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Research Article

Analysis of Fourth Stage of Automatic Depressurization System Failure to Open in AP1000 LOCA

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Abstract: Automatic Depressurization System (ADS) is a very important part of passive core cooling system in passive safety nuclear plant AP1000. ADS have four stages with each stage having two series and only ADS4 utilizes squib valves. During the accident, emergency core injecting is realized by gravity driven passive safety injection system like makeup tank (CMT), accumulator and In-Containment Refueling Water Storage Tank (IRWST). The objective e of this study is to analyze the system response and phenomenon under part of failure of ADS in AP1000 LOCA. The plant model is built by using SCDAP/RELAP5/MOD 3.4 code. The chosen accident scenario is small and medium LOCAs followed by failure of ADS4 to open, whose location is different from the other three stages. The results indicate that long time core cooling from IRWST is postponed greatly through intentional depressurization only by ADS1, 2, 3. In addition, LOCAs with equivalent diameter 25.4 cm and 34.1 cm will not lead to core melt while 5.08 cm break LOCA will. Meanwhile, high water level in the pressurizer will appear during all of three LOCAs.

Keywords: ADS, core melts, IRWST, LOCA, passive safety

INTRODUCTION

Passive core cooling system (PXS) is utilized to manage anticipated transients and LOCA by such as Chinese CPR1000 and Westinghouse's AP1000, which have been building in China. Passive safety injection system and ADS are important function parts of PXS. With regard to preventing high-pressure melt ejection, opening pressurizer safe valves manually by operator is one of the effective strategies in traditional PWR Severe Accident Management strategy (SAM) (Zhang *et al*., 2008). Correspondingly, the actuation of ADS can reduce RCS pressure to the value on which passive safety injection system start to actuate. The opening of the ADS valves is required for the passive core cooling system to function as required to provide emergency core cooling following postulated accident conditions.

In spite of the importance of ADS (Bessette, 1999), only few researchers have investigated the phenomenon of failure of ADS during severe accident because especially ADS4 utilizes squib valves which have already been utilized in aerospace and advanced boiling water reactor (Xu *et al*., 2004). Thus it is considered that the probability of the squib valves failure is very low during accident just as the conclusion given in the AP1000 Final Safety Evaluation Report (FSER) (USNRC, 2004). However, due to the Fucosima nuclear plant accident in Japan, it deserves our attention that little probability accidents such as the reliability of ADS4 and IRWST injection line squib valves in AP1000.

In the present study, SCDAP/RELAP5/MOD 3.4 code was applied for establishing AP1000 nuclear plant model to analyze LOCA in cold and hot leg followed by failure of all of ADS4' valves. It is of interesting and importance to analyze the above scenarios qualitatively even if the probability of the occurrence of the accident is very low.

Plant model: In this study, the model contains two primary loops, secondary system, passive safety injection system, passive residual heat removal system and ADS. Passive safety injection system contains two CMTs; pressure balance lines of two CMTs, two accumulators, IRWST, direct vessel injection line (Schulz, 2006) (Fig. 1).

In addition, ADS is simulated in detail which is composed of twenty valves that are divided into four stages. ADS1, 2, 3 valves are included as part of the pressurizer safety and relief valve module and are connected to nozzles at the top of the pressurizer and fourth-stage valves connect to the hot leg of each reactor coolant loop. The first three stages are clustered into two groups, with each group having one pair of motor-operated valves for each stage in which one is open and another is closed. Two sets of fourth-stage

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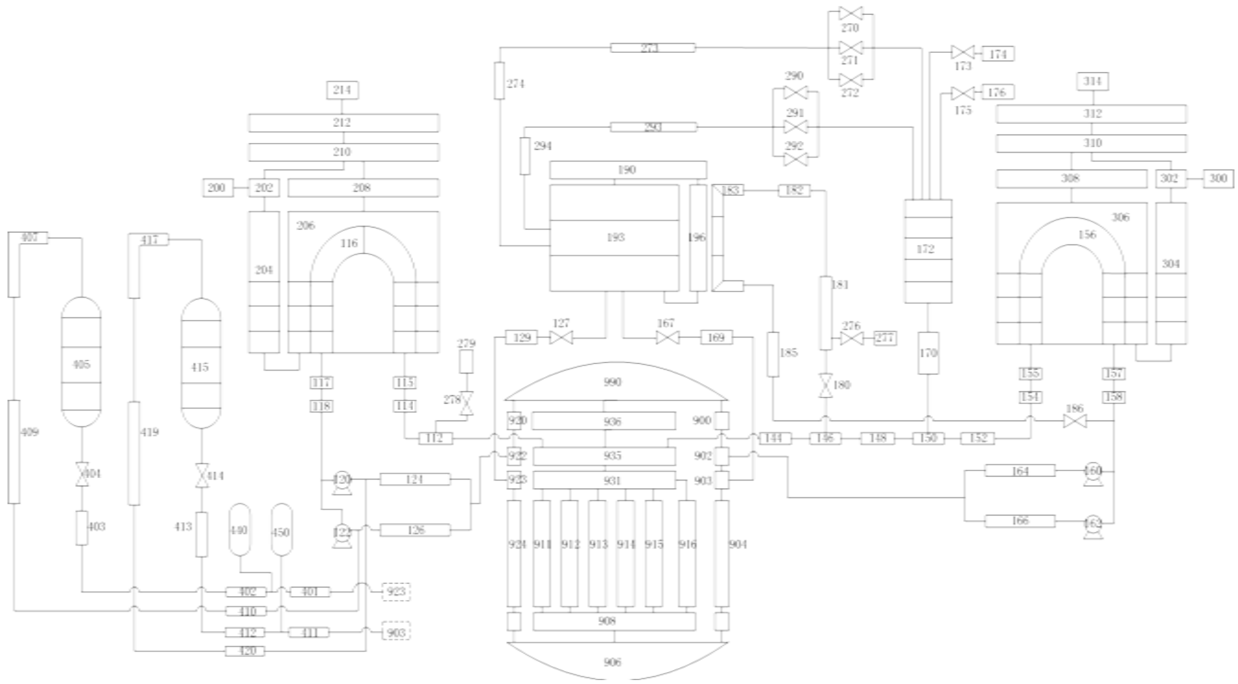

Fig. 1: Plant nodding diagram

automatic depressurization valves consist of two parallel paths of two valves in series (a total of eight valves) and each path has an opened motor-operated valve and a squib valve. All valves in model, except opened ones which are regarded as lines, are simulated by trip valves.

Accident sequences and assumption: According to Final Safety Evaluation Report (FSER) of AP000 (USNRC, 2004), the various LOCA categories of initiating events essentially dominate the Core Damage Frequency (CDF) profile represent approximately an 85% contribution. And among 10 sequences initiated by LOCA event contributing about 80% of the total CDF, small (0.952 cm to 5.08 cm equivalent break diameter) and medium (5.08 cm to 22.9 cm equivalent break diameter) LOCA event coupled with full or part depressurization contribute 2% of the CDF, respectively.

Furthermore, according to Probabilistic Risk Assessment (PRA) of AP1000, one of major contributors to uncertainty associated with CDF is LOCA breaks of all sizes (large, inter-medium, medium and small) and LOCA break section area which is more than 0.093 m^3 is considered as large LOCA. Thus, this paper selects 5.08, 25.4 and 34.1 cm, respectively equivalent break diameter breaks on cool and hot leg as initial accident to discuss for comparing obviously.

In this study the following conditions are assumed: accident starts at 0s; the reactor core can scram; auxiliary feed pumps are available and secondary side can provide effective heat sink; CMTs, accumulators, IRWST and relative lines are effective; PRHR HX is not effective; ADS1, 2 ,3 are effective but ADS4 is not; conservative decay heat assumption which 1.2 times as much as decay heat in ANS5.1-1971 standard; CMT injection delays for 10s; loop compartment pressure which ADS4 link to is atmospheric pressure. And according to FSER, in the LOCA process, core cooling is considered acceptable and the accident is over as long as IRWST begin to inject water into core continuously.

CALCULATION RESULTS AND ANALYSIS

First, system steady state is calculated to adjust the difference between main system parameter such as RCS pressure, temperature, flow, pressurizer pressure, water level, steam generator feed water flow, steam pressure, temperature, flow, etc. and their corresponding best-estimate value to less than 1%.

At the beginning of accident, the RCS pressure drops quickly because of the reactor scram and the depressurization of the breach (Fig. 2 and 3). When triggering the "S" signal by the scram of reactor, 4 coolant pumps start to idle run. After that, accumulators and CMTs begin to inject water into core as long as the RCS pressure drop to respective opening pressure (Table 1 and 2). At the same time, PRHR HX begins to actuate, but the valve fails to open. CMT injecting lasts for a while until the water level in CMT drops to a level low enough that ADS1 actuates and pressurizer electric heater lock followed by activating of ADS 2, 3 (Fig. 4 and 5). When the water level in CMT drops to a level

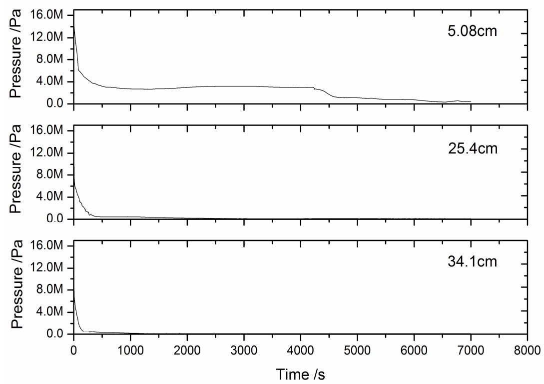

Fig. 2: Pressure in pressurizer in cool leg condition

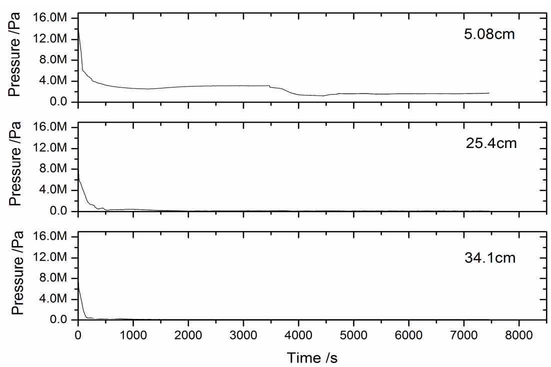

Fig. 3: Pressure in pressurizer in hot leg condition

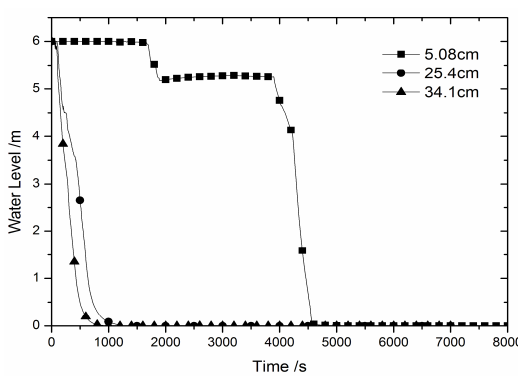

Fig. 4: Water level in CMT in cool leg condition

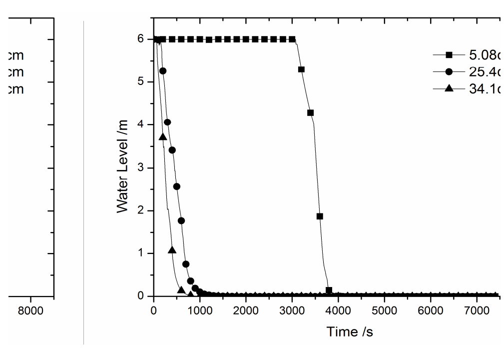

Fig. 5: Water level in CMT in hot leg condition

Table 1: Time window of LOCA in cool leg scenario

Progression (s)	5.08 cm	25.4 cm	34.1 cm
Break	0	0	0
Scram signal	22	5	4
Coolant pump idle run	28	11	10
Accumulator begin to inject	189	50	31
Water level in CMT begin to drop	1582	154	90
Accumulator evacuate	1826	520	345
ADS1 actuates	4225	650	241
ADS2 actuates	4295	720	311
ADS3 actuates	4415	840	431
ADS4 actuates	/	/	/
Water level in CMT drops to 0	4565	1208	1070
IRWST begin to inject	/	1757	726
Reactor core reflood	/	2802	5673
Core melting	7179	/	/

Table 2: Time window of LOCA in hot leg scenario

Progression (s)	5.08 cm	25.4 cm	34.1 cm
Break	0	0	0
Scram signal	26	5	4
Coolant pump idle run	32	11	10
Accumulator begin to inject	195	64	41
Water level in CMT begin to drop	3071	120	69
Accumulator evacuate	1278	448	392
ADS1 actuates	3463	302	183
ADS2 actuates	3533	372	253
ADS3 actuates	3653	492	323
ADS4 actuates	/	/	/
Water level in CMT drops to 0	4007	1429	1139
IRWST begin to inject	/	1436	417
Reactor core reflood	/	1931	1297
Core melting	7337	/	/

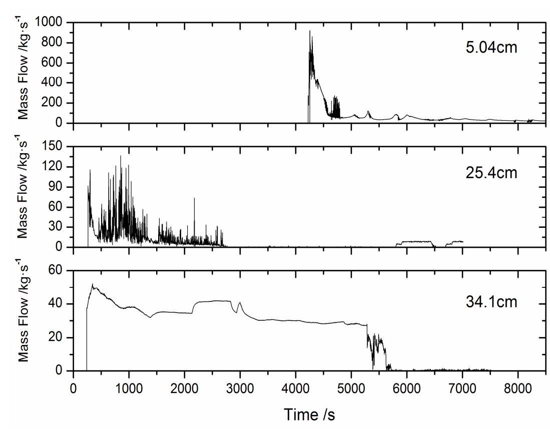

Fig. 6: Mass flow through ADS1, 2, 3 in cool leg condition

for activating ADS4, the squib valves fail to open. Thus, RCS pressure drops continuously due to depressurization only by breach and ADS 1, 2, 3 (Fig. 6 and 7). Consequently, IRWST injection delays and starts to inject until RCS pressure balances with containment pressure.

In the LOCA with break of an equivalent diameter of 5.08 cm in cool leg, RCS pressure, which can be subdivided into four phases (Wright, 2007), has a

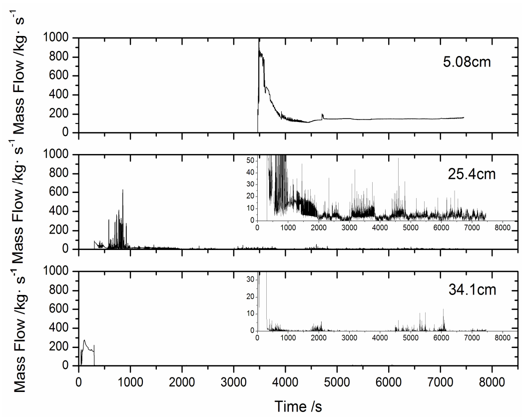

Fig. 7: Mass flow through ADS1, 2, 3 in hot leg condition

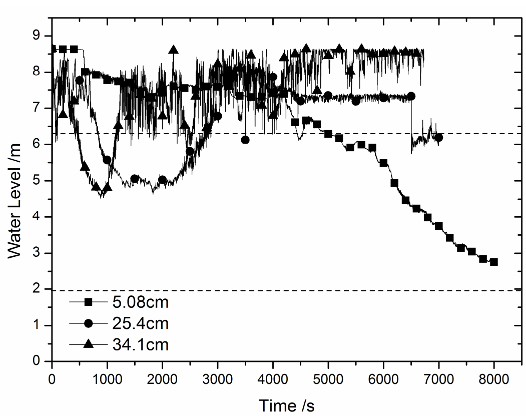

Fig. 8: Water level in pressure vessel in cool leg condition

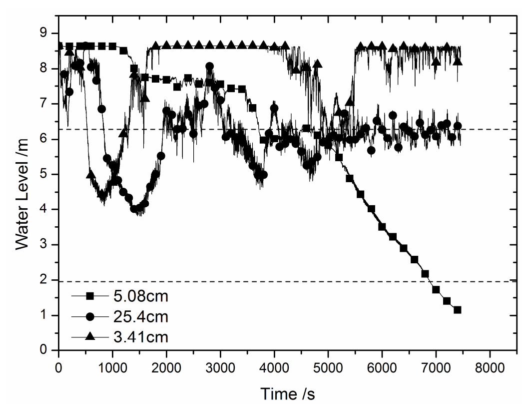

Fig. 9: Water level in pressure vessel in hot leg condition

longer phase of ADS depressurization than in hot leg without depressurization of ADS4. RCS pressure which drops relative slowly leads to IRWST fails to inject water into core and core is uncovered, heated to melt. Thus, there is risk of high-pressure melt. Comparatively, in the LOCA with break of an equivalent of 25.4 cm and 34.0 cm in cool leg, though coolant flow away quickly though breach and ADS1, 2, 3, reactor core is covered as result of IRWST injecting

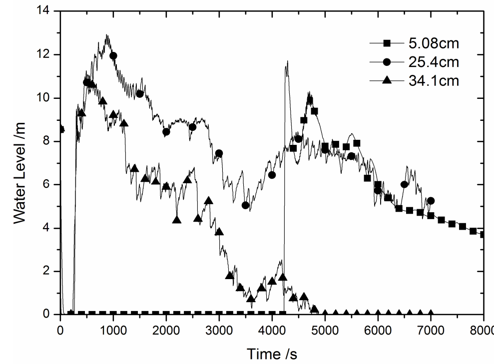

Fig. 10: Water level in pressurizer in cool leg condition

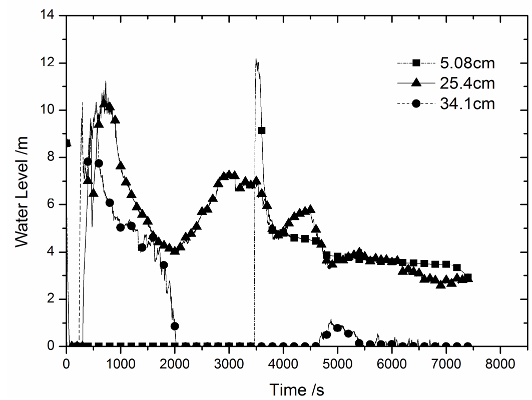

Fig. 11: Water level in pressurizer in hot leg condition

water into core successfully (Fig. 8 and 9). Core heating not happens while the water level in pressurizer rises after CMT and IRWST injecting (Fig. 10 and 11). Since there is steam still discharging to IRWST through ADS1, 2, 3, false water level may appear just like three miles island accident.

In the LOCA in hot leg, pressure dropping trend is similar to the LOCA in cool leg. However, in the LOCA with break of an equivalent diameter of 5.08 cm in cool leg the water level in CMT drops a little and then keeps steady for a relative long time after beginning to inject. And the flow through ADS1, 2, 3 releasing to IRWST in LOCA in hot leg is much higher than LOCA in cool leg. Meanwhile, there is a relative lower water level in pressurizer in LOCA in hot leg. This is because coolant which should flow through pressure balance line linking to cool leg flow away from breach in cool leg and vapor generated in the core passes through balance line into CMTs. When balance between breach flow and injecting flow is established, the water level in CMT keeps steady for a period of time after beginning to inject.

In the LOCAs in hot and cool leg, the temperature peak of fuel clad appears in accident beginning period except LOCAs with a breach of equivalent diameter of 5.08 cm (Fig. 12 and 13). This is because the core is not reflooded without IRWST injection.

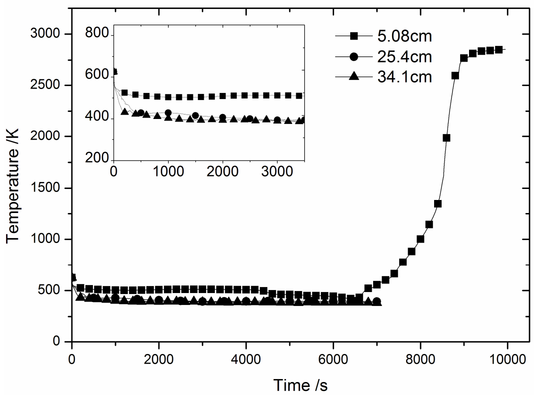

Fig. 12: Fuel clad surface in cool leg condition

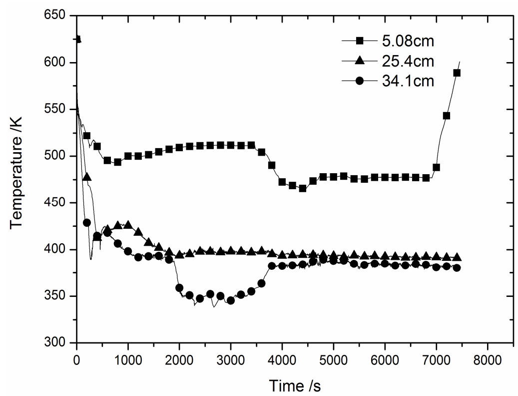

Fig. 13: Fuel clad surface in cool leg condition

CONCLUSION

After the calculation of LOCA with different diameter break coupled with failure of ADS4, the following conclusions can be obtained:

- In small break (5.08 cm equivalent diameter) LOCA coupled with failure of ADS4, IRWST fail to actuate and reactor core is heated to melt.
- In medium break or larger (25.4 cm and 34.1 equivalent diameter) LOCA coupled with failure of ADS4, core heating does not occur even though IRWST injecting delays without ADS4.
- The water level in pressurizer rises in accident because of depressurization only through ADS1, 2, 3.
- The breach in cool or hot leg does not produce affect on whether core is heated or not.

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