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# Sensitivity Studies on Molten Core Concrete Interaction Using MELCOR Code

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## ABSTRACT

The purpose of this study is to analyze the progression and consequence of molten core- concrete interaction (MCCI), and to understand the effects of related uncertain parameters on this issue when a severe accident occurs in a nuclear power plant. The molten core-concrete interaction still has large uncertainties in several phenomena, such as the melt spreading area, debris layering and mixing, heat transfer models, decay heat, debris mass and temperature in the cavity, concrete compositions, and cavity conditions(cooling water availability). Sensitivity analyses for above parameters were performed using MELCOR computer code. As a result, the concrete type is the most sensitive parameter in concrete erosion due to difference in decomposition enthalpy. And other plant specific design parameters, such as corium amount, spreading area, or decay power, are so sensitive that a 10 % variation result in about a 10 % erosion difference.

## 1. INTRODUCTION

The phenomenon known as molten corium-concrete interaction (MCCI) has been 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-condensible gases, or oxidation of combustible gases. The containment integrity is largely affected by the basemat melt-through or containment overpressurization[1]. In postulated degraded core accidents followed by the failure of certain engineered safety features of the reactor system, the core may eventually melt due to the generation of decay heat. If the safety features of the reactor system fail to arrest the accident within the reactor vessel, the corium (molten core debris) will fall into the reactor cavity and attack the concrete walls and floor. Basemat melt-through refers to the process of concrete decomposition and destruction associated with a corium melt interacting with the reactor cavity basemat. Concrete properties, corium amount, corium distribution in the reactor cavity, debris bed configuration and coolability, debris power and heat transfer are important uncertain parameters affecting basemat melt-through. The purpose of this analysis is to understand the effects of related uncertain parameters on this issue via a sensitivity study using MELCOR[2], which is a typical severe accident analysis computer program. The discussion was focused on the impact of the above uncertain parameters on the downward and/or sideward concrete ablation for the 1300 MWth PWR with large dry containment.

- 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 containment shell is adequately embedded in concrete in the reactor cavity area to preclude direct contact of the core debris with the containment. The level of embedment is 0.91 m. Note that since the lower shell provides no structural strength contribution, failure of the shell via melt-through has no mechanical significance. Furthermore, the gap separating the shell and the concrete is minimized by the application of grout at high pressure. Thus, significant seperation of shell and concrete foundation is considered unlikely. The pathway separating the shell and concrete is therefore considered to be sufficiently torturous to preclude fission product released to the environment.

The reactor cavity is designed to satisfy the URD[3] 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.

- Computational Tool Description

The MELCOR/Cavity package, the modeling of which is based on CORCON-Mod3 [4], is used to model the interaction between core debris and concrete. The CORCON-Mod3 code has been developed by the NRC for the purpose of computing concrete erosion rates and profiles during severe accidents. The physical system considered by the Cavity package consists of an axisymmetric concrete cavity containing debris in one or more layers. 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 calculated 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. It is tacitly assumed that the corium crust and the corium melt are in contact and that the melt is impermeable to water ingression.

## 2. ANALYSIS RESULTS

- Basemat Erosion for a Base Case

An analysis of core/concrete interactions inside the flooded cavity region of the reference design has been carried out using the CORCON-MOD3 code, which can be indirectly accessed by means of running MELCOR 1.8.4 code. Assumed melt release conditions from the lower head together with containment cavity conditions at the time of melt release are shown in Table 1. The melt is assumed to be release suddenly over a timescale that is relatively short in relation to the ensuing core-concrete interactions. The released mass is 195,630 Kilograms which represents essentially the full core inventory of uranium dioxide and zircaloy as well as a substantial quantity of in-vessel stainless steel. The zirconium is assumed to have been oxidized in-vessel such that about 50 percent of the zirconium remains unoxidized in metallic form. The relative proportions of metallic melt were assumed to only consist of iron.

MELCOR only treats corium layers that possess cylindrical symmetry, that is, are axisymmetric about a vertical centerline. Thus, while the released melt is free to spread over the floor of the cylindrical cavity and the adjoining instrument tunnel, MELCOR cannot model the combined cavity/tunnel geometry. For this reason, the calculations were performed for the equivalent cylindrical cavity of 5.06 meter (16.6 feet) radius. In particular, the released melt was assumed to spread to a uniform depth over the flat floor area of the cavity and tunnel. The corium is to be released at a temperature of 2,616 degrees Kelvin (4,249 degrees Fahrenheit). This same temperature is assumed for the melt layer at the onset of concrete attack. In this analysis, potential mitigative effects of melt-water interactions that could reduce the temperature of the corium collecting upon the floor have been conservatively ignored. These include breakup, freezing, and quenching of the melt as it relocates through the water pool as well as heat losses from the melt as it collects and spreads over the concrete floor underneath the overlying water.

The melt is to be released from the lower head about 18,600 seconds following reactor scram. For the nominal reactor operating power of 3,816 Megawatts thermal, the corium inside the cavity has an initial power of about 22.8 Megawatts at 18,600 seconds after scram. This corresponds to 0.59 percent of nominal power.

For the base case, the corium oxidic and metallic constituents are assumed to internally mixing by the MELCOR model. The overall initial corium depth above the cavity floor is thus 0.307 meter (10.07 inches). The cavity is assumed to be nominally flooded with subcooled water to a cylindrical cavity water mass of 458,000 Kilograms. The initial water temperature is taken to be 421 degrees Kelvin. At the assumed containment pressure of 0.4569 Megapascal, this is equivalent to initial water subcooling of 3.0 degrees Kelvin. In the reference design, the operator activates the Cavity Flood System (CFS) to make up the cooling water to the cavity. The base case includes the operation of CFS. An analysis without CFS performance is to be included in the next sensitivity studies.

The concrete composition varied over the default compositions assumed in MELCOR for basaltic aggregate, limestone aggregate/common sand, and generic SE United States (limestone) concrete. For the base case, the concrete composition was based on the data of Korean local concrete. The calculations nominally assume the MELCOR slag film model for corium-to-concrete heat transfer and erosion.

In concert with the purpose of the analysis, which relates to cumulative erosions over a twenty-four hour period, most calculations encompass this period. Results of the base case calculation are summarized in Table 2. Figure 1 shows the time dependent downwards (axial) and sidewards (radial) erosion calculated for a base case. Downwards erosion initially proceeds at a much greater rate than that in the sidewards direction. For given concrete composition at base case, the maximum downward/sideward erosions of 1.103/0.648 meter, respectively, are calculated at twenty-four hours following accident initiation.

Figure 2 and Figure 3 show the time dependent intermixing corium temperature and mass for a base case, respectively. Total corium depth above the cavity floor is about 0.307 meter at initial time of corium/concrete interactions. The intermixing model in MELCOR code was denoted to heavy oxide layer with corium mixture, and decreased the temperature of corium mixture from 2,616 degree Kelvin to 2,470 degree Kelvin. This drop of temperature cause to make the conservation of total internal energy during mixing of corium. Heat loss to concrete and overlying water pool is depicted in Figure 4. Heat flux between debris and loss to water pool decreases to about 0.1 MW/m$^2$ at the later stage, which seems to be very smaller value than experimental results.

- Basemat Erosion for Sensitivity Studies

Sensitivity calculations are carried out for eight important parameters, i.e. concrete composition, corium spreading area, initial corium mass, decay power, effects of wet cavity condition, corium layer mixing/stratification, and heat transfer model inside corium. The calculation results are summarized in Table 2 and depicted in Figure 5 through Figure 12.

The concrete composition was varied over the default compositions assumed in MELCOR for basaltic aggregate, limestone aggregate/common sand, and generic SE United States (limestone) concrete. The basaltic concrete has the largest erosion and limestone aggregate- limestone sand has the least erosion. The Korean local concrete (base case) is similar to basaltic.

Corium spreading area and initial corium mass were reduced to 90%, 80% and 70% compared with a base case. Initial corium temperatures of 2400 and 2800 degrees Kelvin were investigated. This case serves to indicate the sensitivity to the initial temperature of corium at the time of reactor vessel failure. The decay power has also uncertainty in this phenomena, so 110% and 90 % of power in base case were examined. The results show that the downward erosion depth is in the range of about 0.8 m and 1.4 m.

The cavity is assumed nominally flooded with subcooled water in the base case. In the reference design, the operator activates the cavity flood system to provide cooling water to the cavity. The dry cavity condition eliminating th effects of heat removal to overlying water results in the calculation of small varying cumulative erosions as shown in Figure 12. The erosions to twenty-four hours provide maximum downwards and sidewards erosions of 1.071 meter and 0.735 meter, respectively. This indicate that the cavity corium has a very impermeable configuration in MELCOR with mixed corium layer model.

MELCOR models density stratification and intermixing of the oxide and metal phases depending upon the noncondensable superficial gas velocity rising through the layer. In addition, the user can specify whether the phases are to be treated as always stratified or always intermixed. Base case was performed, with the oxide and metal assumed to always be mixed independent of the superficial gas velocity. A stratified configuration was selected in this sensitivity study in order to determine the sensitivity of concrete erosion to mixing.

The early corium configuration consists of the heavier oxides stratified as a layer beneath a layer of metals. The stratified configuration involving metal sandwiched between heavy and light oxide phases continues until about 10,000 seconds after the onset of the core-concrete interaction. Until this time, the mean temperature of the underlying heavy oxides is calculated to rapidly fall and remain the oxide phase solidus temperature. This result in relatively lower downward erosion rate. If part or all of a layer becomes frozen heat can be removed by conduction only, which is ordinarily far less effective than convection. The heavy oxide phase has been diluted by the slag erosion products to such an extent that the heavy oxide density falls below that of the overlying metal. When this happens, the suddenly heavier metal is assumed to sink to the bottom to contact the concrete floor. At this time, the metals have a large molten superheat above the metal phase liquidus temperature. The presence of metal at the floor increases the downward concrete erosion rate. The heat loss to the overlying water is larger than mixed layer case. The sideward heat flux is relatively less than mixed layer case.

The base case calculation assumes the MELCOR slag film model for corium-to-concrete heat transfer and erosion. Two additional calculations were carried out. The first case uses a gas film model of both sides. For the second, the sidewards heat transfer and erosion were assumed to be limited by the presence of a stable gas film and the slag film model was still used for downward heat transfer. There is not much difference in the concrete erosion, which is shown in Figure 11.

## 3. CONCLUSION AND DISCUSSION

The referenced reactor cavity has been designed with a large basemat area and a cavity flood system to ensure the presence of water in the reactor cavity following severe accident scenarios. Sensitivity analyses for several uncertain parameters were performed.

Concrete properties, corium amount, corium distribution in the reactor cavity, debris bed configuration and coolability, debris stratification/mixing, debris power, and heat transfer are considered as important uncertain parameters affecting basemat melt-through. The effects of these parameters are studied by sensitivity analysis. The basemat penetration scenario is considered to be relatively benign because of the large surface basemat area for corium spreading and the ample depth of the reactor cavity basemat foundation (more than 3.35 meter).

As a results, the most sensitive parameter in the concrete erosion is the concrete compositions. The basaltic concrete is predicted to exhibit more pronounced erosion due to relatively lower decomposition enthalpy. The limestone concrete has about half of erosion depth compare to basaltic concrete. And the other plant specific design parameters such as corium amount, spreading area, or decay power are so sensitive that 10 % variation result in about 10 % erosion difference.

The sensitivity study of cavity wet/dry condition shows not much difference due to an impermeable corium morphology. In MELCOR models, the debris fragmentation or water ingression into the crust is not considered, which result in very under-estimated heat flux between molten corium and overlying water pool compare to typical experimental results.

## REFERENCES

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2. NUREG/CR-6119, MELCOR Computer Code Manuals, Sandia National Laboratories, February 1990.
3. EPRI, Advanced Light Water Reactor Requirement Document, 1992.
4. NUREG/CR-5843, CORCON-Mod3: An Integrated Computer Model for Analysis of Molten Core-Concrete Interaction –Users manual, April 1993.

Table 1 Initial corium and coolant conditions inside the cavity.

| | |
|---|---|
| Corium mass, kg | 195,630 |
| Cavity radius, m | 5.0576 |
| Cavity Floor Area, $m^2$ | 80.36 |
| Initial corium temperature, K | 2616 |
| Corium layer thickness, m | 0.307 |
| Time since scram, s | 18,623 |
| Initial decay power in Cavity, MW | 22.8 |
| Power level, % | 0.59 |
| Coolant layer depth, m | 7.62 |
| Coolant mass, kg | 458,000 |
| Coolant temperature, K | 421. |
| Coolant subcooling, K | 3.0 |

Table 2 Maximum erosion in cavity after twenty-four hours for sensitivity cases

| Case | Parameter | Base case | Variations | Maximum Downwards erosion, m | Maximum Sidewards erosion, m |
|---|---|---|---|---|---|
| Base | | | | 1.103 | 0.648 |
| 1 | Concrete type | KNGR | Basaltic | 1.151 | 0.655 |
| | | | L-CS | 0.902 | 0.493 |
| | | | L- LS | 0.532 | 0.3152 |
| 2 | Corium Spreading area | 80.36 | 90 % | 1.189 | 0.714 |
| | | | 80 % | 1.284 | 0.781 |
| | | | 70 % | 1.391 | 0.848 |
| 3 | Coolant | with CFS | W/O CFS | 1.071 | 0.735 |
| 4 | Initial Corium Temperature | 2616 | 2400 | 1.090 | 0.626 |
| | | | 2800 | 1.114 | 0.663 |
| 5 | Initial Corium Mass | 195,630 | 90% | 1.011 | 0.575 |
| | | | 80% | 0.919 | 0.521 |
| | | | 70% | 0.816 | 0.410 |
| 6 | Decay Power | 22.8 | 110% | 1.184 | 0.712 |
| | | | 90% | 1.023 | 0.587 |
| 7 | Layer mixing | mixing | Stratification | 1.116 | 0.096 |
| 8 | Heat transfer model | slag film | all gas film | 1.125 | 0.638 |
| | | | side gas film | 1.106 | 0.623 |

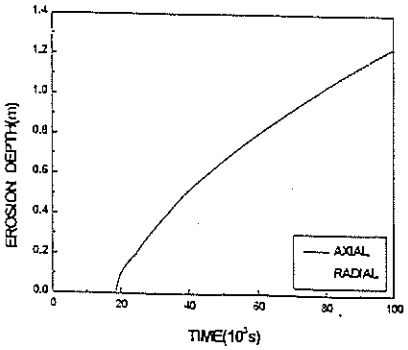

Figure 1 Concrete Erosion Depth in Cavity for Base Case

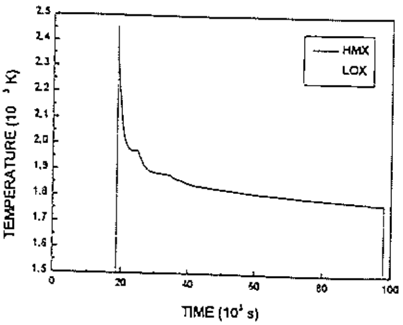

Figure 2 Corium Temperature in Cavity for Base Case

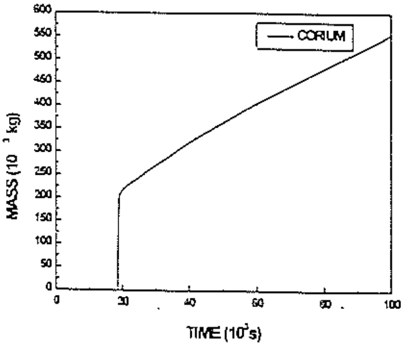

Figure 3 Corium Mass in Cavity for Base Case

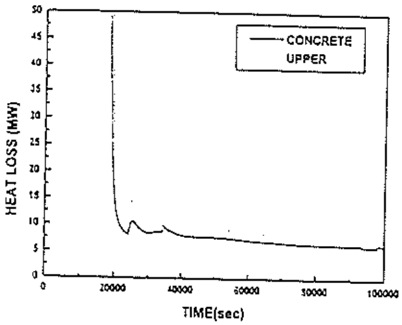

Figure 4 Heat Loss from Debris in Cavity for Base Case

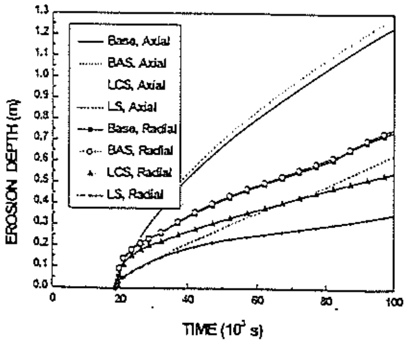

Figure 5 Concrete Erosion Depth for Various Concrete Type

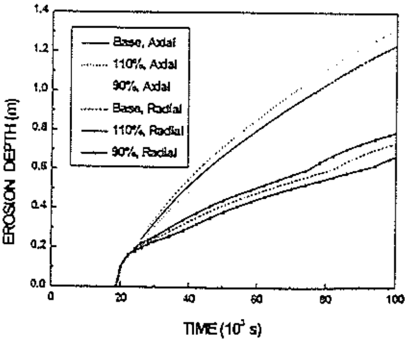

Figure 6 Concrete Erosion Depth for Various Decay Power

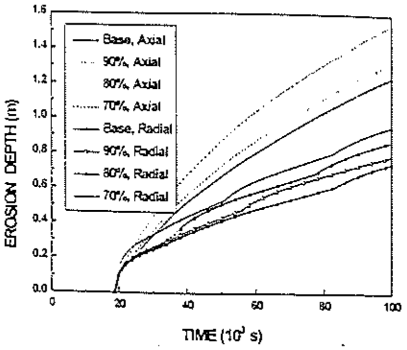

Figure 7 Erosion Depth for Various Spreading Area

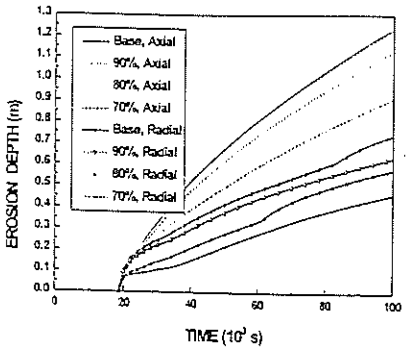

Figure 8 Erosion Depth for Various Initial Corium Mass

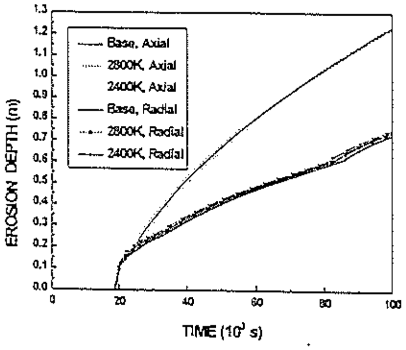

Figure 9 Erosion Depth for Various Initial Corium Temperature

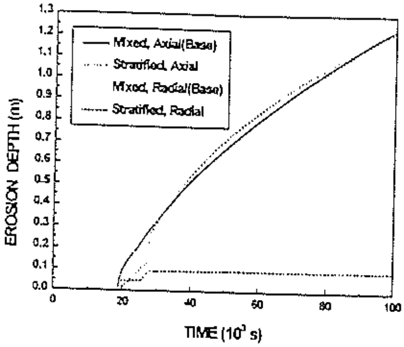

Figure 10 Erosion Depth for Layer Mixed/Stratified Model

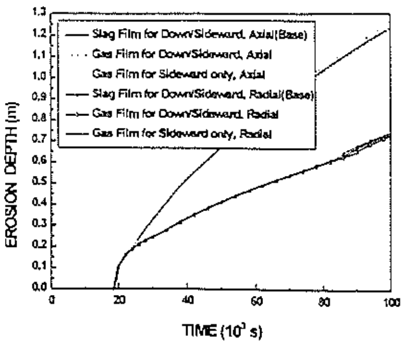

Figure 11 Concrete Erosion Depth for Various Heat Transfer Model

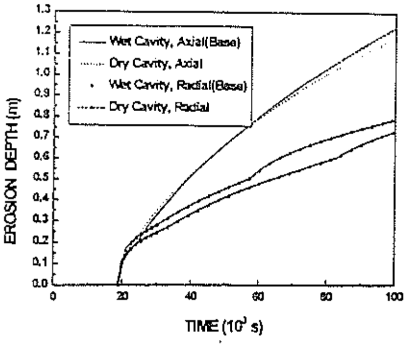

Figure 12 Concrete Erosion Depth for Dry Cavity Case