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Transient Analysis of Station Blackout While Shutdown for OPR1000 Nuclear Power Plant

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1. Introduction

The Fukushima Daiichi event has provided significant insight into the vulnerability of nuclear power plants when Alternating Current (AC) power is lost for an extended period of time. Previous studies [1] have been completed that focus on an Extended Loss of AC Power (ELAP) event initiating from Modes 1 through 4 but little work has focused on events initiating from Modes 5 & 6. Recently, some studies [2] have been performed to support and provide useful insights for operator guidelines to maintain critical safety functions during a Station Blackout (SBO) or ELAP event for shutdown modes. Shutdown SBO Guideline [3] has been issued to provide instructions for responding to a SBO, including an ELAP, while shutdown with SIAS (Safety Injection Actuation Signal) blocked and fuel in the reactor vessel.

The thermal-hydraulic transient analysis using RELAP5/Mod3.3 code was performed to provide insights for shutdown SBO for OPR1000 NPP. It will be helpful for developing a strategy to cope with shutdown SBO for OPR1000 NPP.

2. Nodalization Model

Hanul Units 3&4 was selected as a representative plant for OPR1000 NPP. The nodalization mode is shown in Fig. 1. The nodalization model was developed based on the full power nodalization model [4]. Some models such as Low Temperature Overpressurization Protection (LTOP), Shutdown Cooling System (SCS), pressurizer manway, SG inlet manways, and Reactor Coolant Gas Vent System (RCGVS) were added.

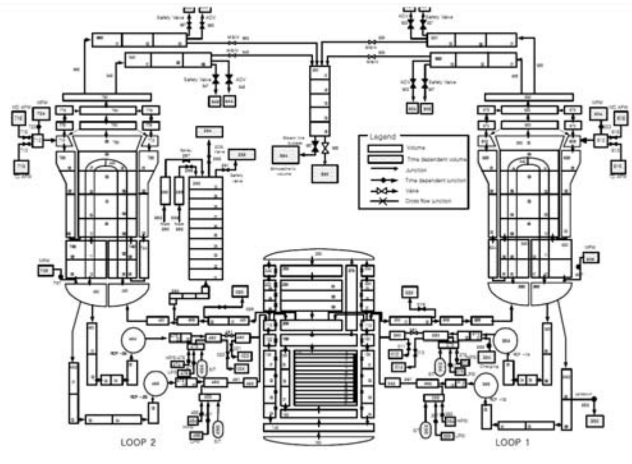

Fig. 1. Hanul Units 3&4 RELAP5 Nodalization Model

3. Plant Shutdown State Category

Plant shutdown state can be divided into the following five categories [2, 3]:

- Shutdown State A: Reactor Coolant System (RCS) intact and full with SGs available
- Shutdown State B: RCS intact but not full
- Shutdown State C: RCS vented with reactor vessel head installed
- Shutdown State D: RCS drained below reactor vessel flange with the upper head removed
- Shutdown State E: Refueling cavity flooded with the upper head removed

These categories are selected based on plant configuration such as RCS intactness, SG availability, and RCS level.

Natural circulation cooling using SG is available for Shutdown State A.

Reflux cooling using SG and Feed & Bleed cooling are available for Shutdown State B. If RCS is intact (it means that RCS can be isolated before RCS begins to boil), reflux cooling using SG is the cooling means. If not, feed & bleed cooling is the cooling means.

Shutdown State C is the most limiting case because there is the least amount of liquid mass in RCS and the decay heat is the largest for a configuration where RCS cannot be isolated. RCS makeup through Refueling Water Storage Tank (RWST) gravity feed, Safety Injection Tank (SIT), or primary external injection is required in this configuration.

Shutdown State D and E have much more liquid than Shutdown State C.

So the shutdown SBO transient analysis is performed here only for Shutdown State A and C.

4. Initial Conditions and Assumptions

4.1 Shutdown State A

Initial conditions for Shutdown State A are as follows:

- Decay heat: 18.033 MWt (32.9 hours after reactor trips)
- Primary side condition
  - Pressurizer level: 48.9%
  - Pressurizer pressure: 2.75 MPa
  - Coldleg temperature: 145℃
  - One RCP per loop in operation
  - One train of SCS in operation
- SG Secondary Side
  - Pressure: 0.463 MPa
  - Narrow range level: 44%

- Isolation of main & auxiliary feedwater
- Isolation of MSIV and ADV

If SBO occurs, the active systems or components such as RCP, SCS, auxiliary feedwater pump, feed & bleed system, pressurizer heater and spray become inoperable. But LTOP is still available. Operator can manually use SG Atmospheric Dump Valve (ADV), and secondary external injection to remove decay heat.

4.2 Shutdown State C

Initial conditions for Shutdown State C are as follows:

- Decay heat: 12.183 MWt (79.5 hours after reactor trips)
- Primary side condition
  - Pressurizer level: hotleg centerline
  - Pressurizer pressure: atmospheric pressure
  - Coldleg temperature: 40℃
  - Pressurizer manway and RCGVS open
  - Both SG inlet manways open
  - LTOP valve operable
  - No RCP in operation
  - One train of Shutdown Cooling System(SCS) in operation
- SG Secondary Side : empty

If SBO occurs, SCS becomes inoperable. Operator can manually use primary RWST gravity feed and primary external injection to remove decay heat.

5. Calculation Results

5.1 Shutdown State A

Table 1 shows the various cases for Shutdown State A. For Case A2 (operator opens SG ADV manually at 4,000 sec), the core uncovery and damage times are extended approximately 3 hours compared with Case A1 (no operator action). 4,000 sec is reasonable time for operator to open SG ADV manually in shutdown SBO situation.

For Case A2, the core begins to boil at 26,300 sec. So secondary external injection is assumed to be initiated at 6 hour in Case A3 to avoid core boiling. For Case A3, the core boiling occurs for a short time, and the fuel cladding is cooled well as shown in Fig. 2 and Fig. 3.

5.2 Shutdown State C

Table 2 shows the various cases for Shutdown State C. If there is no operator action, the core is uncovered and damaged at 6,510 sec and 11,010 sec respectively as shown in Fig. 4 and Fig. 5. If RWST gravity feed by operator is initiated at 4,000sec, then the core is cooled well and the core is not uncovered. But the void fraction in the core region is not removed and still present. 4,000 sec is reasonable time for operator to initiate RWST gravity feed manually in shutdown SBO situation.

The RWST gravity feed flow will be decreased as the water level in RWST is lowered. For long term cooling, RWST should be refilled or primary external injection is required.

Table 1: Event Sequences for Shutdown State A

Event	Time [sec]		
	Case A1	Case A2	Case A3
SBO occurs	0	0	0
SG ADV open	-	4,000	4,000
SG dryout	-	14,680	-
LTOP valve open	6,400	19,810	19,810
Secondary External Injection	-	-	21,600
Core boiling begins	15,110	26,300	21,900
Core uncovered [collapsed water level]	16,290	27,335	-
Core uncovered [void fraction]	21,360	33,160	-
Core damage	24,060	35,870	-
Calculation end	25,883	37,696	86,400

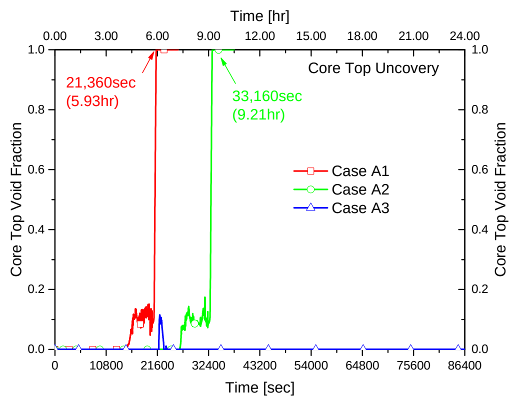

Fig. 2. Core Top Void Fraction - Shutdown state A

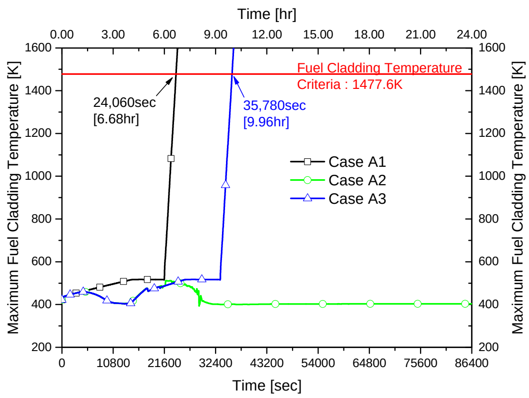

Fig. 3. Maximum Fuel Cladding Temperatures - Shutdown state A

Table 2: Event Sequences for Shutdown State C

Event	Time [sec]	
	Case C1	Case C2
SBO occurs	0	0
Core boiling begins	420	420
Core uncovered [collapsed water level]	2,060	2,060
RWST gravity feed	-	4,000
Core uncovered [void fraction]	6,510	-
Core damage	11,010	-
Calculation end	13,578	86,400

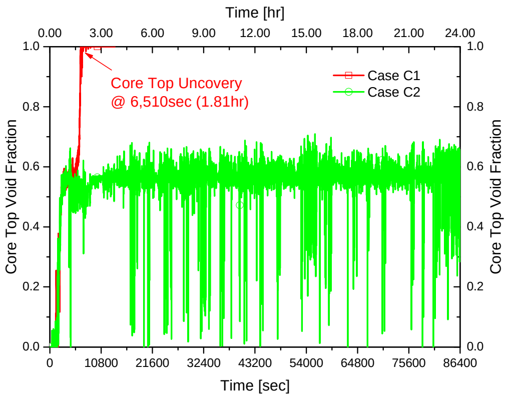

Fig. 4. Core Top Void Fraction - Shutdown state C

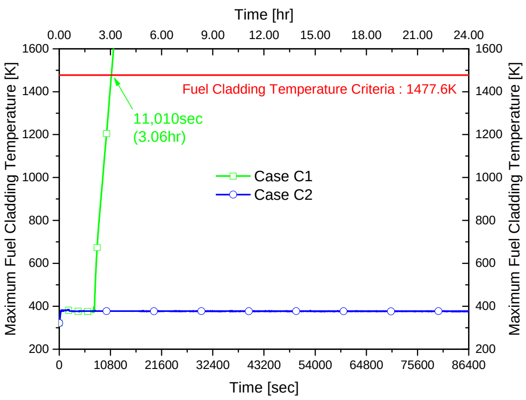

Fig. 5. Maximum Fuel Cladding Temperatures - Shutdown state C

6. Conclusion

The thermal-hydraulic transient analysis was performed to provide insights for shutdown SBO.

For Shutdown State A, if SG ADV is opened by operator manual action within 4,000 sec, then 6 hour is available to avoid core uncovery and damage. 6 hour is sufficient time for operator to prepare the secondary external injection.

For Shutdown State C, if RWST gravity feed is provided by operator manual action within 4,000 sec, then 24 hour is available to avoid core uncovery and damage. 24 hour is sufficient time for operator to prepare the primary external injection or refill RWST.

This calculation results can be directly applied to the development of Plant Specific Technical Guide (PSTG) for OPR1000 NPP.

REFERENCES

[1] Westinghouse, Reactor Coolant System Response to the Extended Loss of AC Power Event for Westinghouse, Combustion Engineering and Babcock & Wilcox NSSS Designs, WCAP-17601-P Revision 0, August 2012.

[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

[3] Westinghouse, Abnormal Procedure Guideline A1 STATION BLACKOUT WHILE SHUTDOWN GUIDELINE Revision 0, December 2014

[4] Da Hee Park, et al., "Sensitivity Analysis of Core Damage by Loss of auxiliary Feed Water during the Extended Loss of All AC", Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 29-30, 2015