ADS-IRWST Transient Evaluation Model for AP1000 SBLOCA Analysis

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ABSTRACT

The AP1000 nuclear power plant safety system is characterized by its unique passive Emergency Core Cooling System (ECCS), including Core Makeup Tanks (CMTs), Automatic Depressurization System (ADS), and In-containment Refueling Water Tank (IRWST), to mitigate SBLOCA accident. The most challenging period of AP1000 SBLOCA transient is the transition from CMT injection to IRWST injection after the actuation of the fourth stage ADS (ADS4). This paper is to report a transient evaluation model for AP1000 SBLOCA analysis during CMT to IRWST transition. The model simulates ADS4, CMT injection, IRWST injection, reactor core mixture level and upper plenum entrainment to hotlegs. Both critical and non-critical flow models are used to calculate mass flow loss through ADS1-4 vents. The most important feature of this model is that it constantly traces core/upper plenum two-phase mixture level, which demonstrates cooling capability of ECCS during the transient. A baseline case is analyzed to study ADS-IRWST transient using AP1000 prototypic information. In addition, a sensitivity analysis is performed to further study the robustness of AP1000 ECCS during SBLOCA transient.

KEYWORDS
Automatic Depressurization System, SBLOCA, AP1000

1. INTRODUCTION

The most important and unique feature of advanced Pressurized Water Reactors (PWR), AP600 and AP1000, is the passive Emergency Core Cooling System (ECCS). In the event of small break LOCA, not like active ECCS used in conventional PWRs, the passive ECCS relies on its 4-stage Automatic Depressurization System (ADS) to rapidly depressurize reactor primary system so that the gravity driven safety injection flow can be initiated and provide adequate cooling for reactor core. For AP600 and AP1000, the most crucial moment in the small break LOCA transient is the successful injection of adequate and stable IRWST [1, 2] to reactor core. For the IRWST to inject, the primary system pressure must decrease below the IRWST static head, which is approximately 0.1 MPa.

Figure 1 illustrates the configuration of AP1000 passive safety system. After the opening of ADS4 (stage 4 of ADS), following transient will occur:

1. rapid primary system depressurization;
2. entrainment of water in hotlegs and reactor vessel (upper plenum) out of ADS4;
3. accumulator injection and depletion;
4. continued drainage of water from the core makeup tanks (CMTs) and depletion;
5. flashing and boiling in reactor vessel;

6. start of IRWST injection;

In the above transient, the coolant inventory in the core is determined by mass flow balance between outflow (break and ADS1-4) and inflow (CMT, accumulator and IRWST). Integral test results (i.e. APEX, ROSA, SPES-2) indicate that the vapor generation and resulting entrainment from upper plenum to ADS4 causes the lowest core inventory observed throughout the entire small break LOCA transient [1, 2]. However, the system analysis codes (i.e. NOTRUMP, WCOBRA-TRAC and RELAP5) are found having limited capability in modeling upper plenum and hotleg entrainment [1, 3].

In order to supplement code simulation and demonstrate conservative results for AP1000 small break LOCA analysis, Brown [4, 5] developed a steady state top-down model for ADS-IRWST transition. Brown made several conservative assumptions on upper plenum and ADS entrainment (maximized coolant loss) in order to justify adequate safety margin in AP1000 passive ECCS. Due to the steady state nature of his model, it does not calculate the timing and flow rate of IRWST injection, which are determined by the primary system pressure. After ADS4 are triggered, ADS1-4 and break flow will experience the transition from critical flow to sub-critical flow. And in Brown's model, the primary system pressure is assumed in sub-critical region.

This paper is to report an ADS transient evaluation model to provide better understanding of pressure transient and core region inventory behavior during the ADS-IRWST period. This evaluation model captures primary system pressure transition from critical to sub-critical region, and traces mixture level in reactor vessel. A limiting break scenario in small break LOCA for AP1000, the double-ended direct vessel injection (De-DVI) line break, is analyzed using this evaluation model. In addition, three sensitivity cases are studied to evaluate passive system responses to core decay heat, ADS4 failure and initial mixture level.

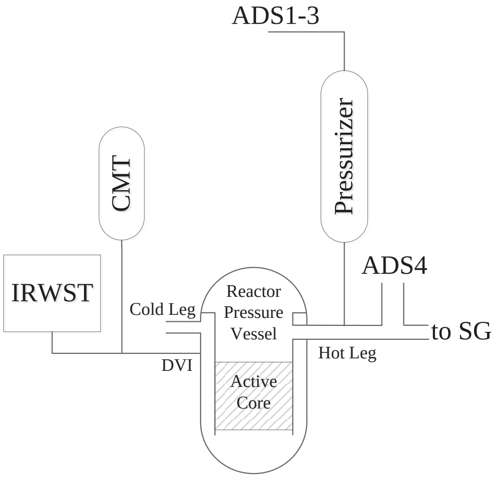


Figure 1. AP1000 Passive ECCS in ADS-IRWST Transition

2. ADS Transient Evaluation Model

2.1 Model Features

The ADS transient evaluation model is a top-down transient depressurization model based on lumped parameter method. The evaluation model consists of five independent regions as shown in Figure 2:

1. Hotleg-ADS (including hotlegs, ADS1-4);

2. Upper plenum;
3. Active core;
4. Downcomer;
5. Safety injection (CMT and IRWST);

The main features and assumptions of ADS transient evaluation model:

1. Mass, static pressure balance and energy equations are solved within the above five regions;
2. Modified drift flux model [6] is used to calculate void fraction in active core and upper plenum;
3. Kataoka and Ishii's pool entrainment model [7] is used to calculate the liquid entrainment from upper plenum to hotleg; Assume all liquid in hotleg escapes from ADS4 or no liquid inventory in hotleg;
4. Track CMT and IRWST inventory and calculate transient CMT/IRWST flow rate;
5. Use HEM model for break flow calculation (critical and sub-critical), use slip ratio=1 in sub-critical break flow calculation (choice of slip ratio will be discussed in section 3);
6. Core decay heat is modeled according to the ANS-1971 standard [8];
7. Pressure equilibrium between hotleg and space above downcomer because of primary loop piping communication through Steam Generator during the ADS-IRWST phase; (This is consistent with AP600 and AP1000 integral effect test experiences.)

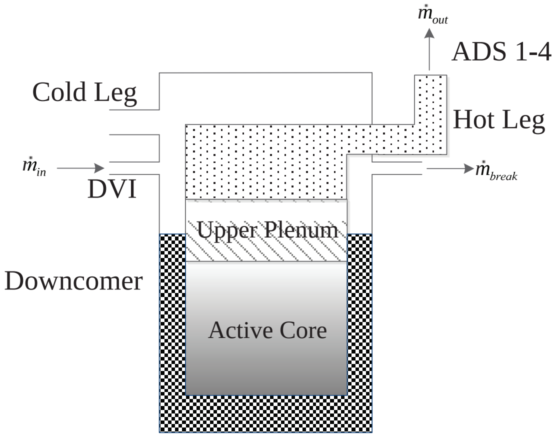


Figure 2. ADS Transient Evaluation Model Configuration

2.2 Mathematical Model and Equations

The conservation of mass equation for reactor cooling system (RCS):

$$\frac{dM}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \tag{1}$$

where $M = M_c + M_{up} + M_{dc}$, $\sum \dot{m}_{in} = \dot{m}_{cmt} + \dot{m}_{irwst}$, $\sum \dot{m}_{out} = \dot{m}_{break} + \dot{m}_{ads1-4}$

As the liquid collapsed level is always below DVI line elevation during the entire ADS-IRWST transient as indicated by AP1000 integral test [**Error! Reference source not found.**], overflow at vessel side of broken DVI line will not occur. Thus, flow condition at broken DVI line is assumed as same as ADS4 for conservativeness.

The conservation of hydraulic pressure head in upper plenum, core and downcomer (pressure balance between hotleg and space above downcomer):

$$\Delta p_{hydr,c} + \Delta p_{hydr,up} = \Delta p_{hydr,dc} \tag{2}$$

The pressure drop in ADS4 vent path consists of three components, acceleration term, gravity term and friction term, and is equal to the pressure difference between space above downcomer/upper plenum and containment. After ADS4 valves are triggered, liquid inventory in RCS drops rapidly due to liquid entrainment in ADS4. And the two phase mixture level in RCS quickly drops to the bottom of hotleg, which results in a steam flow path connecting upper plenum and downcomer through hotlegs, steam generator and cold legs. Due to a large flow area at hotleg, steam generator U-tubes and cold legs, upper plenum and downcomer are able to reach pressure equilibrium. The phenomenon of pressure equilibrium between upper plenum and downcomer is repeatedly observed in AP1000 integral effect test [9].

$$p_{dc} - p_{cont} = \Delta p_{ads4} = \Delta p_{acceleration} + \Delta p_{gravity} + \Delta p_{friction} \tag{3}$$

where
$$\Delta p_{acceleration} = \left(\frac{G_{ads4}^2}{\rho_{ads4}}\right) - \left(\frac{A_{up}}{A_{ads4}}\right)\left(\frac{G_{up}^2}{\rho_{upex}}\right) \tag{4}$$

$$\Delta p_{gravity} = g\,\rho_{upex}\left(Z_{ads4ex} - Z_{hl}\right) \tag{5}$$

$$\Delta p_{friction} = \Phi_{ads4}^2 \left.\frac{R}{(A)^2}\right|_{ads4} \left.\frac{\dot{m}^2}{\rho}\right|_{ads4} \tag{6}$$

The homogenous two phase multiplier Φ_{ads4}^2 is

$$\Phi_{ads4}^2 = \left(1 + x\frac{\Delta\rho}{\rho_g}\right)\left(1 + x\frac{\mu_{fg}}{\mu_g}\right)^{-1/4} \tag{7}$$

$$\rho_{ads4} = \alpha_{ads4}\rho_g + \left(1 - \alpha_{ads4}\right)\rho_f \tag{8}$$

$$\alpha_{ads4} = \frac{1}{1 + \left(\frac{1 - x_{ads4}}{x_{ads4}}\right)\cdot\left(\frac{\rho_g}{\rho_f}\right)\cdot s} \tag{9}$$

The static pressure balance for the CMT and IRWST region:

$$\rho_l g\left(H_{CMT} - H_{DC}\right) = \frac{1}{2}\rho_l u_{dvi}^2 + \rho_l Q_{CMT}^2 gLF_{CMT} \tag{10}$$

$$p_{rcs} - p_{cont} = \rho_l g\left(H_{IRWST} - H_{DC}\right) - \frac{1}{2}\rho_l u_{dvi}^2 - \rho_l Q_{irwst}^2 gLF_{irwst} \tag{11}$$

where *LF* is the flow resistance of the injection line.
The conservation of energy for the primary system:

$$\frac{dMe}{dt} = \sum\left(\dot{m}h\right)_{in} - \sum\left(\dot{m}h\right)_{out} + q_{core} - P\frac{dV}{dt} \tag{12}$$

where ***e*** is the specific internal energy and ***V*** is the RCS volume, ***h*** is the enthalpy of the fluid entering or leaving RCS, $\boldsymbol{q_{core}}$ is the decay heat and ***P*** is the RCS pressure.

The total change in specific internal energy can be written in terms of partial differentials with respect to pressure and specific volume as follows:

$$de = \left(\frac{\partial e}{\partial p}\right)_v dP + \left(\frac{\partial e}{\partial v}\right)_p dv \tag{13}$$

Substitute equation (1) and (13) into (12) and rearrange, one can get:

$$M\left(\frac{\partial e}{\partial p}\right)_v \frac{dP}{dt} = \left(\sum \dot{m}_{in}\right)\left[\bar{h}_{in} - e + v\left(\frac{\partial e}{\partial v}\right)_p\right]_{in} - \left(\sum \dot{m}_{out}\right)\left[\bar{h}_{out} - e + v\left(\frac{\partial e}{\partial v}\right)_p\right]_{out} + q_{core} \tag{14}$$

Equation (14) is the governing equation for depressurization behavior in the RCS. Now, the system energy conservation equation (12) is expressed in term of the depressurization equation.

For $0.1 < p < 0.3MPa$, following relationship can be obtained:

$$\frac{e}{e_0} = \left(\frac{p}{p_0}\right)^{0.2730} \tag{15}$$

Thus, the partial derivative of internal energy with respect to specific volume can be re-written as:

$$\left(\frac{\partial e}{\partial p}\right)_{v_0} = 0.2730\frac{e_0}{p}\left(\frac{p}{p_0}\right)^{0.2730} \tag{16}$$

Kataoka and Ishii's pool entrainment model predicts liquid entrainment by gas flow above two phase pool surface. Due to the configuration of flow path, the liquid entrainment from upper plenum to hotleg is not fully identical to what pool entrainment model assumes. But it is conservative to assume that all liquid entrainment at certain distance above two phase mixture level leaves upper plenum to hotleg if one needs to trace liquid inventory in RPV. This approach is also used in AP1000 LOCA analysis [1].

Yeh's drift flux model is benchmarked against low pressure core boiloff data of FLECHT test [6] and applicable to the scenario of this study. Thus, Yeh's model is used to calculate void fraction in the core and upper plenum regions (below two phase mixture surface):

$$\alpha = c\left(\frac{\rho_g}{\rho_f}\right)^{0.239}\left(\frac{j_g}{j_{ber}}\right)^{b}\left[\frac{j_g}{j_g + j_f}\right]^{0.6} \tag{17}$$

where

$$c = 0.925, b = 0.67, \quad \text{if} \quad j_g / j_{ber} \le 1$$
$$c = 0.925, b = 0.47, \quad \text{if} \quad 1 < j_g / j_{ber} < 4.31$$
$$c = 1.035, b = 0.393, \quad \text{if} \quad j_g / j_{ber} \ge 4.31$$
$$j_{ber} = 1.53\left[\frac{g\sigma\Delta\rho}{\rho_f^2}\right]^{0.25}$$

The single phase critical flow model is used in the ADS1-3 and DVI line break vent:

$$G_{SP,cr} = \rho\sqrt{2c_pT\left[\left(\frac{p_{cont}}{p}\right)^{2/\gamma} - \left(\frac{p_{cont}}{p}\right)^{(\gamma+1)/\gamma}\right]} \tag{18}$$

where $\boldsymbol{p_{cont}}$ is the back pressure (containment pressure)

The HEM model [10] for two phase critical flow is used to calculate ADS-4 flow rate:

$$G_{TP,cr} = \left(\rho'''\right)\sqrt{2\left[h - x_b h_{b,g} - \left(1 - x_b\right)h_{b,f}\right]} \tag{19}$$

where $\rho''' = \left\{\left[\frac{x_b}{\rho_{bg}} + \frac{(1-x_b)S}{\rho_{bf}}\right]\left[x_b + \frac{1-x_b}{S^2}\right]^{1/2}\right\}^{-1}$, The subscript “***b***” represents the parameter after the expansion, and S=1 for HEM model. The criterion of the transition from critical flow to sub-critical flow is based on Figure 11-25 in Ref. [10].

3. Simulation Results and Discussion

One baseline case and three sensitivity cases are analyzed using the ADS-IRWST evaluation model described above. Three key parameters, the initial mixture level at upper plenum, decay heat and number of ADS4 path, are chosen to conduct the sensitivity study for ADS-IRWST transient as shown in Table I.

Table I. Specifications of Baseline and Sensitivity Cases

	Initial Mixture Level at Upper Plenum		Decay Heat Ratio		Number of ADS4 Path	
	1.4m	0.4m	1.2	1.05	3	2
Case #1 (Baseline)	✓			✓	✓	
Case #2	✓		✓		✓	
Case #3	✓			✓		✓
Case #4		✓		✓	✓	

3.1 Baseline Case (case #1)

A limiting break scenario in small break LOCA for AP1000, the double-ended direct vessel injection (De-DVI) line break, is chosen as the baseline case to study the ADS-IRWST Transient. The broken DVI loop consisting of an accumulator, a core makeup tank, and an IRWST injection line results in a total loss of one train of ECCS (one out of two). One ADS4 valve failure is assumed as single failure required by 10 CFR 50.46[11], because the limiting failure in SBLOCA is judged to be one out of four ADS Stage 4 valves failing to open on demand, the failure that most severely impacts depressurization capability [1].

The initial conditions of ADS-IRWST transient is chosen at the moment when accumulator at intact side of DVI lines is depleted, which is about 600 seconds after the break. At this moment, all ADS1-4 valves are opened, but the system pressure (pressure differential between RCS and containment) is still above the IRWST trigger pressure (about 0.1MPa). The initial system pressure is approximately 0.14MPa and two phase mixture level at upper plenum is at the bottom of hotleg based on NOTRUMP code calculation [1]. The initial core power level is set to 105 percent of the nominal decay heat at 600s after break. The containment pressure is chosen at 0.1MPa. Other geometry data used in this analysis are referenced from AP1000 Design Control Document (DCD) [1].

The choice of slip ratio in calculating pressure drop at ADS4 path is studied because this may causes significant difference in depressurization process at sub-critical region. Using Equation 3-9, one can plot relations between total pressure loss at ADS4 and flow quality with different slip ratio (s=1, 5, 10 respectively) as shown in Figure 3. It can be seen that slip ratio of 1 (s=1) gives higher pressure drop with flow qualities larger than 0.1 which results in smaller ADS4 flow and slower depressurization process during ADS-IRWST transient. Figure 4 shows ADS4 flow quality at baseline case, and indicates the ADS4 flow quality is larger than 0.1 during the entire simulation period. Thus, slip ratio of 1 is conservatively chosen for all the simulation cases. The strong fluctuation of flow quality is caused by the discontinuity between momentum controlled region and deposition controlled region in Kataoka's pool entrainment model.

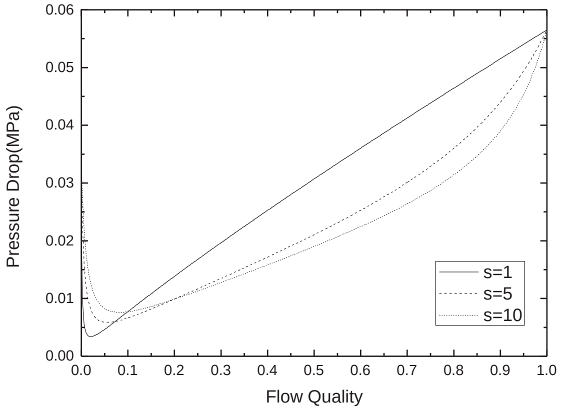


Figure 3. ADS-4 Pressure Drop vs ADS4 Flow Quality with Different Slip Ratio

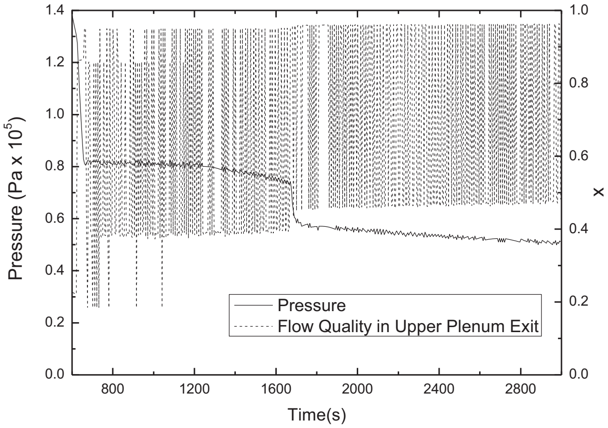
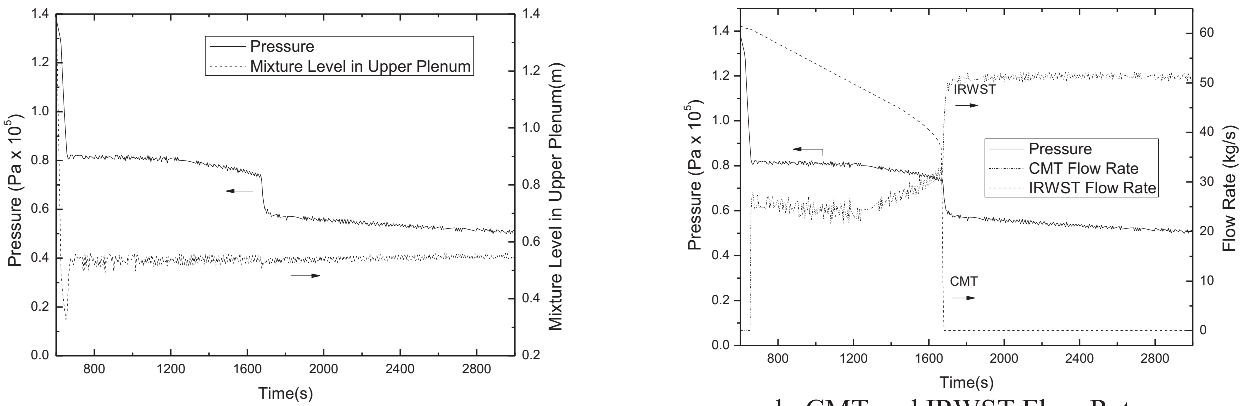


Figure 4. ADS4 Flow Quality in Baseline Case

Figure 5 illustrates major ECCS information (i.e. RCS pressure, two phase mixture level at upper plenum, CMT and IRWST flow rate) during the ADS-IRWST transient for baseline case. All RCS pressures presented in this paper are expressed as the differential pressure between RCS and containment. The RCS is depressurized below the critical pressure 0.081MPa in about 40 seconds due to rapid mass loss through ADS1-4 by core boiling off and flushing. At meantime, the mixture level in the upper plenum decreases quickly as significant amount of liquid escaping from RCS by entrainment. IRWST is triggered at 652 seconds when the RCS pressure is below 0.1MPa. The mixture level in the upper plenum starts to recover until the injection flow (CMT and IRWST) is balanced by break flow (DVI break and ADS1-4). The RCS pressure has a sudden drop at 1700 seconds due to depletion of CMT. After that, the RCS enters into a slow depressurization mode with stable IRWST injection. During the entire ADS-IRWST transient in the baseline case, the lowest mixture level, which is still above reactor active core, happens at the moment just before the start of IRWST injection. The baseline study demonstrates that the passive ECCS is capable of providing adequate cooling to reactor core during ADS-IRWST transient.



a. RCS Pressure and Mixture Level in Upper Plenum

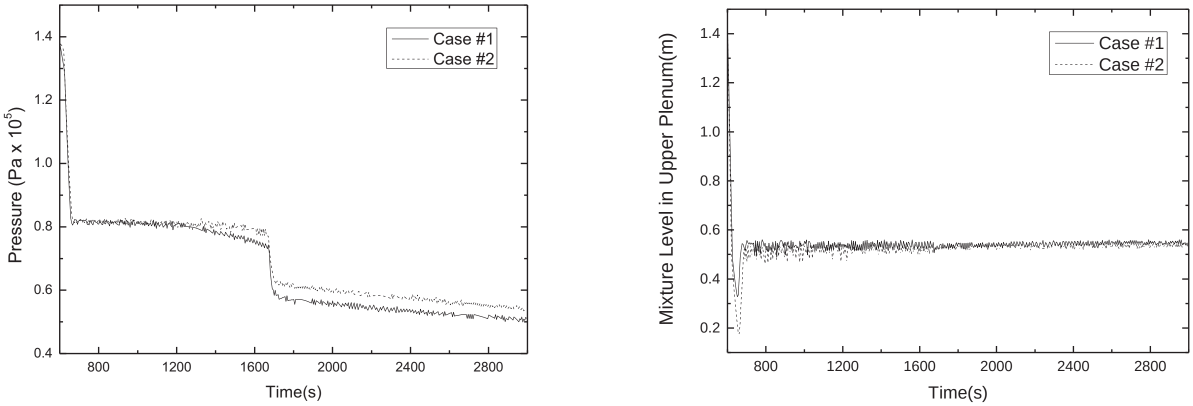
b. CMT and IRWST Flow Rate

Figure 5. Simulation Results of Baseline Case

3.2 Sensitivity Study

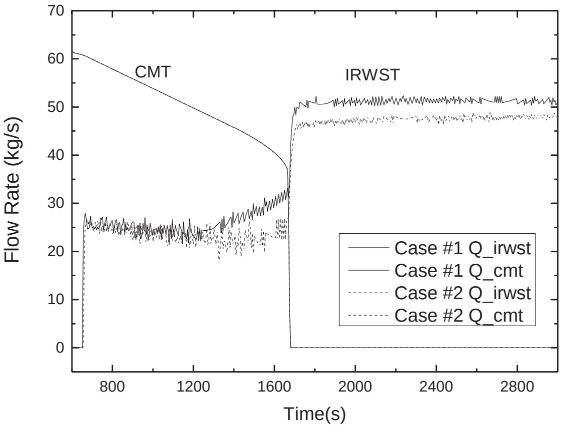
3.2.1 Effect of core decay heat (case #2)

This sensitivity case is to study the effect of higher decay heat on ADS-IRWST transient. Figure 6 compares RCS pressure, mixture level at upper plenum, CMT and IRWST flow rate at 120% nominal decay heat with baseline case. It can be found that the RCS will have a slower depressurization process with higher decay heat which will result in about 5 seconds IRWST injection delay and extra 0.2m mixture level drop compared with baseline case. The CMT injection flow rates in both scenario are almost identical as shown in Figure 6-c, while the steady state IRWST injection flow (after CMT depletion) in higher core power is approximately 5% lower than normal core power. Although this sensitivity study shows that system will have more risk of core uncovery at higher decay heat level, the passive ECCS has some level of safety margin (15% more decay heat) during ADS-IRWST transient. The reactor core is still covered by coolant during the entire transient in higher core power scenario.



a. RCS Pressure

b. Mixture Level at Upper Plenum

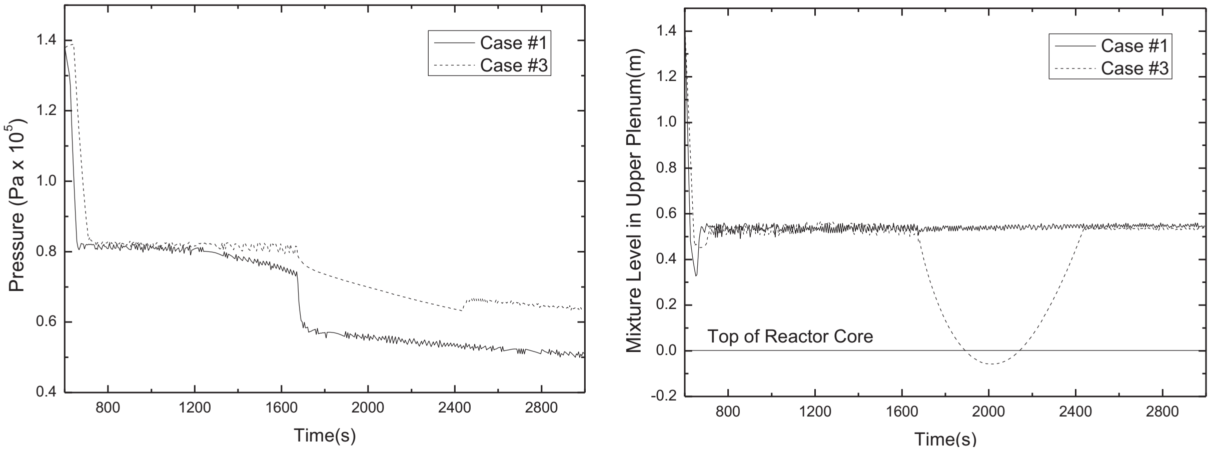


c. CMT and IRWST Flow Rate

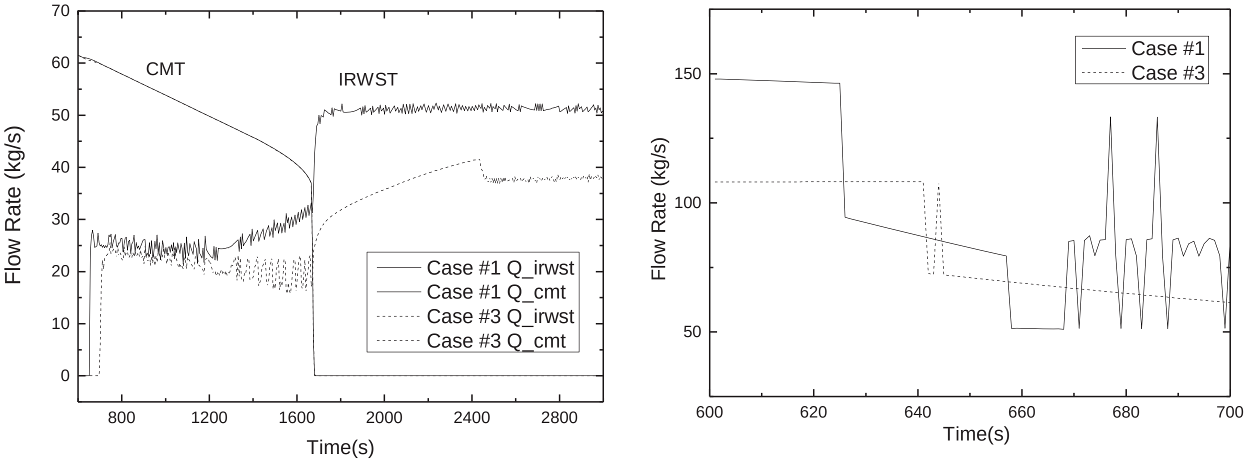
Figure 6. Sensitivity Study of High Decay Power

3.2.2 Effect of ADS4 Flow area (case #3)

This sensitivity study is to analyze the effect of ADS4 flow area on ADS-IRWST transient. A reduced number of ADS4 path (2 instead of 3 as in baseline case) is used to simulate loss of 1/3 of ADS4 flow area. Figure 7 compares RCS pressure, mixture level at upper plenum, RCS outflow rate, CMT and IRWST flow rate with baseline. It can be seen that the RCS depressurization rate is significantly reduced during the entire transient. The cross critical pressure point is delayed by 90 seconds as compared with baseline case. Because reduction of ADS4 flow area also reduces mass outflow through ADS4, the net loss of coolant might be smaller than in baseline. This is true before IRWST enters RCS as shown in Figure 7-b that mixture level dip around 700 seconds in case #3 is lower than baseline. Figure 7-d compares the outflow rate between 600 and 700 seconds of the transient in case #1 and #3. However, due to slower depressurization, the IRWST flow rate is always smaller in case #3 (Figure 7-c) than baseline which results in a big mixture level drop when CMT is depleted at 2000 seconds as demonstrated in Figure 7-b. In fact, the simulation shows that the reactor core is uncovered in case #3. Integral test results from APEX-1000 also indicated a time delay of IRWST injection and core uncovery in the event of double failure of ADS4 valves (2 out of 4)[9]. This sensitivity study indicates that ADS4 flow area has important role in depressurizing RCS and IRWST injection, and AP1000 may experience core uncovery if two ADS4 valves fail to open during ADS-IRWST transient in a postulated De-DVI line break accident.



a. RCS Pressure b. Mixture Level at Upper Plenum



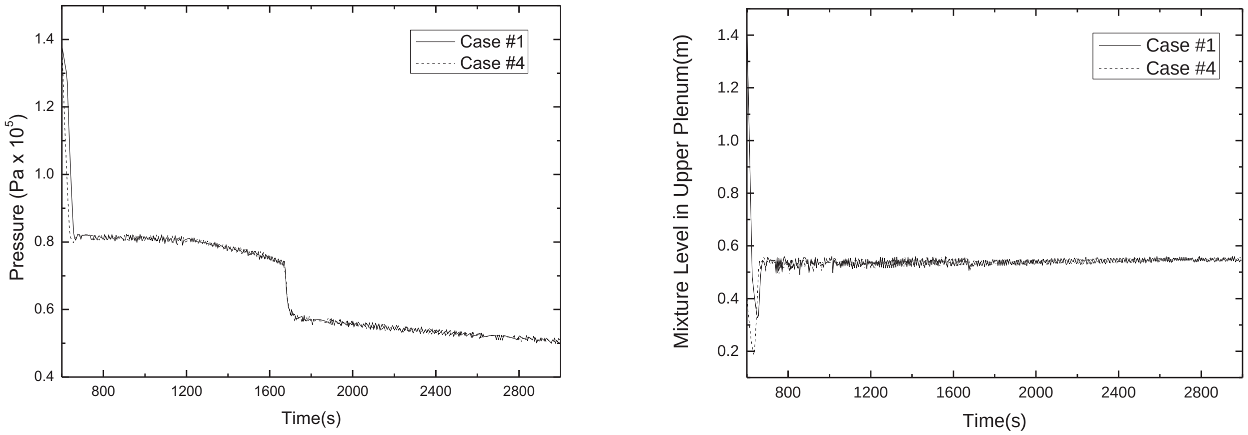
c. CMT and IRWST Flow Rate

d. Outflow Rate

Figure 7. Sensitivity Study of ADS4 Flow Area

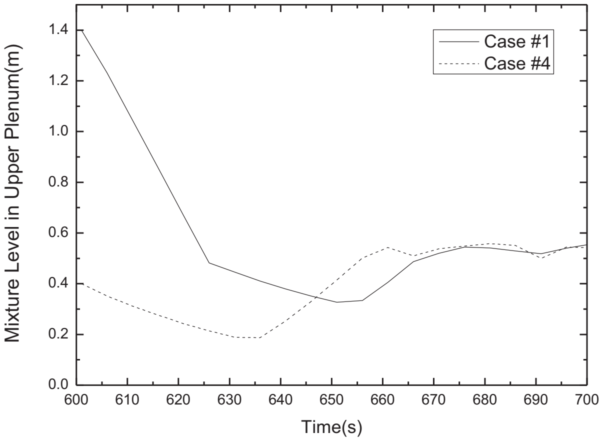
3.2.3 Effect of initial mixture level (case #4)

This sensitivity study is to examine the effect of initial mixture level on ADS-IRWST transient. Figure 8 compares RCS pressure and mixture level at upper plenum between case #1 and #4. It can be found that initial mixture level has little impact on RCS depressurization process, but it causes extra 0.15m drop in mixture level before IRWST injection starts. Considering the initial mixture level is 0.4 in case #4 compared with 1.4 in baseline, the mixture level in upper plenum during the transient is not very sensitive to its initial value. Because the liquid entrainment in momentum region is an order of magnitude larger than in deposition controlled region as calculated by Kataoka's model, the mixture level decreases much faster in momentum control region than deposition controlled region as shown in Figure 8-c (the boundary of momentum control region and deposition region in ADS-IRWST transient is about 0.5m above reactor core). The success of core recovery relies on both RCS depressurization and core liquid inventory. But this analysis shows that RCS depressurization plays more important role in having reactor core covered during the ADS-IRWST transient.



a. RCS Pressure

b. Mixture Level at Upper Plenum



c. Mixture Level at Upper Plenum

Figure 8. Sensitivity Study of Initial Mixture Level

4. CONCLUSIONS

An evaluation model is developed to study passive ECCS effectiveness during ADS-IRWST transient for AP1000. The model simulates the behavior of ADS1-4 discharge, CMT injection, IRWST injection, reactor core mixture level and upper plenum entrainment to hotlegs during the transient. It is shown that slip ratio of 1 gives conservative result in ADS4 pressure drop. One baseline case of a De-DVI line break accident and three sensitivity cases are simulated to study passive ECCS of AP1000 during ADS-IRWST transient. The results of baseline case show that ADS4 provides adequate RCS mass discharge, and the RCS can be rapidly depressurized for IRWST injection. The passive ECCS is able to provide adequate cooling to avoid reactor core uncovery during the entire transient. The decay heat sensitivity study indicates that AP1000 has some level of safety margin (15% more decay heat) during ADS-IRWST transient. The sensitivity study of ADS4 flow area and initial mixture level illustrates that ADS4 flow area plays the most important role in depressurizing RCS and IRWST injection, and AP1000 may experience core uncovery if two ADS4 valves fail to open during ADS-IRWST transient.

NOMENCLATURE

Symbols

A	Flow area
c_p	Specific heat at constant pressure
e	Specific internal energy
G	Mass flux
g	Gravitational acceleration
h	Enthalpy of the fluid entering or leaving RCS
j	Superficial velocity
j_{ber}	Local slip
LF	Flow resistance of the injection line
M	Mass
$\dot{m}$	Mass flow rate

P	RCS pressure
p_{hydr}	Hydraulic pressure head
q_{core}	Decay heat
R	Hydraulic resistance
S	Slip ratio
T	Temperature
V	RCS volume
v	Specific volume
x	Flow quality
Z	Length or elevation

Greek

ρ	density
α	Void fraction
γ	Ratio of specific heat

Subscript

b	After the expansion
$c,core$	Core
$cont$	Containment
cr	Critical
dc	Downcomer
f	Saturated liquid
g	Saturated gas
SP	Single phase
TP	Two phase
up	Upper Plenum

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