12.3 Evaluation of Upward Heat Flux in Ex-vessel Molten Core Heat Transfer using MELCOR

Soo Y. Park, Jong H. Park, See D. Kim, Dong H. Kim, Hee D. Kim
Thermal Hydraulic and Safety Research Team,
Korea Atomic Energy Research Institute
P.O.Box 105, Yusong, Taejon, KOREA, 305-600
Tel:82-42-868-8298 Fax:82-42-868-8256 E-mail:sypark@nanum.kaeri.re.kr

Abstract

The purpose of this study is to share experiences of MELCOR application to resolve the molten corium- concrete interaction (MCCI) issue in the Korea Next Generation Reactor (KNGR). In the evaluation of concrete erosion, the heat transfer modeling from the molten corium internal to the corium pool surface is very important and uncertain. MELCOR employs Kutateladze or Greene's bubble-enhanced heat transfer model for the internal heat transfer. The phenomenological uncertainty is so large that the model provides several model parameters in addition to the phenomenological model for user flexibility. However, the model parameters do not work on Kutateladze correlation at the top of the molten layer. From our experience, a code modification is suggested to match the upward heat flux with the experimental results. In this analysis, minor modification was carried out to calculate heat flux from the top molten layer to corium surface, and efforts were made to find out the best value of the model parameter based on upward heat flux of MACE test M1B. Discussion also includes its application to KNGR.

Keywords

Molten Core Concrete Interaction, MCCI, Severe Accident, Molten Pool Heat Transfer

1. Introduction

A molten corium-concrete interaction analysis has been performed for licensing purpose using the MELCOR computer program. This phenomenon is recognized as an important aspect in severe reactor accidents. The potential hazard of MCCI is the integrity of the containment building due to the possibility of a basemat melt-through, containment overpressurization by non-condensable gases, or oxidation of combustible gases. The containment integrity is largely affected by the basemat melt-through or containment over-pressurization[1]. Basemat melt-through refers to the process of concrete decomposition and destruction associated with a corium melt interacting with the reactor cavity basemat. Concerning to MCCI, the NRC staff recommends that both the evolutionary and passive light water reactor designs meet the following criteria[2]:

- provide reactor cavity floor space to enhance debris spreading
- provide a means to flood to reactor cavity to assist in the cooling process
- protect the containment liner and other structural members with concrete, if necessary ensure that the best estimate environment condition (pressure and temperature) resulting from concrete interactions do not exceed Factored Load Category for concrete containment, for approximately 24 hours.

The purpose of this study is to share experiences of MELCOR application to resolve the molten corium- concrete interaction issue in the KNGR.

2. Review of Code Modeling for Ex-vessel Debris Pool

As there are so many uncertainties in phenomena of molten core-concrete interaction (MCCI), the typical integrated severe accident programs such as MELCOR 1.8.4 and MAAP4 have different models for the treatment of debris layering and mixing, concrete ablation, and gas generation. The cavity(CAV) package in MELCOR models the attack on the basemat concrete by molten core materials. The package consists of models taken from the CORCON-MOD3 code together with all necessary interfaces to the MELCOR. In the mean time, the DECOMP is a phenomenology subroutine in MAAP to calculate the concrete ablation rate and subsequent gas release due to the presence of molten core material. A concrete ablation is largely affected by the heat flux from the core debris to the concrete. The MAAP model calculates the concrete ablation based on the user specified heat transfer coefficients, while the MELCOR allows this interfacial heat flux to be calculated using either a gas film or a slag film model. Five possible types of debris layers (light oxide, light oxide-metal mixed phases, metal, heavy oxide-metal mixed phases, heavy oxide) are considered in MELCOR, which is discussed in reference[3]. Three options are available for the treatment of layering and mixing of debris: (1) enforcement of complete mixing, (2) enforcement of complete stratification, and (3) mechanistic modeling of the entrainment and separation processes. On the contrary, the MAAP assumes that all the debris is homogeneously mixed. Followings are description of molten pool heat transfer.

2.1 MELCOR

A multi-layered pool model is employed, for which it is convenient to consider heat transfer one layer at a time. The model allows for several possible configurations in each layer. The layer may be completely molten, it may have a solid crust, or it may be completely solid. Here, heat transfer in a liquid layer or the liquid portion of a partially-solidified layer will be addressed. Heat transfer coefficients are required from the interior of a liquid layer to its surfaces. If the layer were a right circular cylinder type, there would be three such coefficients, that is, to the upper, lower, and radial surfaces. Models are included for gas injection at the bottom surface of the melt, and gas agitation along the sides of the melt.

For the bottom interface of the melt pool, where gas bubbles may be injected from the incoming concrete, the heat transfer coefficient for a liquid layer is calculated using the correlation devised by Kutateladze. The Kutateladze correlation[4] is given by

$$Nu_a = 1.5\times10^{-3} Ku^{2/3} f(\eta) \qquad (1)$$

where Nu_a is the Nusselt number, Ku is the dimensionless number ,and is the dimensionless gas velocity

For liquid layers within the melt pool, a correlation devised by Greene is used to calculate the heat transfer coefficient in each layer, except for the uppermost melt layer. Greene's correlation[5] is

$$h = 1.95k(\mathrm{Re\ Pr})^{0.72} / r_b \qquad (2)$$

where k is the thermal conductivity, Re is the Reynolds number for the liquid based on the characteristic length r_b and the superficial gas velocity j_g, Pr is the Prandtl number for the liquid, and r_b is the average bubble radius in the layer.

For the uppermost melt layer (adjacent to the atmosphere or coolant), the heat transfer coefficient is calculated using a modified form of the Kutatelaze correlation, which accounts for the greater surface area of the unstable surface. For the upper melt surface, the Kutatelaze correlation is simply multiplied by an area enhancement derived by Farmer,M.T.[6]:

$$A = 1 + 4.5\frac{j_g}{U_b} \qquad (3)$$

where A is the area enhancement factor, j_g is the superficial gas velocity, and U_b is the bubble rise velocity.

2.2 MAAP

The debris pool has a single lumped energy and a mass balance capability for up to 50 condensed phase compounds from the standard MAAP list. The debris pool consists of molten liquid and three independent crusts, the lower, side, and upper crust. The bottom and side crust thickness may be different from each other because the convective heat transfer coefficients for sideward and downward may be different. The upper crust is treated separately because its energy is transferred by radiation to the cavity wall and convection to the gas. Due to the internal heating, three independent crusts are assumed to have parabolic temperature profiles. For example, the temperature profile within the lower crust which can be expressed by the steady-state expression[7].

$$\frac{T-T_i}{T_{F,m}-T_i}=1-\left(\frac{x}{x_c}\right)^2 \qquad (4)$$

where $T_{F,m}$ is the corium mixture melting point, T_i is the interface temperature of the crust and the concrete, and x_c is crust thickness. T_i is assumed to equal the concrete surface temperature.

For those cases where the corium-concrete mixture pool is too deep to transfer the energy generated by thermal conduction, the central region of the pool would be molten. Under these conditions, the heat flux from the molten central region to the crust can transferred out of the crust using the conduction equation ;

$$q''=-kF\left.\frac{dT}{dx}\right)_{x=xc} \qquad (5)$$

3. Cavity Design of Reference Plant

The reactor cavity is configured to promote retention of the postulated core debris and to remove decay heat by a cavity flooding system during a severe accident, thus serving several roles in accident mitigation. The large cavity floor area allows for spreading of the core debris, enhancing its coolability within the reactor cavity region. The cavity includes approximately 566m^3(20,000 ft^3) of free volume. This large volume benefits the plant design when cavity pressurization issues are considered. Large and well vented volumes are not prone to significant pressurization resulting from vessel breach or during corium quench processes. It has been designed to maximize the unobstructed floor area available to the spreading of corium debris. The cavity floor is free from obstructions and comprises an floor area available for corium debris spreading of approximately 80.36m^2(865 ft^2).

The reactor cavity is designed to satisfy the URD[8] requirement that the distance between the floor elevation and the embedded portion of the containment shell is a minimum of 0.91meter. An additional 3.35 meter of concrete is available below the linear elevation.

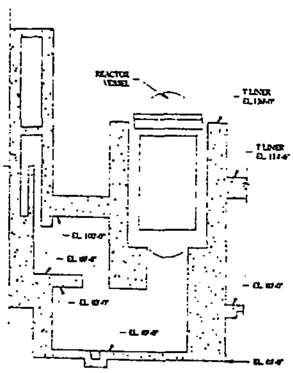

Figure 2-1 Section-view of Cavity

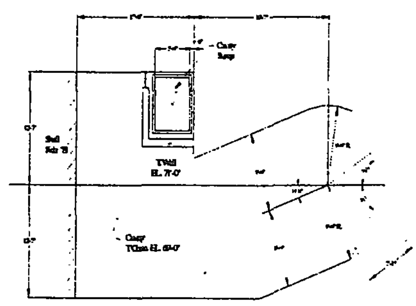

Figure 2-2 Plane-view of Cavity Floor

4. Concrete Erosion Analysis

The erosion was calculated using MAAP and MELCOR codes. After a hypothetical accident scenario was simulated by MAAP, the conditions of molten corium in the reactor cavity such as mass, temperature or decay heat at the time of reactor vessel failure were used as initial conditions of MELCOR. By doing this, two codes would have the similar initial conditions for the erosion calculations in the cavity.

4.1 Analyzed Case Description

The sequence simulated is a 6 inch-diameter-break loss of coolant accident (LOCA). Following a LOCA , the reactor trips and high pressure safety injection systems are not available to deliver water from the refueling water storage tank to the cold legs. The only water available to make up the primary side is the inventory of four safety injection tanks. As the water inventory in the reactor coolant system decreases, the core becomes uncovered. The reactor vessel eventually fails and 195,630 kilograms of corium discharged into the cavity. Since the pressure of the primary system has already decreased enough, all the discharged corium is captured in the reactor cavity.

Calculations of five cases were carried out to investigate the concrete erosion and the upward heat flux. The first case was calculated by MELCOR with default model parameter values (Case 1-MEL). Forced mixed layer option and slag film model was used. Parameter value of HTRINT was set to zero, which is default CORCON-Mod3 model. HTRINT is one of model parameters which controls the debris-to-pool heat transfer. The second case(Case 1-MAAP) was calculated by MAAP with default model parameter values. FCHF, which is a flat plate critical heat flux Kutateladze number that controls the pool boiling heat flux, was set to zero. The third case(Case2-MEL) was the same as Case 1-MEL except that HTRINT value has been changed to 10 in order to increase the upward heat flux artificially. The next case (Case 2-1-MEL) was the same as Case 2-MEL but the code was modified because the parameter change did not work properly. The final case (Case 2-MAAP) was the same as Case 1-MAAP except that FCHF value has been changed from 0.9 to 0.015 in order to decrease the upward heat flux artificially. In the cases of Case 2-1-MEL and Case 2-MAAP, we tried to match the upward heat flux to the MACE test of M1B results. M1B result shows that initial melt/water heat flux reached to about 3.6 MW/m^2 followed by a plateau at about 1.6 MW/m^2 which lasted about 6 minutes. Thereafter, the heat flux gradually decreased to 200 kW/m^2 at 200 minutes after water was added [9]

4.2 Calculation Results

- Case1-MEL & Case 1-MAAP

Figure 3 and Figure 4 shows the erosion depth and upward heat flux, respectively. Axial/Radial erosions reach to 1.12m/ 0.65m at 24 hours following Rx trip in MELCOR results and the erosions are negligible in MAAP. It results from the difference of upward heat flux from molten debris to the overlying water pool. The heat flux of Case 1-MEL is much lower than test M1B and that of Case 1-MAAP is much higher than M1B.

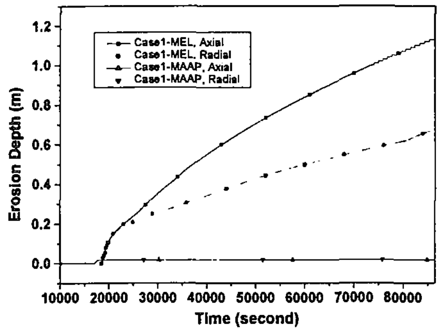

Figure 3. Concrete erosion depth for Case1-MEL & Case 1-MAAP

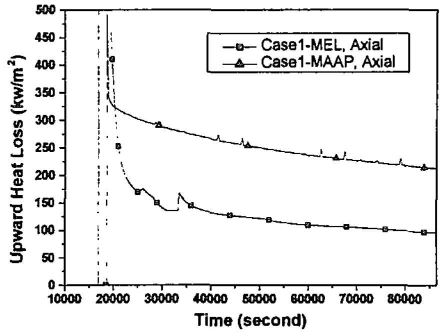

Figure 4. Upward heat flux for Case1-MEL & Case 1-MAAP

- Case2-MEL & Case 2-1-MEL

HTRINT has been changed to 10 in Case2-MEL in order to increase the upward heat flux to the M1B test results, but MELCOR did not work properly. As shown in Figure 5 & Figure 6, the erosion and heat flux did not changed. Model parameters of HTRBOT, HTRINT, HTRSIDE are not applied to Kutateladze's correlation in current coding. Therefore minor code modification is needed to increase the heat flux artificially. Axial/Radial erosions reach to 0.79m/ 0.27m at 24 hours following Rx trip in modified MELCOR results.

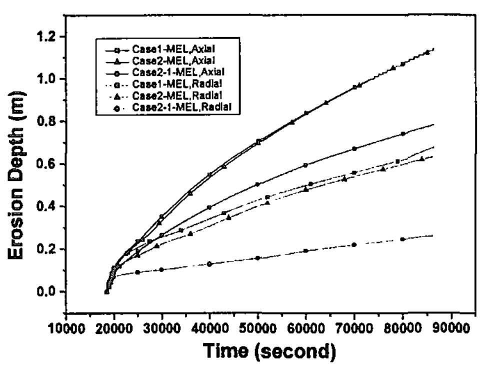

Figure 5. Concrete erosion depth for Case2-MEL & Case2-1-MEL

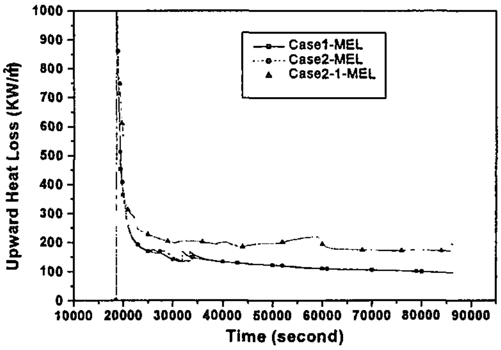

Figure 6. Upward heat flux for Case2-MEL & Case2- 1-MEL

- Case2-MAAP

FCHF has been changed from 0.09 to 0.015 in Case2-MAAP in order to decrease the upward heat flux to the M1B test results. As shown in Figure 8, initial high melt/water heat flux of about 1500 seconds, which result in complete debris quenching in Case1-MAAP, has disappeared in Case2-MAAP. And long term heat flux of about 200 KW/m^2 meets the liner protection requirement. Axial/Radial erosions reach to 0.89m/ 0.78m at 24 hours following Rx trip (Figure 7).

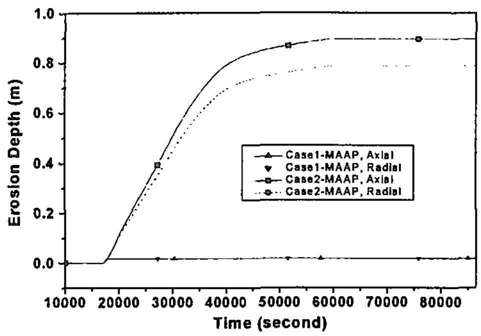

Figure 7. Concrete erosion depth for Case 2-MAAP

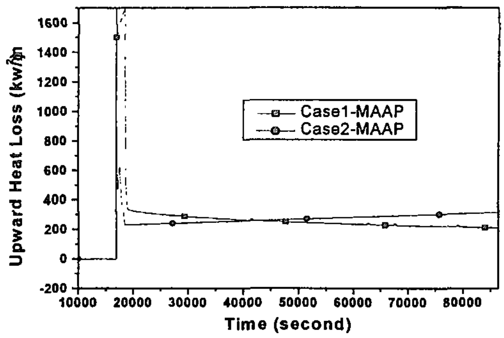

Figure 8. Upward heat flux for Case 2-MAAP

5. Summary

Following observations are made from this analysis;

- MELCOR with default parameter value tends to under-estimate the upward heat transfer compare to the MACE experimental result. And MAAP tends to over-estimate it.
- MELCOR with HTRINT=10 and MAAP with FCHF=0.015 result in similar upward heat transfer rate to the MACE experimental result.
- Minor code modification of MELCOR is needed for user flexibility to increase the heat flux from debris pool into overlying water pool when the mixing option is selected
- Long term upward heat flux of 200-350 kw/m^2 in ex-vessel debris meets the liner protection requirement of SECY-93-087 for the KNGR

ACKNOWLEDGE MENTS

This Project has been carried out under the Nuclear R&D Program by MOST.

REFERENCES

1. J.W. Park et al., study on the Influence Diagrams for the Application to Containment Performance Analysis, Journal of Korean Nuclear Society, Vol.28, Number2, April 1996, pp.129-136.
2. SECY-93-087, olicy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light Water Reactor Designs April, 1993
3. Summers, R.M., and al., ELCOR Computer Code Manuals, NUREG/CR-6119, September 1994.
4. Kutateladze,S.S., and I.G.Malenkov, oiling and Bubbling Heat Transfer Under Conditions of Free and Forced Convection, 6th Internal Heat Transfer Conference,Toronto,Canada.1978
5. Green,G.A., and T.F. Irvine, eat Transfer Between Stratified Immiscible Liquid Layers Driven by Gas Bubbling Across the Interface, in ANS Proceedings of the 1988 National Heat Transfer Conference,Houston, TX, July 24-27, 1988.
6. Farmer,M.T., J.J.Sienicki, and B.W.Spencer, ORQUENCH: A Model for Gas Sparging-Enhanced Melt-Water, Film Boiling Heat Transfer, ANS Special Session on Thermal Hydrolics of Severe Accidents, November 11-15,1990.
7. FAI , odular Accident Analysis Program, May,1994.
8. EPRI, Advanced Light Water Reactor Requirement Document, 1992.
9. Presentation material, verview of MACE Test M1b B.W. Apencer, ANL, 1992. June.