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Transient Analysis of Loss of All AC Power While on Shutdown Cooling for WH 2-Loop Nuclear Power Plant

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1. Introduction

The Fukushima Daiichi nuclear power plant (NPP) accident was caused by tsunami. As a result, the plant had been performed Station Black-Out (SBO), and occurred reactor core melt-down and release of radioactive materials. After the accident, the equipment and strategies against the Extended Loss of All AC Power (ELAP) were recommended strongly in the nuclear industry and regulatory body in the world.

The purpose of this study is to provide strategies for maintaining core cooling and protecting the reactor core in the event of complete loss of all AC power while on Residual Heat Removal (RHR) cooling. In this study, in order to comprehend the Fukushima accident, the transient analysis was performed to provide insights into mitigating strategies for SBO while on a shutdown state using the RELAP5/MOD3.3 code.

2. Modeling for Analysis

The RELAP5/MOD3.3 code has been developed for best-estimate transient simulation of reactor coolant system during accident [1]. This code is a tool that allows users to model the coupled behavior of the reactor coolant system and reactor core during accidents. The reactor coolant system behavior is calculated using a two-phase model, which allows unequal temperatures and velocities for the two phase flow.

The objective of this analysis is to have insights on the behavior of the RCS in a sequence of the time to boil-off, core uncovery and core damage etc.

The modeling of the Westinghouse (WH) 2-Loop NPP has been developed using the design data. Fig.1 shows the nodalization model of WH 2-Loop NPP for the analysis. Kori Unit 2 was chosen as a reference plant. The nodes of reactor are composed of the down-comer, lower plenum, upper plenum, core, and junction to connect with the hot leg.

The pressurizer includes the 10 sub-control volumes and imaginary control volume to maintain the pressure uniformly during the steady state. However, this volume is removed during the transient state.

The secondary side of SG includes the nodes of the main feed-water system, evaporator, riser, separator, and dome.

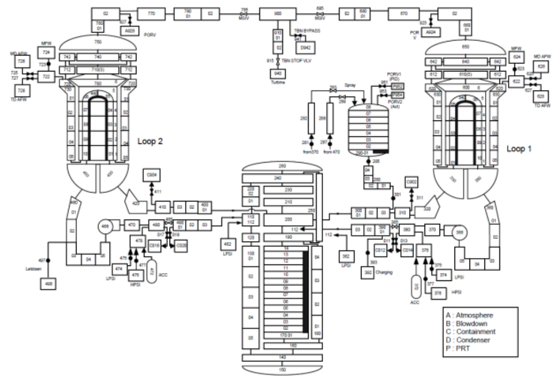

Fig.1. Nodalization Model of WH 2-Loop NPP

3. Analysis Assumption and Results

3.1 Shutdown State A

In Shutdown State A, the reactor coolant system is intact, and one or more of the SGs are available for heat removal. The RHR system is the primary means of decay heat removal and Low Temperature Overpressurization Protection (LTOP) are in the system. Additionally, the SGs are either in operation or can readily be placed in operation and dumping steam using SG Power-Operated Relief Valves (PORVs) is possible through remote or local means or both [2]. In Shutdown State A, the only available systems are LTOP, SG PORV and secondary external injection.

3.1.1 Assumption (Case-A1 ~ A3)

Assumptions in the analysis are as follows:

<u>Case-A1</u>
- The SBO occurs at 0 seconds
- No operator actions

<u>Case-A2</u>
- The SBO occurs at 0 seconds
- One SG PORV open by operator (4,000 sec)

<u>Case-A3</u>
- The SBO occurs at 0 seconds
- One SG PORV open by operator (4,000 sec)
- Secondary external injection (initial flow rate : 9.97 kg/sec, external water source) (5 hr)

3.1.2 Results (Case-A1 ~ A3)

In Case-A1 ~ A3, the sequence of events is provided in Table 1. Fig.2 and 3 show core void fraction and fuel cladding temperature (Case-A1~A2). In Case-A1, there are no operator actions so that the upper core was uncovered at 15,120 sec (4.20 hr) and core damage occurred at 17,800 sec (4.94 hr) during SBO. In Case-A2 (operator opens a SG PORV manually), upper core was uncovered at 28,660 sec (7.96 hr) and core damage occurred at 31,580 sec (8.77 hr). It is confirmed that the core uncovery time can be extended about 3.7 hours. It is assumed in Case-A3 that secondary external injection by operator is provided at 5 hours to avoid core boiling. According to Case-A2, core boiling occurred at 22,190 sec (6.16 hr). Fig.4 and 5 show core void fraction and fuel cladding temperature (Case-A3). The fuel cladding temperature does not increase and the core boiling does not happen. Core boiling is defined as the growth of bubbles or pops on heated surface, which rises from discrete points on a surface.

Table 1. Event Sequences for Shutdown State A

Event	Case-A1	Case-A2	Case-A3
SBO occurs	0 sec	0 sec	0 sec
SG PORV open	-	4,000 sec (1.10 hr)	4,000 sec (1.11 hr)
Secondary External injection	-	-	18,000 sec (5.00 hr)
Core boiling begins	8,150 sec (2.26 hr)	22,190 sec (6.16 hr)	
Core uncovery	15,120 sec (4.20 hr)	28,660 sec (7.96 hr)	-
Core damage	17,800 sec (4.94 hr)	31,580 sec (8.77 hr)	-

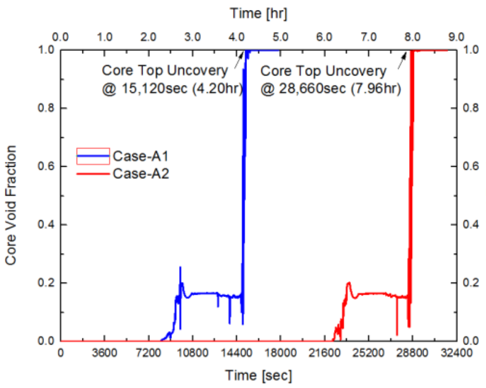

Fig.2. Core void fraction (Case-A1~A2)

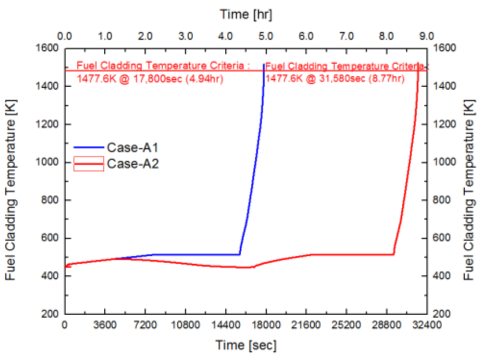

Fig.3. Fuel cladding temperature (Case- A1~A2)

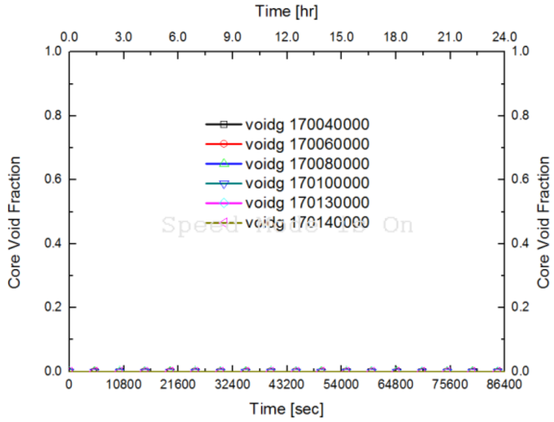

Fig.4 Core void fraction (Case-A3)

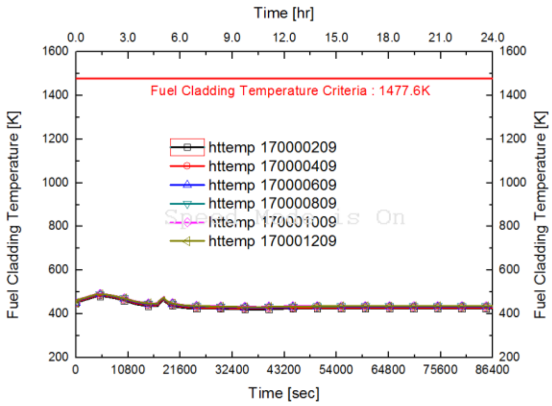

Fig.5. Fuel cladding temperature (Case-A3)

3.2 Shutdown State C

In Shutdown State C, the reactor coolant system (RCS) is vented and has been drained to the mid-plane of the hot leg. The RHR system is the only means of decay heat removal. There are no SGs available to provide core cooling. This Shutdown State is the most limiting case of the five configurations [2]. In Shutdown State C, the only available systems are LTOP, gravity feed from RWST to the primary side by operator and external injection to the primary side by operator.

3.2.1 Assumption (Case-C1 ~ C2)

Assumptions in the analysis are as follows:

Case-C1
· The SBO occurs at 0 seconds
· No operator actions

Case-C2
· The SBO occurs at 0 seconds
· Gravity feed from RWST by operator (4,000 sec)

3.1.2 Results (Case- C1 ~ C2)

In Case-C1 ~ C2, the sequence of events is provided in Table 2. In Case-C1, there are no operator actions so that the upper core was uncovered at 7,210 sec(2.00 hr) and core damage occurred at 10,980 sec(3.05 hr) during

SBO as shown in Fig.6 and 7. The core uncovery time is defined as the point when the fuel rods are no longer covered by coolant and can begin to heat up. The injecting into RCS should be initiated at least 2 hours to prevent core uncovery. Fig.8 and 9 show core void fraction and fuel cladding temperature (Case-C2). In Case-C2, the gravity feed into RCS from RWST was provided by operator at 4,000 sec, the core was not uncovered and the integrity of core was also maintained. However, the bubble in core region is not removed. The water provided by RWST gravity feed is directed to core through the downcomer, and discharged to SG manway in the shape of liquid or vapor phase. The RWST gravity feed flow will be decreased as the water level in RWST is lowered. Therefore, the long-term cooling strategy should be established by primary external injection or RWST refill.

Table.2. Event Sequences for Shutdown State C

Event	Case-C1	Case-C2
SBO occurs	0 sec	0 sec
Core boiling begins	460 sec (0.13 hr)	460 sec (0.13 hr)
Gravity feed from RWST	-	4,000 sec (1.11 hr)
Core uncovery	7,210 sec (2.00 hr)	-
Core damage	10,980 sec (3.05 hr)	-

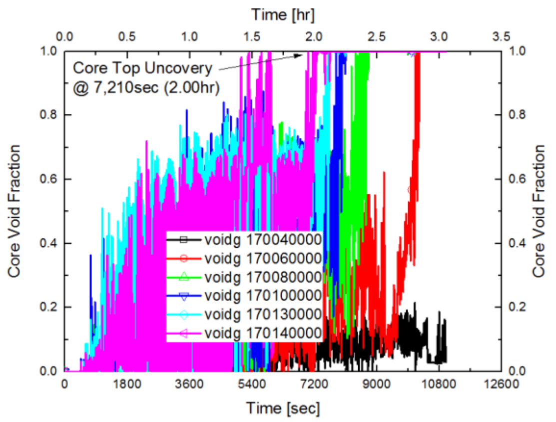

Fig.6. Core void fraction (Case-C1)

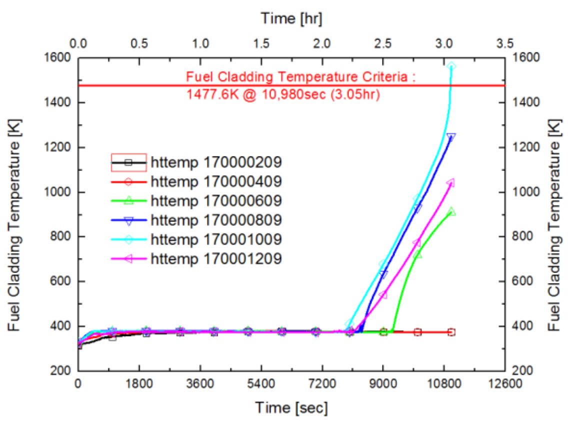

Fig.7. Fuel cladding temperature (Case-C1)

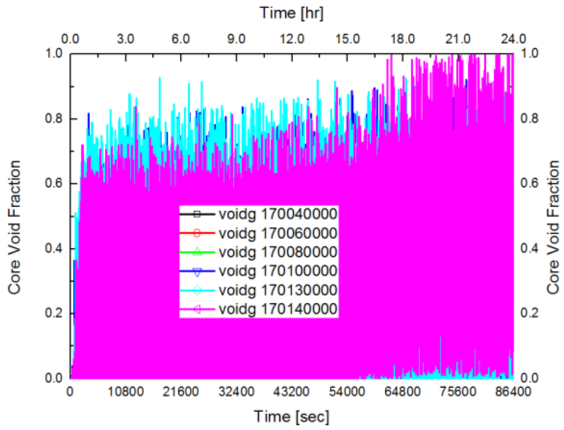

Fig.8. Core void fraction (Case-C2)

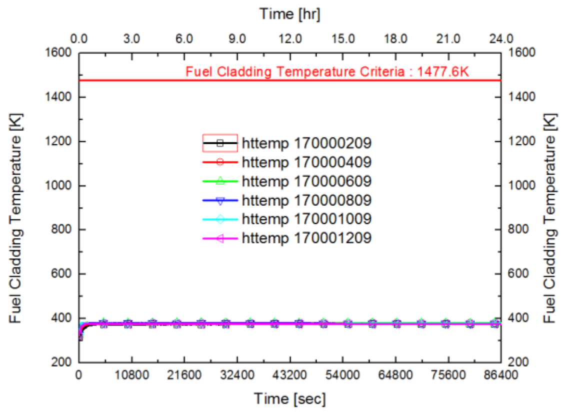

Fig.9. Fuel cladding temperature (Case-C2)

4. Conclusions

The analysis was performed to provide useful insights for operator guidelines to maintain critical safety functions during SBO for shutdown modes.

For Shutdown State A, if the SG PORV is manually opened at 4,000 sec by operator and secondary external injection by operator was provided at 5hours, the core boiling is not expected and core is cooled well.

For Shutdown State C, if RWST gravity feed by operator is provided at 4,000 sec, the core is not uncovered and core is cooled well.

This study would be useful for improving a strategy to cope with loss of all AC power while on shutdown cooling.

REFERENCES

[1] NUREG/CR-6150, "SCDAP/RELAP5/MOD 3.3 CODE MANUAL," Rev.2, Vol.3, Jan, 2001.

[2] Westinghouse, Supplemental Information for Operator Response to Extended Loss of AC Power in Modes 4, 5 and 6, PWROG-14073-P, Revision 0, March 2015.