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Effects of New MCCI Models Implemented in MAAP5 on MCCI in NPP Application

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1. Introduction

In the case of severe accident, the containment integrity is a key issue, because the containment is the final barrier against the release of fission products into the environment [1]. Therefore the progression of Molten Core-Concrete Interaction (MCCI) takes significant importance and has a role to threaten the integrity of the containment and the subsequent release of radioactivity in the case of core melting leading to vessel melt-through in a way of pressurization due to heat and steam/gas generation, generation of combustible gases, release of radioactive aerosols, and containment liner failure.

To evaluate MCCI phenomenon under the severe accident condition, Modular Accident Analysis Program (MAAP) which developed by Electric Power Research Institute (EPRI) has been widely used in the utility field. In particular, the last version of MAAP code implements new MCCI models [2] based on experimental observations [3,4,5]. This paper introduces the features of new MCCI models realized in MAAP5 and the effects of new models on MCCI consequences for a large dry type PWR plant application with the pre-flooding accident management strategy.

2. MCCI Models Introduced in MAAP5

If the water is present in the reactor cavity at the time of vessel failure, the corium can be stabilized and finally cool-down by heat transfer to water. According to MCCI experiments several cooling mechanisms were identified [5]. Among these cooling mechanisms, water ingression and particle bed generation by melt eruption shows a dominant cooling performance. Bulk cooling mechanism, which shows very high heat removal in the very first short time frame will be introduced in the next version of MAAP5.04.

2.1 Water Ingression Model

Because the corium material mainly contains ceramic components of UO_2 and ZrO_2, the crust generated at the surface of corium pool can easily have crack when the large temperature gradient is supposed across the crust. The cracks allow the water and steam to reach into the higher temperature zone of the corium pool. Subsequently new cracks can be generated in the near field of solidified zone and it allow the water to ingress further.

To account for the heat removal through the upper crust toward the overlying water pool, mechanistic model proposed by Epstein [6] (implemented since MAAP5.01) is applicable in the present MAAP5 code.

MAAP5 user can select an alternative model i.e. parametric model (implemented since MAAP4) to get the heat removal through the upper crust. In the parametric model, the enhanced heat transfer by water ingression is represented at a rate given by the critical heat flux (CHF) multiplied by the Kutateladze number for the pool CHF. This legacy parametric model has a user-input parametric variable, FCHF. When the water totally covers the debris and the debris curst surface temperature is sufficiently low, the quenching rate of the debris is proportional to the FCHF. This quenching rate is assumed to remain constant as long as the average temperature of the debris is above the water saturation temperature. The larger FCHF value, the higher heat removal is achieved.

When user run MAAP4 code to investigate MCCI phenomenon, one can adjust the user-define parameter, FCHF, to control heat removal and consequently the overall behavior of corium cooling process. Mechanistic water ingression model enables that reduction of user-dependency on heat removal through the upper crust and consequently provision of more precise investigation with the various MCCI environmental conditions.

2.2 Particle Bed and Melt Eruption Model

A particle bed is a porous layer with a huge number of solidified corium particles. Particle bed can be generated at ex-vessel scope by i) jet breakup during the corium jet penetrates the water pool and ii) melt eruption during the MCCI, as illustrated in Fig. 1. These two models are implemented since MAAP5.02.

Jet breakup model used in MAAP5 is based on the entrainment similarity assumption. In the jet breakup model, the amount of jet breakup is determined by user-input entrainment coefficient, ENT0C. As the particles are stripped off from the continuous jet the particles are subject to quenching by water and finally placing on top of the corium pool.

Corium melt eruption can occur when gas released from the concrete decomposition can carry the mass and energy of the molten corium pool through a break in the upper crust. Therefore the test using the siliceous concrete which has limited gas content did not show the melt eruption. In contrast experiments with limestone-like concrete whose gas content is high shows a remarkable melt eruption is taken place. MAAP5 melt eruption model has been made by the CCI-6 test results as well as previous reactor material tests with limestone-common sand concrete, and simulant material tests. It models the time averaged rate of melt eruption to the overlying water pool based the Ricou-Spalding entrainment equation [7]. The mass, energy and number of particle addition rate into the particle bed are dependent on the mass flow rate of the off-gas, the diameter of the entrained particle ranges between 1 mm to 10 mm, and the entrainment coefficient, ENT0.

In the case of flooded reactor cavity, the particle bed generated on the top of the upper crust can be cooldown because the particle bed layer is permeable to water and steam leads to high heat removal. Heat transfer from the particle bed to the water is assumed to occur by boiling since the particle bed has a higher temperature than the saturation temperature of water. Heat transfer rate in MAAP5 is modeled by the nucleate boiling heat transfer coefficient, total heat transfer area within the bed, and the temperature difference. To account for the situation that if the particle temperature is high enough to limit the nucleate boiling by the CHF, the heat transfer rate of film boiling is calculated by radiation heat transfer and film boiling heat transfer coefficient.

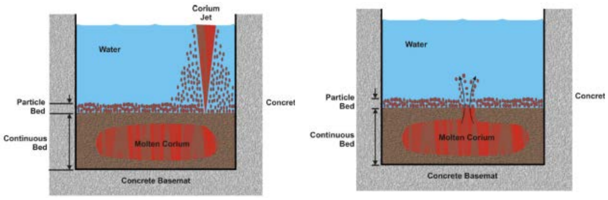

Fig. 1. Particle bed generation (left) through jet break up, and (right) through melt eruption [2]

3. Effects of New MCCI Models in NPP Application

New MCCI models introduced in the latest MAAP5 code are incorporated to MCCI analysis in NPP application. Selected accident sequence and the containment model for MAAP5 is modified from the previous studies [8].

3.1 Water Ingression Model

To investigate the effect of water ingression model, three cases with difference water ingression option available in MAAP5.03 is constructed - Mechanistic water ingression model, low value of FCHF (0.0036), and high value of FCHF (0.02). Two different values of FCHF are bounding ones suggested by developer to reflect the phenomenological uncertainty based on NUPEC/FAI uncertainty analysis. As discussed in section 2.1, mechanistic water ingression model can calculate the heat removal based on the thermal properties and accident condition. Parametric water ingression model influenced by user-input FCHF value mimics the flat plate boiling correlation to the upper crust layer. Melt eruption and particle bed formation option is set to be disable to isolate water ingression impact. Thermal conductivity of the upper crust can impact on the heat transfer to the water or steam. Conservatively the thermal conductivity of oxide corium is chosen in the present study.

Fig.2 shows the heat flux to overlying water pool and the average corium molten pool layer temperature according to the water ingression models. As expected when we suppose the conservative heat removal condition, i.e. lower bounding value of FCHF (=0.0036) the time required to quench the molten pool is longer than the other cases. Amount of heat flux to overlying water pool in case of mechanistic water ingression model is placed between two bounding FCHF cases. Note that upper bounding value of FCHF shows a too rapidly heat removal under the present condition.

Fig. 3 illustrates the concrete floor erosion depth for three cases. Two bounding parametric approaches show unrealistic ablation, but mechanistic water ingression model indicates a reasonable ablation depth.

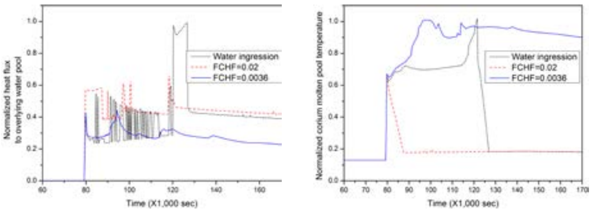

Fig. 2. Effect of water ingression model on (left) heat flux to overlying water layer, and (right) averaged corium pool temperature.

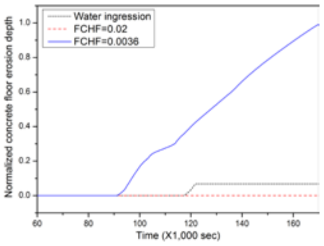

Fig. 3. Concrete floor erosion depth according to water ingression models.

3.2 Particle Bed and Melt Eruption Model

As discussed in section 2.2, MAAP5.03 provides user option for particle bed formation due to jet breakup and melt eruption. Obviously the jet breakup option off case can show apparent melt eruption and particle bed formation. Also generic limestone concrete type whose gas content is high is selected as a cavity floor to enhance melt eruption effect. Mechanical water ingression option is set to be active. An entrainment coefficient of 0.08 is employed in the present study.

Fig. 4 shows masses of particle bed, upper crust, and molten pool in the cavity. The integrated total mass of corium including oxidic and metallic composition is also presented in the figure. Before the formation of massive particle bed by melt eruption, molten corium pool is cooled by water ingression phenomenon throughout the upper crust. As MCCI started a particle bed is generated by effective melt eruption. Under the present MCCI condition concrete erosion is terminated quickly due to effective heat loss and leading to a limited concrete ablation in the order of a few centimeters. For a long-term period a particle bed formation is stopped due to the concrete ablation terminated however water ingression still gives an effective heat removal.

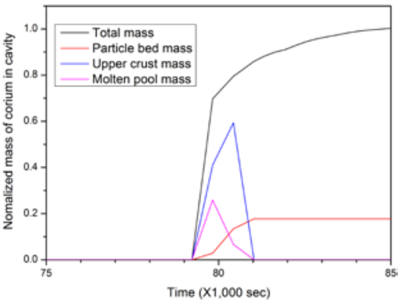

Fig. 4. Normalized cavity corium mass

4. Conclusions

MAAP5.03 calculation using new MCCI models were carried out for the NPP application. Among the known cooling mechanism during MCCI, dominant two mechanisms – water ingression and melt eruption are incorporated in MAAP5.

Regarding the water ingression model two bounding value of user-input parameter is applied in parametric model. Comparing with the mechanistic water ingression model, the bounding FCHF value case show a limiting result of ablation and quenching. When one employ the parametric water ingression model, a precisely review and choose FCHF value is essential to reduce the user-dependency in MCCI evaluation, however mechanistic water ingression model derived in MAAP5 clearly provides the realistic and best-estimate heat removal through the upper crust.

Melt eruption and resultant formation of particle bed on top of the upper crust is tested using MAAP5. Once MCCI starts the formation of particle bed is apparent due to off gases from the decomposition of the floor concrete. Since higher gas contents in the basemat concrete more affective heat removal is achievable, limestone or limestone-common sand type concrete is preferred as cavity floor material like Shin-Kori Unit 3 and 4.

Although uncertainties still remain in terms of material properties and model coefficients applied for water ingression and melt eruption, these two effective heat removal mechanism provides the pre-flooding approach is effective to mitigate and terminate MCCI in plant application. The influence of the uncertainty involved in two cooling mechanism will be studied in the future.

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