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Vessel failure study with IVI strategy base on MAAP code

KyoungTae Kim, Mi-Ro Seo, Sangwoo Shin
Korea Hydro & Nuclear Power., LTD, Central Research Institute, [34101] 70, Yuseong-daero 1312 beon-gil, Yuseong-gu, Daejeon, Korea
lucky.kt0318@khnp.co.kr

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1. Introduction

A severe accident (SA) refers to a series of events starting from core damage to the rupture of the reactor vessel and containment building. It includes various physical phenomena that can occur during these processes. At nuclear power plants, numerous strategies are being devised to counteract and to mitigate the threat due to severe accident phenomena. Among them, the strategy of mitigating severe accidents through in-vessel injection (IVI) is performed directly injecting the coolant into the reactor pressure vessel (RPV) to confine the molten core material inside the RPV during a severe accident. In-vessel injection has slight difference depending on whether it is performed before or after the molten core material is relocated. If IVI is performed before the molten core material, it can be expected to reduce the amount of molten core material, thereby confining it inside the pressure vessel. If IVI is performed after the molten core material is relocated to the bottom of the pressure vessel, it may help cool decay heat, but there is significant uncertainty about its behavior. The Accident Management Plan (AMP) of nuclear power plants in Republic of Korea guides the implementation of in-vessel (coolant) injection strategies to mitigate severe accidents. To verify the effectiveness of this strategy and confirm the integrity of the vessel, this study aims to evaluate accidents without IVI strategy, with IVI strategy and delaying the IVI time by 10 minutes compared to the original strategy.

2. Analysis Methodologies

In this study, the progression of severe accidents and their strategic analysis utilize the Modular Accident Analysis Program (MAAP 5.06 version), developed by EPRI. And the accident scenarios and analysis conditions for this study are detailed below.

2.1 Accident Scenarios

The conditions for nuclear power plants entering into severe accidents are various. These diverse severe accidents can be classified into high-pressure and low-pressure accidents. High-pressure accidents occur when the pressure within the reactor coolant system remains elevated, while low-pressure accidents happen when coolant is lost due to pipe ruptures or similar incidents. If appropriate operator actions are not taken in either type of accident or if there are additional equipment failures, it may develop into a severe accident. Generally, the five deterministic accident scenarios were considered, such as large, medium, and small loss of coolant accidents (LLOCA, MLOCA, SLOCA), loss of feedwater (LOFW) and station blackout (SBO). Specifically, loss of feedwater (LOFW) is selected as the high-pressure accident scenario, and large-break loss of coolant accident (LLOCA) is chosen as the low-pressure accident scenario. For conservative accident simulation, the LLOCA (9.5 inches) among low-pressure accidents was selected, and among high-pressure accidents, LOFW was chosen since vessel failure occurs faster than SBO in the both case (without IVI strategy and delaying IVI time). And the targeted power plant for this analysis is the Westinghouse (WH) 3-loop type.

2.2 Major Assumption for Analysis

The major assumptions for initial condition used in these analyses were described in Table I.

Table I. Initial condition of each scenario

Scenarios / Description	LOFW	LLOCA
HPI FORCED OFF	O	O
LPI FORCED OFF	O	O
CHARGING PUMPS FORCED OFF	O	O
FANS/COOLERS FORCED OFF	O	O
ESF UPPER/LOWER COMPARTMENT SPRAYS FORCED OFF	O	O
MAIN FW SHUT OFF	O	X
MOTOR-DRIVEN AUX FEED WATER FORCED OFF	O	O
Break in the Cold Leg	X	O (9.5″)

3. Analysis Result

3.1 Simulation without in-vessel injection

Simulations of LOFW and LLOCA scenarios without IVI resulted in vessel failure represented the ICI tube failure mode. In both cases, failure occurred at the same location —node 8 — corresponding to the lower head of the reactor vessel. From these results, it can be checked that vessel failures around the weld area occurred similarly in both high-pressure (LOFW) and low-pressure accidents (LLOCA), indicating significant vulnerability during severe accidents. These details can be confirmed in the MAAP results and can be organized as shown in Table II.

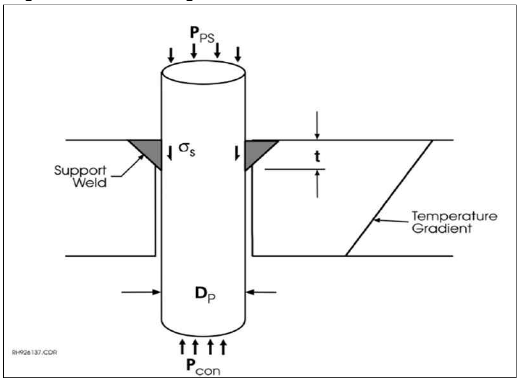
Table II. Vessel Failure Result without IVI

Scenarios / Description	LOFW	LLOCA
V.F. mode	ICI tube failure	ICI tube failure
No. of node	8[1)]	8
V.F. timing	5.73hr	2.24hr

1)node number: In the MAAP code, the low head vessel is divided into 25 nodes.

And failure of penetration among vessel failure mechanisms can be confirmed through Fig.1 below. [1]

Fig I. Forces Acting on a Reactor Vessel Penetration.



3.2 Simulation with in-vessel injection

When IVI was applied after the onset of severe accident conditions, vessel failure was successfully prevented in both LOFW and LLOCA scenarios. The injected coolant suppressed core temperature escalation and stabilized the pressure vessel. These results confirm that IVI is an effective countermeasure when deployed promptly.

3.3 Simulation with in-vessel injection time delay

To assess the sensitivity of IVI effectiveness to injection timing, simulations were conducted with incremental delays of 10 minutes.

- In the LOFW scenario, vessel failure occurred when IVI was delayed by 80 minutes.
- In the LLOCA scenario, vessel failure occurred when IVI was delayed by 40 minutes.

Table III: Vessel Failure Result with incremental delays of IVI

Scenarios / Description	LOFW	LLOCA
IVI strategy[2)] +30min delay	-	Relocation
IVI strategy +40min delay	-	**Relocation and Vessel Failure**
IVI strategy +50min delay	Relocation	Relocation and Vessel Failure
IVI strategy +60min delay	Relocation	Relocation and Vessel Failure
IVI strategy +70min delay	Relocation	Relocation and Vessel Failure
IVI strategy +80min delay	**Relocation and Vessel Failure**	Relocation and Vessel Failure

2)IVI strategy: severe accident entry time + 2hr

These results indicate that while IVI remains effective within a certain time to protect vessel failure, its protective capacity diminishes significantly beyond that point. And as examined in Section 3.1, the mode of vessel failure here is ICI tube failure, and the location of occurrence is identical in both incidents at node No.7.

Table IV. Vessel Failure Result with delaying IVI

Scenarios / Description	LOFW	LLOCA
V.F. mode	ICI tube failure	ICI tube failure
No. of node	7	7
V.F. timing	7.21hr	3.65hr

4. Conclusions

The MAAP-based analysis confirms that in-vessel injection is a highly effective strategy for mitigating severe accident progression in nuclear reactors. Even when delayed, IVI can maintain vessel integrity up to a critical threshold, offering valuable flexibility in emergency response. In this study, it is difficult to identify the vessel failure location's difference between that the IVI strategy was not performed (node 8) and the IVI strategy was delayed (node 7). To develop this study, if analyses using structural analysis are conducted, it will be possible to accurately assess the structural integrity of the RPV.

REFERENCES

[1] MAAP5 User manual, EPRI, 2021