	No	Average	Increasing	0.064	4	1813	Yes	Default	Default	Case 11 + Incr. top area	0.0228	0.196
13	No	No	Oxide	Corium is only	0.08	4	1813	No	Default	Default	Case 3 + smaller area[3]	0.197	0

				in cavity.							in cavity		

3.1.4 FANR Conclusions from the Review

FANR concluded that:

- The provision of the 90 cm of concrete above the leak tight liner of the containment is a provision to mitigate the effects of molten core debris concrete interaction and thus considered to meet the requirements of FANR-REG-03 Article (24) item 1 d. and Article (60) 2.
- The best estimate/realistic scenario, the SBO, had been identified for analysis based on the contribution to CDF. This was considered acceptable.
- The integrated analysis of the scenario was performed using the MAAP5.02 code which contained new models for water ingression into, and melt eruption through, the corium crust.
- The base case selected for the analysis assumed jet breakup as the corium drops through the flooded cavity and the formation of a particle bed on the cavity floor. The justification for this assumption was documented and considered acceptable.
- To address uncertainties in the phenomena and code modelling, the analysis included an additional 12 sensitivity cases. The assumptions and variability in the sensitivity parameters was explained and considered adequate to cater for the uncertainties.
- All 13 cases indicated that the corium will stabilise in the cavity and cavity sump prior to reaching the containment liner, with a minimum margin of 22 cm. The average margin of the 11 cases with cavity sump ablation was 43 cm corresponding to 47% of the total concrete depth to the liner. These results were considered adequate to demonstrate compliance with FANR-RG-004 Article (12) 3.d) and Article (12) 3.f).
- The variation in the ablation depths for the cavity and cavity sump were considered reasonable given the description of the various models in the MAAP5.02 code.
- The official MAAP benchmarking document for MCCI did not include any calculations using MAAP5.02. Appendix C of the report excerpted from the MAAP5 user’s manual volume 3 MCCI benchmarks, had been calculated with a previous version of MAAP5 and its applicability to MAAP5.02 was uncertain. Appendix D was the only documentation available related to the validation of the wet MCCI experiments against the MAAP5.02 version. It was recognised that limited benchmarking information is available and there is a fair degree of uncertainty associated with the results, however the demonstration of the validity of the code should have been performed with the version of the code that was used in the BNPP safety analysis in order to establish full compliance with FANR-REG-03 Article (44) 2. This outstanding item

was addressed by the applicant in response to an RAI and the validity of the analysis code was considered adequate to support the construction license.

3.2 KINS review of KHNP submission

3.2.1 KINS Regulatory Basis

In Korea there are no legally binding regulatory requirements related to Molten Corium Concrete Interaction (MCCI) during severe accident conditions. Since the declaration of "policy statement on severe accident for Korean NPPs" by Ministry of Science and Technology in 2001, *de facto*, preventive and mitigation features against severe accident has been in place during design and operation process. Chapter 16 of KINS/RS-N16.00 "*Regulatory standards and guidelines for PWR in Korea*" (in Korean) provides detailed guidelines for the assessment of severe accident and associated risk. KINS/RS-N16.00 is endorsed by the aforementioned policy statement.

It is recommended that design should demonstrate to secure the integrity of containment and limit radiological release within acceptable level against following considerable threats.

Section 16.1.II.1 "Designing the capability of countering severe accident"
Securing the capability and functionality of containment is critical to limit any undesirable radiological release due to a severe accident. Containment should be designed systematically to eliminate threats that may breach containment during severe accidents, or, the capability and functionality of containment should be demonstrated to be adequate to cope with target threats. Containment should limit radiological release with minimizing required emergency response action as practicable as low. Related to the aforementioned design provision for coping with severe accidents, provision "d" addressed a recommendation for mitigating MCCI:

Provision d.
The threats to the integrity of containment caused from melting-through of basement concrete of containment structures or over-pressure due to non-condensable gases generated during MCCI process.

Section 16.1.II.2 "Deployment of counter measures for severe accidents"
The counter measures against severe accident should be taken into consideration in design or should be demonstrated to be adequate to mitigate the consequences while reflecting the following aspects:

Provision e.
It is required to cool down core melt by making use of methods such as designing the large floor area of reactor cavity for facilitating dispersion and cooling of the core melt to response against of reactor cavity concrete and generation of non-condensable gases by reaction of core melt and concrete at reactor cavity after rupture of reactor vessel.

It is required to keep integrity of containment building intact by satisfying Class C acceptable operating limit or acceptable factored load category of the Korea Electric power Industry Code for at least 24 hours after core damage accident under the conditions of pressure and temperature elevation by reaction of core melt and concrete. Containment building shall keep margin enough for accommodating uncertainty by reaction of core melt and concrete.

Provision f.
Integrity of containment building shall be protected from pressure and temperature elevation by reaction of core melt and coolant outside the reactor vessel, or impact from steam explosion or missile.

Provision g.
As for the requirement defined in subparagraphs e and f above, containment building shall keep the barrier function for responding against release of uncontrollable fission products after 24 hours of core damage accident.

3.2.2 KHNP Submission

3.2.2.1 Analysis Methodology

In November of 2011, KHNP provided a series of analyses result associated with MCCI, using MAAP 4.06 and MELCOR 1.8.6 which addressed items arising in FSAR 6.2.7.1 (Analyses for Corium-Concrete Interaction and its cooling capability) and entitled "Integrated Report on Severe Accident" as the supplementary report to FSAR 6.2.7.1. However, the excessive concrete erosion demonstrated in the analyses failed to provide KINS reviewers with a demonstration of adequate cooling capability of the molten corium in the reactor cavity during the MCCI process. As a result of the review, KINS issued RAIs FSAR-I-6.2.7.1-1 and FSAR-II-6.2.7.1-1 related to the aforementioned issues in April 2012.

In February 2014, KHNP responded to the MCCI related RAIs and submitted the final analysis report on the phenomena of MCCI in the reactor cavity for SKN 3&4 using MAAP 5.02 code [Fauske & Associates, 2012b.] The recently introduced MAAP5.01.1146 code had major enhancements on corium pool model and water ingression model which reflected evidence derived from experiments. The major enhancement to the models applied in the new version of MAAP 5.02 code can be summarized as follows:

a) A new particle bed model was introduced for the containment corium pool. The updated particle bed concept can be characterized as additional fragmentation of molten corium with Jet-breakup and melt eruption mechanisms. These major model improvements result in a change of the geometrical configuration of the molten corium from the existing continuous corium pool with a stratified crust, to a model which reflects sedimentation of a particle bed over the upper crust of a continuous corium pool. The jet break-up mechanism, as the corium leaves the reactor vessel and flows through a flooded reactor cavity, causes additional fragmentation of the corium pool and enhances the cooling capacity by enlargement of the surface area of the corium pool.

b) The improvement of the water ingression model employed an additional decay heat generation term into the governing equation, which results in better cooling of the crust of the molten corium. The previous model had not taken into account this heat removal mechanism.

3.2.2.2 Selection of sequence of events to be analysed

Four representative event sequences were chosen for the MCCI analysis based on the frequencies of initiating events identified from the Level 1 internal events PSA and further complemented by deterministic decision making. The scenarios presented were:

- Small Break LOCA (SLOCA-23)
- Station Black Out (SBO-25)
- Total Loss of Feedwater (LOFW-17)
- Large LOCA (LLOCA-04)

KHNP provided the analyses results for the event sequences SLOCA-23, SBO-25 and LOFW-17 in Appendix B of the Integrated Severe Accident Analysis report. KHNP selected the LOCA-04 sequence as the representative sequence and carried out further sensitivity studies for the MCCI evaluation which was provided in Appendix A of the report. The LOCA-04 sequence is characterized as the core-melt sequence induced from a LBLOCA following a 10 inch pipe break (break area of 0.0465 m^2) with failure of SIT injection and fail to run of SI pumps.

3.2.2.3 Analyses Assumptions

For conservatism, the analysis assumed that only two SIT are available. Complete relocation of molten corium into the reactor cavity takes place at the same time as the breach of the reactor vessel at 7,500 sec. Relocation of molten corium into the lower plenum of the reactor vessel follows failure of the core support plate at 6,000sec. The analysis assumes the reactor vessel fails by failure of the In-Core Instrumentation (ICI) penetration.

KHNP made a design modification for reactor cavity floor to install additional blocking wall for preventing excessive intrusion of corium into the cavity sump located at lower elevation. The design modification brought about a reduction of the cavity floor area from 80 m^2 to 72 m^2. For conservatism, the area of the reactor cavity floor was assumed as 70 m^2 rather than 72 m^2 in the analysis to elevate the relocated corium height to 33 cm. The initial conditions of the molten corium in the reactor cavity were assumed as 32.5 MW of decay heat and mean temperature of 2,486 K based on the MAAP5.02 calculation. These assumptions were more conservative than the values used by KINS (27.6 MW, 2,035 K) in the confirmatory analyses which was performed with the MELCOR 1.8.6 code. It is determined that the analysis assumptions were acceptable in terms of conservatism.

3.2.2.4 Analysis Results

Table 3 summarizes the MCCI analysis results performed by KHNP using MAAP5.02 with further considerations related to the composition of concrete where an additional 30cm thick limestone concrete (SW1) layer is present over the reactor cavity floor. Cases number 1 and 2 take jet-breakup into account. Case 2 assumed a limited molten corium spreading radius of 3 m as an additional conservatism. Case 3 excluded the jet-breakup effect as a conservative assumption while molten corium is fully spread over the reactor cavity floor.

Table 3. Results of Demonstrative Analysis for MCCI with MAAP 5.02

			Results of MCCI Analysis for SW1concrete (at 28hr of Calculation Time)			
Case No.	Consideration of Jet Breakup	Spreading Area (m^2)	Depth of Erosion (cm)	Mass of Upper Crust (ton)	Mass of Particle Bed (ton)	Final Quenching Time (Hr)
1	with	70	5.1	74.4	131.3	2.75
2	with	29	21.0	60.0	151.0	3.60
3	without	70	18.8	11.95	106.7	6.17

As shown in Table 3, the results of case 1, considering the effect of Jet breakup, predicted that the concrete eroded to a depth of 5 cm and the molten corium cooled down within 3 hrs. Given the same inventory of molten corium ejected from the reactor vessel as with case 1, case 2 predicted deeper concrete erosion (21cm) and a longer quenching time (4hr) than case 1. It was considered that fragmentation of molten corium prevent fully developed spreading of corium and contributed to the delay in cooling the corium in case 2.

Case 3, without considering jet breakup, predicted 19 cm concrete erosion depth and 6 hrs to cool down the corium.

Considering the phenomenological uncertainty and conservative analysis assumptions including inventory of molten corium, decay heat, jet-breakup assumptions and limited corium spreading, the cases studied for MCCI demonstrated that MCCI would not threaten the robustness of the steel liner embedded in the basemat concrete structure.

3.2.3 KINS Review Comments

3.2.3.1 Analysis Methodology

KINS staff members reviewed the analysis methodology, analysis assumptions and code applicability in the submitted reports. The models related to MCCI incorporated in MAAP5.02 are comprised of the following detailed model elements dealing with various phenomena on discomposing concrete, formation of particle bed and water ingression due to MCCI:

- Discomposing Concrete
  - Concrete Erosion
  - Formation of crust
  - Chemical Reaction
  - Coolant effects
- Formation of particle bed and heat transfer
  - Jet break up
  - Melt eruption
- Water ingression
  - Heat conduction
  - Dry heat flux
  - Estimation of heat transfer (Wet and Dry)

KINS staff members evaluated the applicability of the models embedded into MAAP 5.0.2 by reviewing the benchmarking study FAI/14-1092, Nov. 2014. This report by FAI was based on the experimental results of the ACE, SURC, BETA and CCI tests which assessed the impact of characteristics of concrete composition, for example, CCI-2 used SLC concrete and CCI-3 used SIL concrete. While the benchmarking study was not entirely adequate to provide the reviewers full justification regarding the MCCI models, it was determined that, considering the current state-of-the-art of the assessment codes, MAAP 5.0.2 provides reasonable predictability of the depth of concrete erosion and corium configuration

3.2.3.2 Selection of sequence of events

KHNP chose four event sequences to be analysed including SLOCA-23, SBO-25 LOFW-17 and LOCA-04. As the representative sequence for the MCCI evaluation, the sequence of LOCA-04 was selected and carried out the evaluation, which is the core-melt sequence induced from a LBLOCA following a 10 inch pipe break (break area of 0.0465 m^2) with failure of SIT injection and fail to run of SI pumps.

KINS staff members assent to the selected sequence of event (LOCA-04) that provides a relatively fast accident progression, conservative decay heat of the relocated molten corium into the reactor cavity floor, and, severe consequences in terms of the magnitude of erosion of the concrete by MCCI due to the time for relocation of the molten corium into the reactor cavity.

KINS staff members concluded that the selection of event sequences to be analysed were in compliance with the regulatory position addressed in Regulatory review guidance Section. 19.2 II.2.a.

3.2.3.3 Analyses Assumptions

KINS staff member reviewed the analyses assumptions on availability of ECCS, failure mode of reactor vessel and area of cavity floor associated with the design modification of reactor cavity and initial condition of corium. KINS staff member concluded that the analysis assumptions including the availability of only two SITs, reduced area of cavity floor (70 m^2) and 32.5MW of decay heat and mean temperature of 2,486 K provide agreeable conservatism.

3.2.3.4 Analysis Results

It is consider that the fragmentation of molten corium prevent fully developed spreading of corium and contributed to the delay in cooling down of corium in case 2.

Considering the phenomenological uncertainty and conservative analysis assumptions including inventory of molten corium, decay heat, jet-breakup assumptions and limited corium spreading, the cases studied for MCCI demonstrated that MCCI would not threaten the robustness of the steel liner embedded in the basemat concrete structure.

3.2.4 KINS Conclusions from Review

KINS staff members concluded that the design of the reactor cavity at SKN 3&4 would be adequate to protect the steel liner embedded in the basemat of the containment structure, and to cool down the molten corium relocated to the reactor cavity floor taking into consideration the measures for making up cooling water into reactor cavity including cavity flooding system and the additional installation of a 30 cm limestone concrete layer in the reactor cavity and additional installation of blocking wall to prevent corium intrusion from cavity floor to cavity sump.

3.3 U.S. Nuclear Regulatory Commission (NRC) review of KHNP submission

3.3.1 NRC Regulatory Basis

Section 52.47(a)(23) of Title 10 of the Code of Federal Regulations (CFR), states that a design certification application for light-water reactor designs must contain a Final Safety Analysis Report 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.

The NRC staff followed the guidance[1] provided in SECY-93-087, "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor (ALWR) Designs" and NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (SRP), Chapter 19.0, "Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors.

SRP 19.0 states the following:

> *SECY-93-087 and the Commission's SRM provide guidance for meeting the deterministic containment performance goal (CPG) in the evaluation of the passive Advanced Light Water Reactors (ALWRs) as a complement to the conditional containment failure probability (CCFP) approach. The expectation in SECY-93-087 with respect to the deterministic containment performance assessment is as follows:*
>
> *The containment should maintain its role as a reliable, leaktight barrier (e.g., by ensuring that containment stresses do not exceed American Society of Mechanical Engineers (ASME) Service Level C limits for metal containment or factored load category for concrete containments) for approximately 24 hours following the onset of core damage under the most likely severe accident challenges, and following this period, the containment should continue to provide a barrier against the uncontrolled release of fission products.*

In SECY-93-087 the NRC staff recommended that the Commission approve the position that both the evolutionary and passive LWR designs meet the following criteria:

- Provide reactor cavity floor space to enhance debris spreading
- Provide a means to flood the reactor cavity to assist in the cooling process

[1] Guidance is not a substitute for regulations, and compliance with it is not required. Methods and solutions that differ from those set forth in guidance will be deemed acceptable if they provide a basis for the findings required for the issuance of a certification by the Commission.

- Protect the containment liner and other structural members with concrete, if necessary

- Ensure that the best estimate environmental conditions (pressure and temperature) resulting from core-concrete interactions do not exceed Service Level C for steel containments or Factored Load Category for concrete containments, for approximately 24 hours. Ensure that the containment capability has margin to accommodate uncertainties in the environmental conditions from core-concrete interactions.

In its July 21, 1993, Staff Requirement Memorandum, the Commission approved the staff's position.

3.3.2 KHNP Submission.

Korea Electric Power Corporation, and Korea Hydro & Nuclear Power Co., Ltd., (referred to as KHNP hereafter) submitted an Application for Design Certification of the APR1400 Standard Design to U.S. Nuclear Regulatory Commission on 23 December 2014 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15006A059). The application contained a Design Control Document (DCD), Tier 2, Section 19.2, which describes the APR1400 features that are designed to prevent and mitigate severe accidents, including MCCI. APR1400-E-P-NR-14003-P, “Severe Accident Analysis Report [SAAR],” December 2014, provided details of severe accident analysis.

APR1400 provides the following severe accident mitigation features for addressing MCCI and Core Debris Coolability:

- The corium in the APR1400 reactor cavity is quenched, and the integrity of containment liners is maintained when the Cavity Flooding System (CFS) is available.
- An acceptable stable state can be achieved ex-vessel as long as the CFS has been actuated prior to vessel breach. Having a water-filled reactor cavity initially reduces and ultimately terminates erosion of concrete in the cavity.
- The cavity floor is free from obstructions and comprises an area available for core debris spreading such that the floor area/reactor thermal power ratio is larger than 0.02 m^2/MWt.
- Uniform distribution of 100% of the corium debris within the reactor cavity results in a relatively shallow debris bed and consequently, effective debris cooling is expected in the reactor cavity.

As stated in the SAAR, KHNP used MAAP 4.0.8 with the following assumptions for MCCI analysis:

- The corium is homogeneously mixed due to the agitation by the off-gases from concrete ablation, i.e., no stratification is considered in the corium.
- The corium pool is represented by a single average internal energy.
- The oxide corium is treated as a pseudo-binary system of core oxides (UO_2, ZrO_2) and concrete oxides (SiO2, CaO, MgO, Al_2O_3, etc.).
- Chemical reactions can be treated by an equilibrium model.
- Corium crust has the same composition as molten debris.
- Temperature distribution in the crust is close to steady-state profile.
- All energy involved in the concrete phase change and endothermic chemical reactions can be lumped together as a single effective latent heat.
- The temperature profile in the concrete slab is essentially one-dimensional in the direction of erosion. Fine nodes are used near the erosion interface to track the melting front.
- Gases released from the concrete floor ablation will enter the corium mixture at 100%. Gases released from the (vertical) concrete sidewall ablation will also enter the corium mixture at a user specified fraction.
- The heat transfer rate from the corium to water above it is given by a formulation for CHF rate, which can be adjusted by a user specified parameter FCHF.
- The reactor cavity floor is a flat one-piece concrete slab, i.e., it has no deep concaving part such as sump. (Note: KHNP analyzed MCCI in the sump separately as discussed later in this report.)

KHNP selected sequences for MCCI analysis based on their core damage frequencies and bounding features. Based on the results of PRA analysis performed prior to the analysis presented in APR1400 DCD, KHNP considered ten sequences having high core damage frequencies as shown in Table 4. In response to NRC staff request for additional information (RAI) in a different area or review, KHNP provided a comparison of these sequences to these sequences provided in APR1400 DCD Tier 2 Section 19.1 (KHNP response to RAI 8363, Question 19-71 (ADAMS Accession No. ML16196A260)). The KHNP information showed that "[b] the top10 sequences (87.6% of CDF) in draft Level 1 study and top 30 sequences (93.7 % of CDF) in final Level 1 study is mainly composed by SBO, LLOCA, SLOCA, LOFW, and SGTR."

Table 4. Ten PRA Sequences with High CDF Considered for MCCI Analysis

Sequence Identifier	Description
R1_TLOES-003-MCCI	Total loss of essential service water
R2_MLOCA003-MCCI	Medium LOCA in hot leg. High pressure injection is off after 2 hours
R3_LOOP-004-MCCI	Temporary loss of AC power with failure of auxiliary feedwater (AFW)
R4_SBO-002-MCCI	Loss of AC power for 0.5 hour. Motor-driven AFW recovers when power recovers
R5_SBO-005-MCCI	Loss of AC power. Turbine-driven AFW runs for 16 hours until battery is out

R6_SLOCA008-MCCI	Small LOCA of 2 inch break in hot leg
R7_PR-A-SL_007-MCCI	One POSRV stuck open when it is first opened
R8_MLOCA002-MCCI	Medium LOCA in hot leg. High pressure injection is available
R9_SBO-006-MCCI	Loss of AC power. Turbine-driven AFW runs for 2 hours until battery is out
R10_SGTR10-MCCI	Steam generator tube rupture (SGTR) with failure of safety injection

Out of the ten sequences in Table 4, KHNP selected four for MCCI analysis: total loss of essential service water (R1_TLOES-003-MCCI), Medium LOCA (R2_MLOCA003-MCCI), Temporary Loss of AC power (R3_LOOP-004-MCCI), and Loss of AC power with turbine-driven AFW off after 2 hours (R9_SBO-006-MCCI). The remaining six sequences were not considered as limiting sequences for MCCI analysis because they will lead to delayed core damage. In addition to the four PRA sequences, KHNP selected a Large LOCA sequence from the containment performance analysis (LLOCA-C04- NoECSBS-MCCI), because it will lead to early core damage and vessel breach. KHNP provided the initial and boundary conditions and results of the analysis, including floor and side-wall ablation rates and containment pressure.

3.3.3 NRC Review Comments

KHNP performed the MCCI analysis for the reactor cavity with the MAAP computer code using model parameters that were adjusted according to the results of the debris coolability code CORQUENCH. However, the DCD does not describe how the model parameters were adjusted. Therefore, in RAI 8377, Question 19-67, the NRC staff asked the applicant to describe how the model parameters were adjusted. In addition, the NRC staff asked KHNP to provide MCCI results for a case with no overlying water present in the cavity as a sensitivity case.

KHNP responded to this RAI on November 10, 2016, describing how it used CORQUENCH calculation results to adjust the MAAP model parameters ENT0C and FCHF for the purposes of MCCI analysis (ADAMS Accession No. ML16309A628). ENT0C is a coefficient multiplier to the total mass of particles stripped from the corium jet when it flows into a deep-water pool. The applicant set ENT0C to a low value to disable particle stripping and thus the 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 resulted in more corium at high temperature reaching the concrete, which increases the calculated ablation depth. FCHF is the Kutateladze number for corium to water heat transfer, which controls the magnitude of the heat flux. KHNP adjusted FCHF so that the reactor cavity ablation depth predicted by MAAP 4.0.8 was 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 staff found that KHNP's response acceptable because it described how MAAP model parameters were adequately adjusted using CORQUENCH.

In addition, KHNP provided a report that included MCCI calculation results for a case with a dry cavity for staff audit. This case is the Release Category 11 as discussed in APR1400 DCD Tier 2 Section 19.1.4.2.1.3:

> *This category represents those sequences in which the containment fails late due to basemat melt-through. In this category, there are significant CCI and concrete erosion after [reactor vessel] failure. Since the containment failure occurs below the containment basemat, there is a very small release of airborne fission products to the environment, and the release characteristics of this category are expected to be as an underground water release. However, due to MAAP limitations for underground release evaluation, the basemat failures are conservatively treated as airborne releases at ground elevation. This conservatism does not significantly impact the source terms because the releases of this category are late and small.*

As listed on APR1400 DCD Tier 2 Table 19.1-29, releases of CsI, TeO_2, CsOH, and Te_2 are 0.0088, 0.0016, 0.0059, and 0.0017 percent of total fission product inventory of the core, respectively. The staff reviewed the calculation and found that initial and boundary conditions and results were reasonable and therefore acceptable.

The largest amount of concrete erosion in the reactor cavity was 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. MAAP predicted an ablation depth of 0.24 m (0.79 ft), which is less than the 0.91 m depth of the containment liner embedded in the reactor cavity. As shown in APR1400 DCD, Tier 2, Figure 19.2.3-12, the predicted containment pressure remains below the 8.7 kg/cm^2 (123.7 psia) for 24 hours following the onset of core damage.

The APR1400 design has a reactor cavity sump in which corium may accumulate to a deeper level compared to the rest of the cavity area. The APR1400 DCD did not provide details of the MCCI analysis performed for the reactor cavity sump, and therefore, in RAI 8377, Question 19-65, the staff asked the applicant to provide details. In its response, dated May 14, 2016, the applicant proposed to update DCD Tier 2 Sections 19.2.3.3.3.2 and 19.2.3.3.3.3.2 summarizing the MCCI analysis performed for the reactor cavity sump (ADAMS Accession No. ML16135A003). KHNP used the CORQUENCH computer code for a large-break LOCA sequence for analyzing MCCI for the reactor cavity sump. The update to DCD Tier 2 Section 19.2.3.3.3.2 provided initial conditions and the types of concrete used for the analysis as limestone and LCS (limestone and limestone common sand). The update to DCD Tier 2 Section 19.2.3.3.3.3.2 states the following:

> *The limiting case for MCCI analysis is a LBLOCA with 100 percent core relocation into the reactor cavity resulting in complete spreading into the cavity sump. Approximately 35,000 kg (77,000 lbm) of debris flows into the sump. The CORQUENCH results for this sequence indicate that the corium in the sump is stabilized in less than 10 hours and the*

> *maximum ablation depth of the concrete is approximately 0.44 m (1.44 ft), well short of the containment liner.*

The staff determined that the applicant response was acceptable because it updated the DCD providing details of the MCCI analysis performed for the reactor cavity sump.

KHNP also provided a technical report, "Ex-Vessel Severe Accident Analysis for the APR1400 with the MELTSPREAD and CORQUENCH Codes," dated August 28, 2012, for NRC audit. Table 9 of this report listed calculation results of concrete ablation depth for three different types of concrete for the cavity: siliceous, limestone-common sand, and limestone-limestone. However, Table 9 did not list calculation results of ablation depth for siliceous concrete for the reactor cavity sump. Therefore, during an audit teleconference on May 18, 2015, the NRC staff asked KHNP to clarify. In response, in a letter, dated October 1, 2015, KHNP stated the following (PRA Issue List #PRA-128, ADAMS Accession No. ML15274A284):

> *The corium pool in the reactor cavity sump has a different cross-section area from the pool in the remaining cavity, and the walls and the floor in the sump may be subject to deeper ablation than the remaining cavity walls and floor because of the dimensions of the reactor cavity sump provided above. The siliceous type shows deeper ablation than the other types which are the limestone-limestone and the limestone-common sand. Accordingly, the ablation depth in the reactor cavity sump for the siliceous concrete does not meet the requirement and it is not included as the applicable materials in the Table 9.*

The NRC staff found that KHNP's clarification acceptable and determined that having higher ablation temperature and higher heat of decomposition than siliceous concrete, limestone-common sand and limestone-limestone concrete would be more appropriate for protecting the containment liner during severe accidents.

3.3.4 NRC Conclusions from Review

Based on the review of APR1400 design features for addressing MCCI and core debris coolability and KHNP's MAAP computer code analysis performed for limestone and limestone common sand concrete types, the NRC staff determined that the APR1400 design provides severe accident mitigation features consistent with SRP 19.0 and SECY-93-087 and meets 10 CFR 52.47(a)(23), and therefore, acceptable.

4. Overall Conclusions of the APR1400 MCCI Review

FANR, KINS, and NRC have concluded that the evidence provided by their respective applicants is adequate to demonstrate that the applicable regulatory requirements are met and that the MCCI phenomena does not present an unacceptable threat to containment integrity.

Should a severe accident occur and large amounts of corium be relocated into the reactor cavity, the use of basaltic concrete layer above the containment liner plate in the reactor cavity would not necessarily prevent a breach of the containment liner prior to quenching of corium. The assessments indicate that limestone concrete is a more appropriate material for the reactor cavity since it has a higher ablation temperature and produces more non-condensable gases during the decomposition process than basaltic concrete. The non-condensable gas production enhances heat removal from the corium pool as evidenced in several experiments related to the MCCI phenomena.