# In-Vessel Retention (IVR) as a Severe Accident Management Strategy

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## Introduction

During a rare accident involving severe core damage in a Nuclear Power Plant (NPP), if the molten core material can be contained within the boundary of the reactor vessel, the severity of the accident is expected to be greatly reduced. Therefore, the severe accident management strategy based on in-vessel retention (IVR) of molten core debris is highly desirable, and has been adopted by advanced reactor designs such as VVER, AP1000 and APR1400. In these designs, the IVR strategy requires NPP operators to perform specific actions including:

a) Opening valves to depressurize the reactor vessel and reduce the stress in the reactor vessel lower head
b) Flooding the reactor cavity to a certain high level to ensure the reactor vessel is covered and cooled by water from the outside
c) Injecting water into the reactor vessel after the vessel is fully depressurized to increase the probability of IVR success

One of advantages of the IVR strategy is that the actions required in this strategy can be performed without AC power.

## Issues Related to IVR Success

Success of IVR depends on the heat flux from the molten core material (corium) to the reactor vessel wall. The heat flux must not exceed the mechanical and thermal limits that fail the vessel. The mechanical limit is due to the fact that the reactor vessel wall must be ablated to a very small thickness that allows the heat flux to be conducted through it. However, if the vessel wall is too thin, it is unable to support the corium in the lower head and the dead weight of the lower head wall. In this case, the vessel will creep to failure. The thermal limit is due to the fact that the heat flux must not exceed the critical heat flux (CHF) on the outer surface of the reactor vessel wall. If the heat flux exceeds the CHF, the reactor vessel wall temperature will increase rapidly and lead to failure.

The heat flux from the in-vessel corium to the reactor vessel is non-uniform along the vessel wall. It has been agreed among IVR researchers that the highest heat flux may occur at the top of the corium, where the metallic material in the corium pool is segregated from the heavier oxidic material to form a metal layer. The thinner the metal layer is, the larger the heat flux to the wall, resulting in so-called "focusing effect." Ideally there would be a sufficient amount of metals including steel and unoxidized Zr to form a thick metal layer at the top. However, in certain conditions, unoxidized Zr in the corium can reduce $UO_2$ in the corium to form U metal. The eutectic U, Zr and steel is heavier than the oxidic material and stays at the bottom of the corium to form a heavy metal layer. The heavy metal is postulated to remove the steel in the top (light) metal layer, making the light metal layer thinner and the "focusing effect" worse.

## Capabilities of MAAP5 Code for IVR Analysis Application

IVR analysis is challenging and, in many situations, requires simulations using integral a severe accident thermal hydraulic code. An appropriate code is the Modular Accident Analysis Program (MAAP), which is owned by the Electric Power Research Institute (EPRI) and developed and maintained by Fauske & Associates, LLC (FAI). The latest official revision of the MAAP5 code, MAAP5.03, is equipped with comprehensive models of the corium pool in the lower plenum, reactor vessel and in- and ex-vessel heat transfer. The key features of the models are discussed below.

As shown in Figure 1(a), MAAP5 assumes that metallic material forms a light metal layer once the corium is present in the lower head. If the corium enters a water-flooded lower head, corium can be fragmented due to fuel coolant interaction (FCI). The fragmented frozen corium particles remain as a particle bed on top of the crust separating the metal layer and oxidic layer. As the particle bed is melted, the molten mass is added into the light metal layer and the oxidic layer, eventually leading to a two-layer model as shown in Figure 1(b). At certain conditions, a heavy metal layer can be formed in the lower portion of the oxidic layer, and the corium pool is then modeled as a three-layer structure as shown in Figure 1(c).

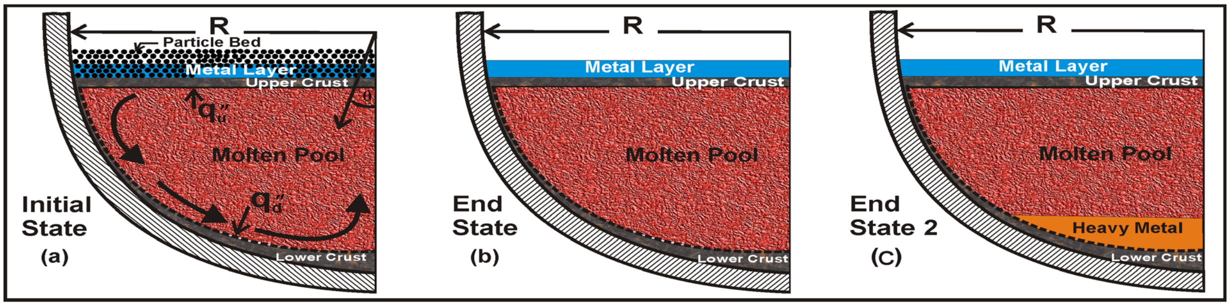


**Figure 1: Corium structure in MAAP5.03: (a) initial state; (b) end state with two layers; (c) end state with three layers**

One of the improvements in the MAAP5.03 code is the consideration of heavy metal formation if the temperature in the molten part of the oxidic layer is more than the miscibility gap transition temperature (2670 K). In this condition, once the whole core has effectively dropped into the lower plenum, the potential to form a heavy metal layer is assessed. The amount of material that participates in the reaction of heavy metal is given by:

| | |
|---|---|
| UO2, ZrO2 | 100% of the mass in the lower plenum corium pool |
| Un-oxidized Zr | User specified fraction of the un-oxidized Zr that participate in the heavy metal generation |
| Steel | Minimum of steel in the lower plenum equipment and the User specified amount of steel that participates in the heavy metal generation |

The amount and composition of the heavy metal is based on a simplified quaternary phase diagram of U-Zr-O-Fe [Salay and Fichot, 2004]. Figure 2 shows the comparison of the mass fraction of heavy metal between the MAAP model and the MASCA experiment data [Salay and Fichot, 2004]. Very good agreement is observed.

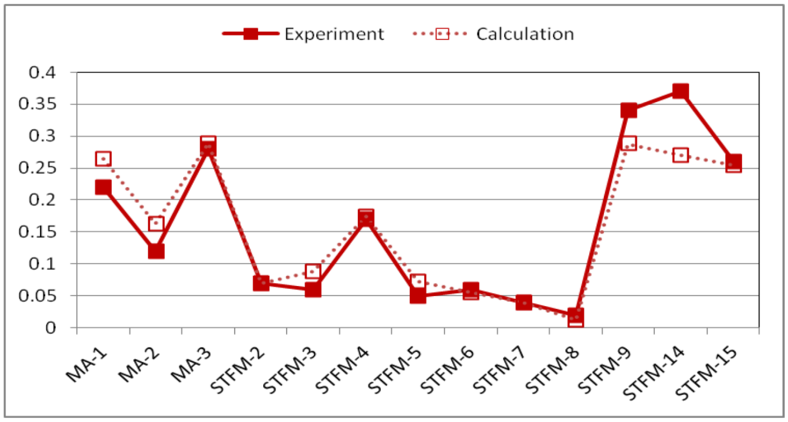


**Figure 2: Comparison of heavy metal mass fraction between the model and MASCA experiment data [Salay and Fichot, 2004]**

The heat flux from the oxidic layer to the reactor vessel wall depends on the convective heat transfer from the molten center in the oxidic layer to the surrounding crust (see Figure 1). The modeling approach in MAAP5.03 is to use experiment based correlations for the convective heat transfer calculations. Currently there are three correlations available for the user's selection: Jahn and Reineke correlation [Jahn and Reineke, 1974], BALI correlation [Bonnet and Seiler, 1999], and ACOPO correlation [Theofanous, 1997]. These correlations provide not only the average convective heat transfer coefficients, but also the distribution of the heat transfer coefficient as a function of the inclination angle along the lower head wall. Figure 3 shows the comparison of the angular distribution used in MAAP5.03 and the experiment data [Jahn and Reineke, 1974]. The same correlations are also applied to the heat transfer from the center of a heavy metal layer to the surrounding crust.

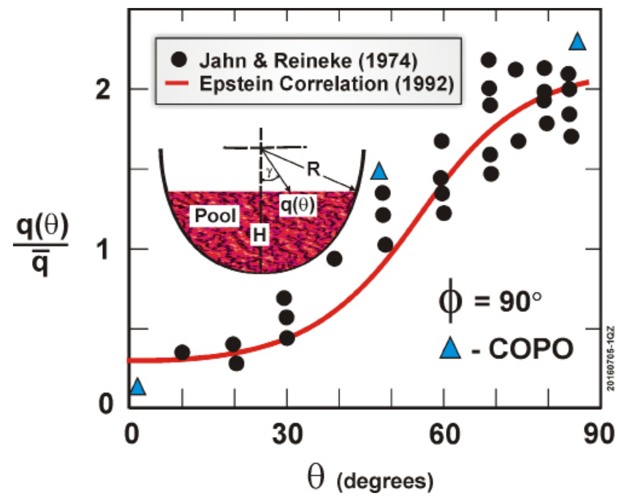


**Figure 3: Comparison of the angular distribution used in MAAP5.03 and experiment data [Jahn and Reineke, 1974]**

Heat transfer from the light metal layer to the reactor vessel wall is the key for success of IVR. It is different from the heat transfer from the oxidic and heavy metal layers because there is no crust separating the light metal layer, and the thermal conductivity in the light metal layer is much higher. The axial direction heat transfer coefficient is now modeled using the Globe-Dropkin correlation [Globe and Dropkin, 1959], while the lateral direction heat transfer coefficient is modeled using the Churchill-Chu correlation [Churchill and Chu, 1975]. Besides these correlations, MAAP5.03 is also equipped with a model to address eddy diffusivity when the light metal layer is very thin. Figure 4 shows the comparison of the heat flux from the metal layer to the vessel wall with and without the eddy diffusivity model. If eddy diffusivity is considered, the heat flux to the reactor vessel wall will not be increasing as the thickness of the light metal layer is decreasing. Instead, it reaches a maximum then decreases with decreasing thickness of the light metal layer.

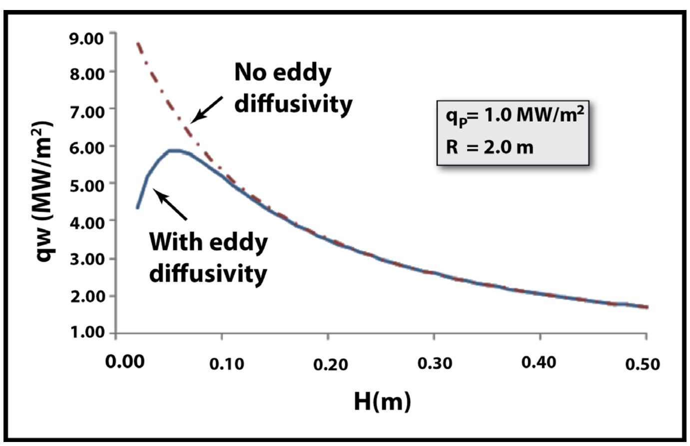


**Figure 4: Comparison of heat flux from the light metal layer to the reactor vessel with and without the Eddy Diffusivity Model**

If water is present in the vessel, MAAP5.03 evaluates the heat transfer from the corium to the water. Particularly, it models a gap that may be created between the crust surrounding the oxidic layer and reactor vessel wall. Water may penetrate into the gap and cool the vessel wall from the inside.

The most important feature of IVR is to flood the reactor cavity so that the vessel can be cooled from the outside. The CHF on the outer surface of the vessel wall imposes the thermal limit. In designs such as AP1000 or APR1400, an insulator (baffle) was added around the reactor vessel to create a cooling channel, so that natural circulation can be established between the water pool in the cavity and the cooling channel. The natural circulation flow will increase the CHF. MAAP5.03 uses experiment based correlations to model the heat transfer coefficient between the reactor vessel wall and the cooling channel. These include Yang's correlation for a plain vessel with and without enhanced natural circulation, and ULPU-2000 correlations.

If the heat flux exceeds the flux limits, the reactor vessel may fail due to creep rupture. It may also fail because of jet impingement or penetration tube failure. MAAP5.03 models creep rupture and other mechanisms when the vessel wall is thermally attacked by the corium from the inside.

In summary, MAAP5.03 models key phenomena related to the corium pool, reactor vessel wall and heat transfer mechanisms. It provides capability and flexibility for severe accident analyses involving IVR specific designs and actions.

## Sample IVR Calculation

MAAP5.03 has been used to evaluate the IVR in a Pressurized Water Reactor (PWR) plant with passive safety systems. The evaluation assumes a direct vessel injection (DVI) line break with failure of in-vessel injection at time zero. It also assumes AC power is unavailable and only passive safety systems are available. The hemispherical lower head is nodalized into 25 nodes from the bottom (0°) to the top (90°). To simulate the heavy metal layer, it is assumed that 100% of unoxidized Zr is mixing with the oxidic layer and participates in the heavy metal generation. It also assumes that 5000 kg of steel which is in the lower plenum equipment is mixing with the oxidic layer to generate the heavy metal. The rest of the steel in the lower head corium pool floats to the top to form the light metal layer. A conservative emissivity of 0.43 is assumed at the top of the light metal layer for radiation heater transfer calculations.

Figure 5 shows the evolution of the corium pool. Corium is present in the lower head around 3000 s after the DVI line break. The fragmented corium forms a particle bed on top of the upper crust. As the water in the lower head dries out, the particle bed is melted and eventually merged with the oxidic layer and the metal layer. A heavy metal layer is generated at around 5500 s, with the total mass of heavy metal at 17,510 kg. The thickness of the heavy metal layer is about 0.6 m. At the time of heavy metal formation, the light metal layer thickness is around 0.71 m.

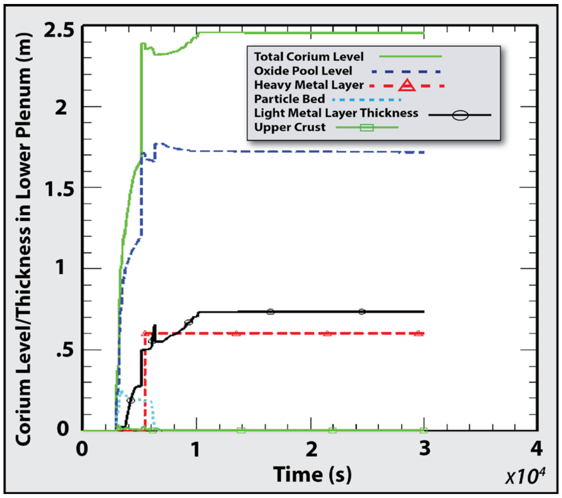


**Figure 5: Level and thickness of regions in the corium pool**

Figure 6 shows the ratio of the heat flux from the light metal layer to the reactor vessel wall nodes (node number 23, 24 and 25) to the CHFs on the outer surface of the vessel wall. The peak ratio is around 70%. This shows IVR for this postulated severe accident condition is successful and the margin of the heat flux to CHF is around 30%.

Figure 7 shows a snap shot of the lower plenum corium pool and the reactor lower head wall. The wall thickness is nodalized into 5 nodes or layers. Figure 7 shows that for the lower head wall portion covered by the light metal layer, the inner most 4 nodes are fully ablated and only the 5th node still exists. The results are consistent with the expectation of IVR success for this plant.

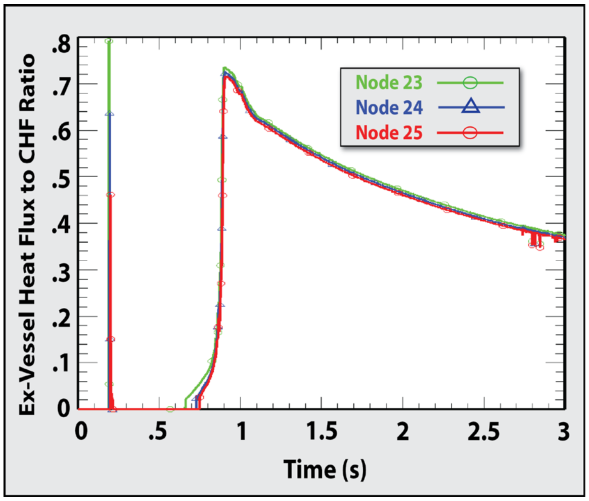


**Figure 6: Ratio of inner surface heat flux to CHF on the outer surface in the nodes covered by light metal layer**

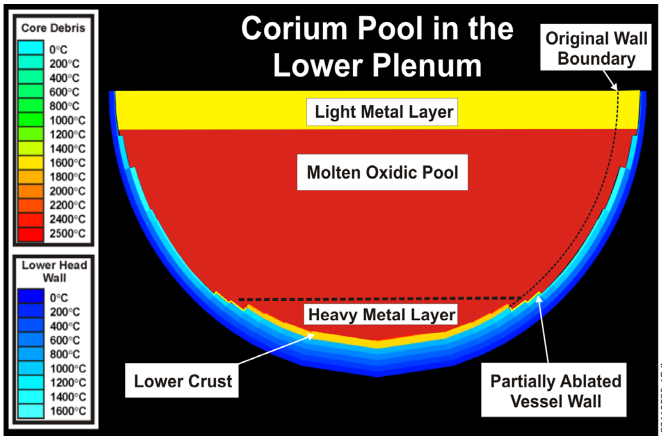


**Figure 7: Snap shot of lower head corium pool and reactor vessel wall**

## Summary

IVR is a preferred severe accident management strategy used by a number of new PWR designs. The latest MAAP5.03 release has been significantly improved to provide the capabilities to users to perform IVR analysis. These include a new heavy metal layer model and improved models for in-vessel and ex-vessel heat transfers. With the latest MAAP5.03 code, users should be able to perform IVR calculations in their plant with a one-time analysis starting from an initiating event. This will help users to perform their analyses supporting PRA and deterministic studies of IVR in a more efficient way.

## References

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