In-Vessel Retention Analysis for Pressurized Light Water Reactors with In-Vessel Injection and External Reactor Vessel Cooling using MAAP5 Code

Jeong Seong Lee*, In Chul Ryu
KEPCO E&C, 269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660
**Corresponding author: letojslee@kepco-enc.com*

1. Introduction

If the reactor vessel fails, molten core debris will relocate into the reactor vessel cavity where it can release fission products and challenge containment integrity due to molten-core-concrete interaction. In-vessel retention of the molten core is a key goal of severe accident management strategies. In order to achieve this goal, lower head failure must be prevented by stabilization of the molten core. In-vessel injection (IVI) is capable of stabilizing the molten core, prior to relocation into the lower plenum if injection is initiated early enough. External reactor vessel cooling (ERVC) is achieved by flooding the reactor vessel cavity such that water removes decay heat through the reactor vessel wall.

The purpose of this paper is to evaluate in-vessel retention capabilities with IVI and external reactor ERVC available in a reactor application by using the integrated severe accident analysis code.

2. Analysis Methods and Inputs

The general approach taken in this paper to determine the in-vessel retention capability for a PWR is to analyze severe accident sequences using the Modular Accident Analysis Program version 5.03 (MAAP5.03)[1] to determine the capability for core debris to be retained in-vessel when some combination of IVI and ERVC are available to mitigate an accident. The reactor design includes a reliable reactor vessel depressurization method, a reactor vessel insulation design that promotes heat transfer to water, and a heavy metal layer model. The reliable depressurization method is important because it reduces the strain on the reactor vessel lower head during In-Vessel Retention (IVR) and it allows for the injection of water into the vessel using portable low pressure pumps. The insulation design increases the amount of heat that can be removed from the outside of the reactor vessel lower head when it is submerged in water. The MAAP5.03 code is equipped with a heavy metal layer model to assess heavy metal formation. If the temperature in the molten part of oxidic pool is greater than the miscibility gap transition temperature (2,670 K) the chemical reactions forming heavy metal are evaluated in the code.

2.1 Key MAAP5.03 Models

The ability to retain core debris in-vessel is governed by 3 competing phenomena:

1. Heat generation within the debris and the transfer of heat to surrounding materials,
2. Vessel failure due to heat transfer to the vessel wall, and
3. Heat removal from the debris and vessel wall by the addition of water.

MAAP5 models include the fraction of un-reacted Zr remaining in the metal layer, emissivity of the metal layer, existence of instrument penetration tubes in the lower head, and the in-vessel fission product release model, which affects the decay heat in the debris.

2.2 Ex-Vessel Cooling

The MAAP5 model for external RPV cooling channel is structured to be consistent with the RPV nodalization scheme in the lower head and cylindrical section. Water flow over the external surfaces is driven by the natural circulation due to the density difference between water outside the cooling channel and two-phase mixture in the channel. Fig. 1 shows the nodalization used in the cooling channel.

Quasi-steady state is assumed to determine the average density of the two-phase mixture and level in the cooling channel. Starting from the bottom of the channel, mass, momentum, and energy equations are written for individual channel nodes.

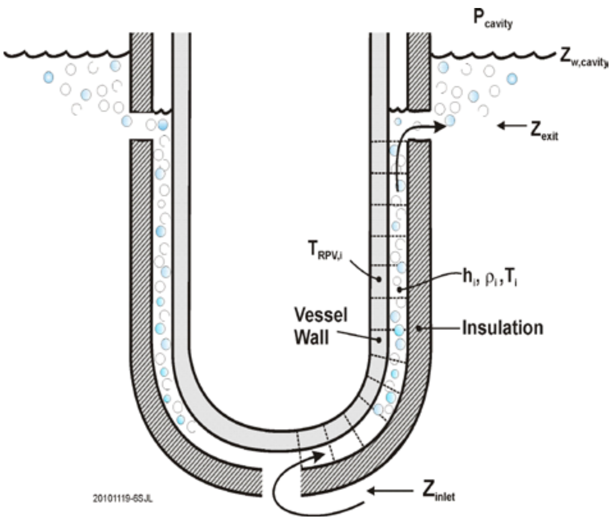

Fig. 1. Nodalization in cooling channel

2.3 Determination Gap Thickness

One of the key inputs that influences the calculation of in-vessel retention capabilities is the initial gap size between core debris in the reactor vessel lower head and the reactor vessel lower head wall. This input governs the amount of the heat that is able to be removed from the side curst of the corium pool by means of gap cooling.

The gap thickness model is combined with an equation for the bending stress in an elastic plate to rationalize the gap behavior observation of Kang et al [2] and the reported thermal response of the TMI-2 vessel wall to corium relocation event [3].

2.4 Sequence Definitions

Three initiators are considered in this analysis: a Large Break Loss of Coolant Accident (LBLOCA), a Small Break Loss of Coolant Accident (SBLOCA), and a Total Loss of Feedwater (TLOFW). All sequences are run assuming that ERVC is initiated via one shutdown cooling pump at the time when core exit temperature exceeds 1,200 °F. For all initiators except the LBLOCA, the RCS is assumed to be depressurized using 2 POSRVs at the same time of ERVC initiating.

3. Analysis Results

3.1 LBLOCA Sequence results

LBLOCA sequence has an IVI delay of 60 minutes and does not result in vessel failure. Fig. 2 shows a comparison of the core material mass distribution. Fig. 3 shows a plot of the temperature of core debris at various locations. A key function of IVI is to arrest core melt progression in-core and limit the amount of core material relocated to the lower head. Fig. 4 shows the snapshot of the core debris in the lower plenum at the end of the run. The lighter metal layer sits on top of the heavier oxidic corium pool, with a thin upper crust between them. Table I summarizes the key results for this sequence.

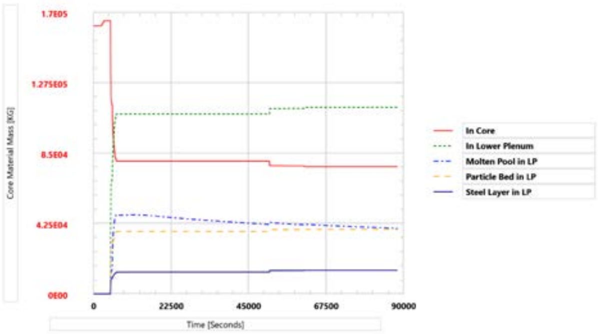

Fig. 2. Core Material Mass Distribution for LBLOCA Sequence

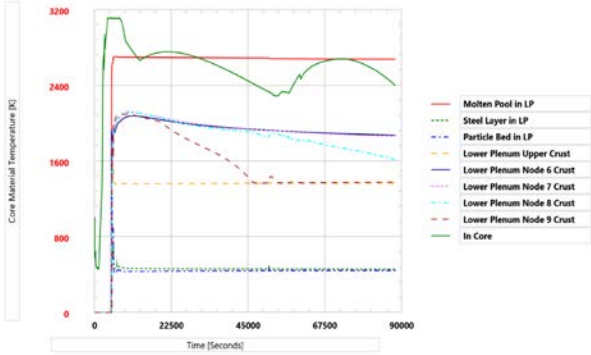

Fig. 3. Core Material Temperature Distribution for LBLOCA Sequence

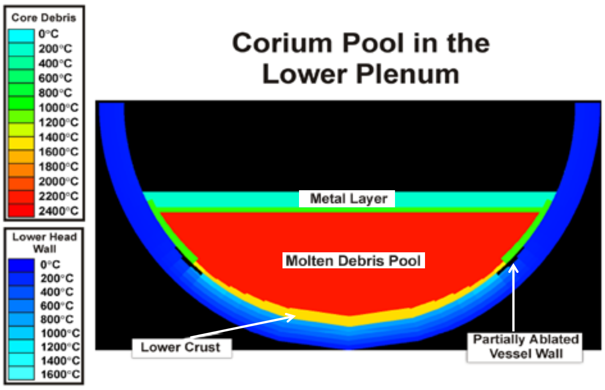

Fig. 4. Corium pool in the lower plenum at the end of run for LBLOCA Sequence

Table I: Run Results Summary for LBLOCA Sequence

Core Damage	29.96 minutes
ERVC Actuated	29.96 minutes
Depressurization via POSRVs Actuated	Not actuated
Core Relocation	1.35 hours
IVI Actuated	1.50 hours
Vessel Failure	No vessel failure
Vessel Failure Mechanism	N/A.

3.2 SBLOCA Sequence results

SBLOCA sequence has an IVI delay of 4 hours and does not result in vessel failure. Fig. 5 shows a comparison of the core material mass distribution. Table II summarizes the key results for this sequence.

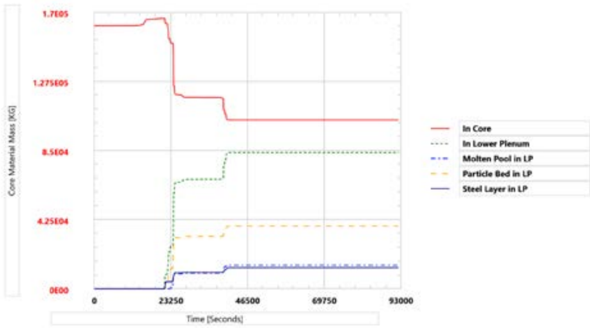

Fig. 5. Core Material Mass Distribution for SBLOCA Sequence

Table II: Run Results Summary for SBLOCA Sequence

Core Damage	1.62 hours
ERVC Actuated	1.62 hours
Depressurization via POSRVs Actuated	1.62 hours
Core Relocation	5.94 hours
IVI Actuated	5.62 hours
Vessel Failure	No vessel failure
Vessel Failure Mechanism	N/A.

3.3 TLOFW Sequence results

TLOFW sequence has an IVI delay of 3 hours and does not result in vessel failure. Fig. 6 shows a comparison of the core material mass distribution. Fig. 7 shows the primary system pressure, in-vessel injection mass flow rate, and water level in the core region. Table III summarizes the key results for this sequence.

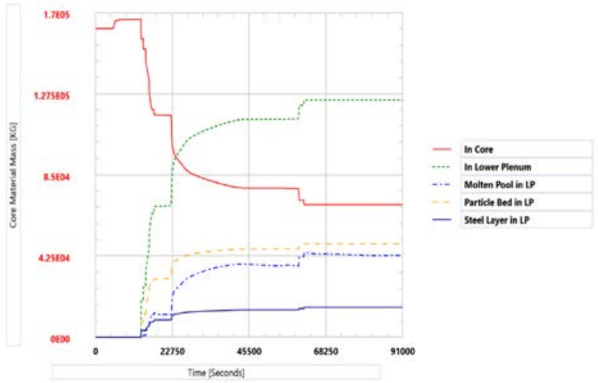

Fig. 6. Core Material Mass Distribution for TLOFW Sequence

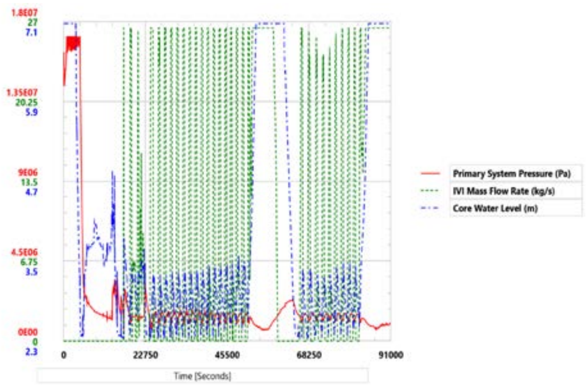

Fig. 7. In-Vessel Injection Conditions for TLOFW Sequence

Table III: Run Results Summary for TLOFW Sequence

Core Damage	1.25 hours
ERVC Actuated	1.25 hours
Depressurization via POSRVs Actuated	1.25 hours
Core Relocation	3.74 hours
IVI Actuated	4.25 hours
Vessel Failure	No vessel failure
Vessel Failure Mechanism	N/A.

4. Conclusions

The general approach taken in this paper to determine the in-vessel retention capability for PWR is to analyze severe accident sequences using MAAP5.03 code to determine the capability for core debris to be retained in-vessel when some combination of IVI and ERVC.

The MAAP5 models were improved to facilitate evaluation of the in-vessel retention capability of a PWR. In-vessel retention capabilities have been analyzed for the PWR using the MAAP5.03 code.

The results show that in-vessel retention is feasible when in-vessel injection is initiated within a relatively early timeframe under the simulation condition used in the present study.

REFERENCES

[1] EPRI, MAAP5 User's Guidance, August 2014.
[2] Kang, K.H. et al., 2006, "Experimental Investigations on In-Vessel Corium Retention Through Inherent Gap Cooling Mechanisms," J. Nuclear Science and Technology 43, pp. 1490-1500.
[3] Wolf, J. R. and Rempe, J. L., 1993, "TMI-2 Vessel Investigation Report," Idaho Nat'l Eng. Lab. Report TMI V(93) EG10 (October).