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Evaluation for In-Vessel Retention Capabilities with In-Vessel Injection and External Reactor Vessel Cooling

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1. Introduction

If a severe accident were to occur in a nuclear reactor, it would be due to inadequate heat removal brought about by either a loss of coolant or a loss of sufficient heat removal capacity as might be the case in a station blackout scenario. Given such a state, the most important objective of accident management actions is to establish cooling of the nuclear fuel. If the accident has not progressed to the point of substantial changes in the core geometry, establishing adequate cooling is as straightforward as re-establishing flow through the reactor core. However, if the accident has progressed to the point where the core geometry is substantially altered as a result of material melting and relocation, as was the case in the TMI-2 accident[1], the means of cooling the debris are not as straightforward. In the TMI-2 accident, the core configuration was significantly degraded at the time that the 2B reactor coolant pump was restarted at two hours and fifty-four minutes into the accident[2]. From this time on, the reactor core was either completely or nearly covered by water, with high pressure injection flow initiated shortly after three hours into the accident. However, the core debris was not coolable in this configuration and a substantial quantity of molten core material drained into the bypass region, with approximately twenty metric tons of molten debris draining into the reactor pressure vessel (RPV) lower head. Hence, the core configuration developed at approximately three hours into the accident was not coolable, even submerged in water.

The purpose of this paper is to evaluate in-vessel retention capabilities with in-vessel injection (IVI) and external reactor vessel cooling (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 APR1400 is to analyze various severe accident sequences using the Modular Accident Analysis Program version 5.03 (MAAP5.03)[3] to determine the capability for core debris to be retained in-vessel when some combination of In-Vessel Injection (IVI) and ERVC are available to mitigate an accident.

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.

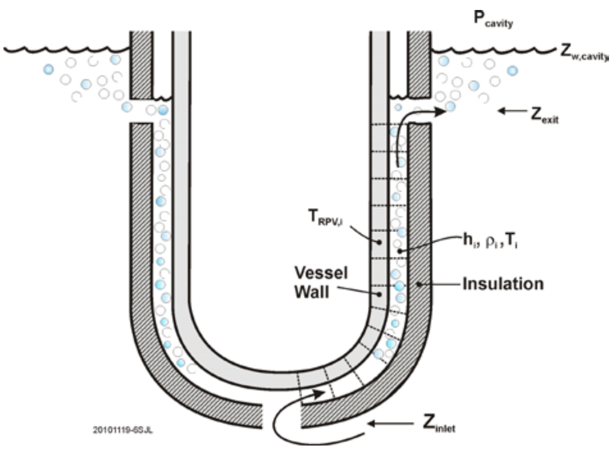

Fig. 1. Nodalization in cooling channel

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.

2.3 Sequence Definitions

One initiator is considered in this analysis: a Large Break Loss of Coolant Accident(LLOCA). The sequence is run assuming that ERVC is initiated via one shutdown cooling pump at the time when core exit temperature exceeds 1,200 °F.

3. Analysis Results

LLOCA 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 the lower plenum corium pool depth. 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.

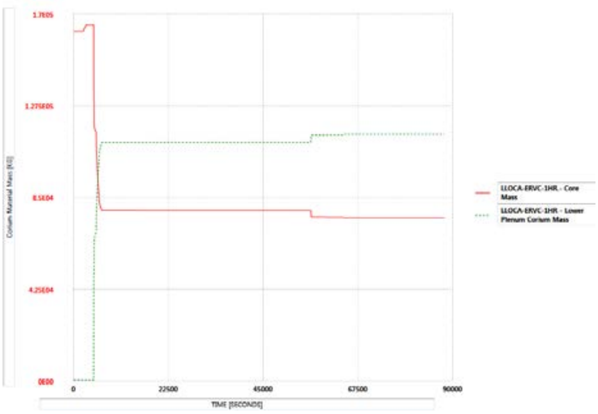

Fig. 2. Core Material Mass Distribution for LLOCA Sequence

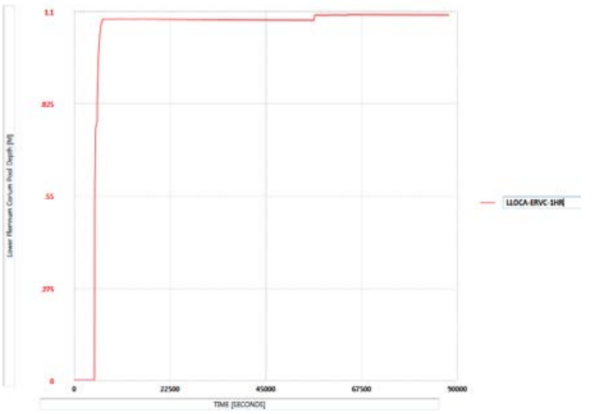

Fig. 3. Lower Plenum Corium Pool Depth for LLOCA Sequence

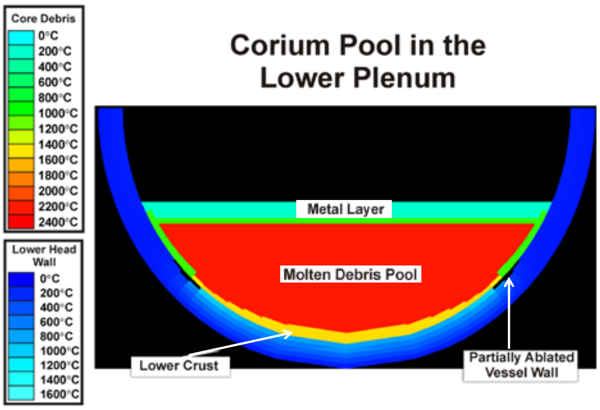

Fig. 4. Corium pool in the lower plenum at the end of run for LLOCA Sequence

Table I: Run Results Summary for LLOCA 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.

4. Conclusions

The MAAP5 models were improved to facilitate evaluation of the in-vessel retention capability of APR1400. In-vessel retention capabilities have been analyzed for the APR1400 using the MAAP5.03 code.

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

REFERENCES

[1] Wolf, J. R. and Rempe, J. L., 1993, "TMI-2 Vessel Investigation Report," Idaho Nat'l Eng. Lab. Report TMI V(93) EG10 (October).
[2] Nuclear Safety Analysis Center (NSAC), 1980, “Analysis of Three Mile Island-Unit 2 Accident,” Nuclear Safety Analysis Center Report, NSAC-80-1.
[3] EPRI, MAAP5 User’s Guidance, August 2014.