Scaling Analysis for DVI Line Break Accident of APR1400 based on ATLAS Experiment

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ABSTRACT

The Advanced Thermal-Hydraulic Test Loop for Accident Simulation (ATLAS) facility has been established by Korea Atomic Energy Research Institute to conduct integral effect tests for Advanced Power Reactor 1400 (APR1400). ATLAS has been scaled by using the three-level scaling methodology suggested by Ishii et al with the scaling ratio of 1/2 and 1/144 in length and flow area, respectively. Thus the transient in ATLAS occurs 1.414 times faster than that in the prototype, APR1400. In order to address the scalability of ATLAS, a DVI (Direct Vessel Injection) line guillotine break accident at APR1400 has been analyzed by using a system code, MARS-KS. Since the main idea of the analysis is to figure out if the phenomena at ATLAS during the accident are reproduced at APR1400, initial and boundary conditions are taken from the relevant experiment at ATLAS. The final analysis result reveals that plant general behavior, important phenomena and parameters during the accident including break flow, loop seal clearing and peak cladding temperature are well reproduced in the analysis, which indicates the scalability of ATLAS to APR1400 for the DVI line guillotine break accident.

KEYWORDS
APR1400, ATLAS, DVI Line Break, Scaling Analysis

1. INTRODUCTION

Korea Atomic Energy Research Institute (KAERI) has established and operated the Advanced Thermal-Hydraulic Test Loop for Accident Simulation (ATLAS) which is a scaled-down integral test facility of APR1400 (Advanced Pressurized Reactor 1400). The facility has the capacity to simulate a broad range of DBAs (Design Basis Accidents) [1] that comes to resolve licensing issues raised by the regulatory body.

The prototype of ATLAS, APR1400, has a special safety injection feature, namely direct vessel injection (DVI). While conventional safety injection systems are connected to the cold legs, the DVI system makes the safety injection to the upper downcomer of the reactor pressure vessel (RPV). In APR1400, four DVI lines are connected to the RPV, and the safety injection of each DVI line comes from a safety injection pump (SIP) and a safety injection tank (SIT). While the SIP needs electric power to be operated, the SIT operates by pressure difference as same as accumulator in previous reactor designs. In addition, there are two emergency diesel generators (EDGs) to provide the electricity to the SIPs under loss of offsite power conditions and thus, each EDG is designed to supply electric power to two SIPs. Considering the configuration of the DVI system, it is clear that the worst single failure is the failure of an EDG since the system loses two active safety injections from SIPs at once. The most significant accident regarding the DVI system is the guillotine break of a DVI line because the safety injections from both one SIP and one SIT will be lost. Therefore, from the safety injection point of view, the most limiting accident scenario with DVI line is a DVI line guillotine break with the failure of single EDG as single failure. In this case, the system has the least safety injections coming from three SITs and one SIP.

An integral effect test for the DVI line guillotine break accident has been performed by using the ATALS facility and the phenomena occurred during the test was analyzed by means of both experimental data and analysis by using a system code [2]. The experimental result was also utilized as a reference data set for the 1st domestic standard problem exercise (DSP-01) [3]. More than 10 organizations participating in DSP-01 revealed that the important phenomena as well as general behavior of the system were well reproduced by the state-of-the-art system codes such as RELAP5 [4], TRACE [5], and MARS-KS [6]. However, the analysis was limited to the phenomena occurred in the ATLAS facility and scalability to the prototype, APR1400, was discussed only by means of scaling law applied for the experimental facility. Thus, it is required to conduct a comparative study between model and prototype in order to address the scalability explicitly.

This paper aims at presenting a scaling analysis for the DVI line guillotine break of APR1400 based on the ATLAS experiment. The analysis was done by simulating the experiment conducted at ATLAS with APR1400 model for thermal hydraulic safety analyses. The MARS-KS code has been employed for the system thermal hydraulic analysis and the APR1400 model for MARS-KS calculations has been developed on the basis of a base input deck developed by Korea Institute of Nuclear Safety (KINS). Thermal hydraulic conditions at ATLAS were scaled up according to the corresponding scaling ratio applied for the ATLAS design.

2. DESCRIPTION OF ATLAS FACILITY

The ATLAS facility is an integral effect test facility scaled-down from APR1400 with scaling ratios of 1/2 and 1/288 for length and volume, respectively. The facility has been designed to simulate thermal hydraulic conditions up to full pressure and temperature conditions of APR1400. As depicted in Figure 1 [7], ATLAS is composed of two steam generators (SGs), two hot legs, four cold legs and reactor coolant pumps, and a pressurizer which are the same configuration of major component to APR1400. The reactor pressure vessel includes the reactor core simulated with electric heater rods, and integrated annular downcomer. As mentioned before, the safety injection at APR1400 is established via the DVI system which is connected to the upper downcomer. Therefore, four nozzles to model connection to the DVI line are installed at the upper downcomer. In addition, ATLAS has a connection to the safety injection system at each cold leg which allows making a comparative study for the DVI and cold leg injection systems.

Scaling law applied for ATLAS is the three-level scaling methodology developed by Ishii and Kataoka [8]. According to the scaling law, the half-height scaling will determine $\sqrt{2}$ times faster velocity at ATLAS than one at APR1400. Thus, events at ATLAS generally occur 1.414 times faster than prototype plant. The maximum core power of ATLAS is 1.96 MWth representing 10 % of the scaled power. The core has electric heater rods and guide tubes with the same diameter and pitch to the reference design. The total number of fuel rods was scaled on the basis of an area ratio of 1/144. A list of scaling parameters is given in Table I.

Each SIT of APR1400 is equipped with a fluidic device in order to control the discharge flow rate passively. The fluidic device changes the SIT operation mode from high flow to low flow mode by using its unique geometry [9]. Because of a complicated geometry of the fluidic device, ATLAS models the function of the fluidic device using a control valve.

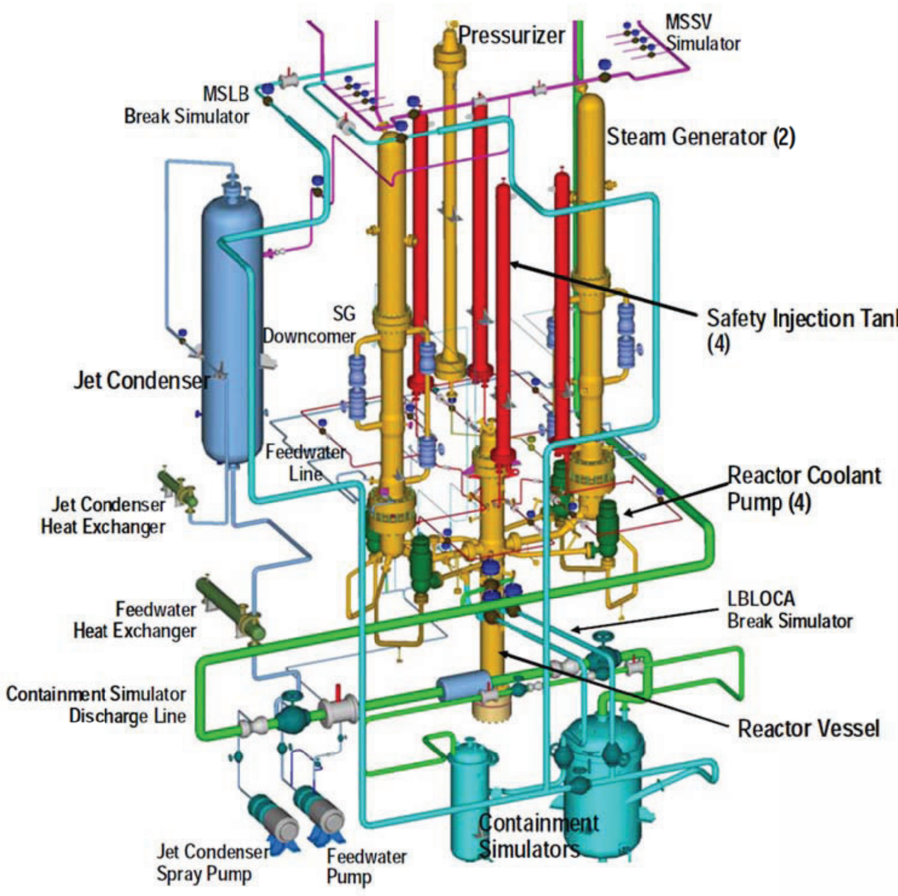

Figure 1. Schematic representation of ATLAS facility.

Table I. Scaling parameter of ATALS

Parameters	Scaling law	ATLAS Design
Length	l_{0R}	1/2
Diameter	d_{0R}	1/12
Area	d_{oR}^2	1/144
Volume	$l_{0R}d_{oR}^2$	1/288
Core DT	ΔT_{0R}	1
Velocity	$l_{0R}^{1/2}$	$1/\sqrt{2}$
Time	$l_{0R}^{1/2}$	$1/\sqrt{2}$
Heat Flux	$l_{0R}^{-1/2}$	$\sqrt{2}$
Core Power	$l_{0R}^{1/2}d_{oR}^2$	1/203.6
Pressure Drop	l_{0R}	1/2
Flow Rate	$l_{0R}^{1/2}d_{oR}^2$	1/203.6

3. MODELING OF APR1400 FOR MARS-KS ANALYSIS

3.1. MARS-KS

MARS-KS (Multi-Dimensional Analysis of Reactor Safety) has been developed by KAERI by consolidating the thermal hydraulic system code, RELAP5/MOD3.2, with integration of multi-dimensional subchannel analysis code, COBRA-TF [10]. MARS-KS has been written in FORTRAN90 which allows more convenient and effective development and maintenance of the code. A graphic user interface with real-time plot for minor edit variables is also one of the most important features of enhanced user-friendly environment. MARS-KS can be coupled with the three-dimensional reactor kinetics code, MASTER, and containment analysis codes such as CONTEMPT4 and CONTAIN. In addition to the capacity of both thermal hydraulic codes, MARS-KS extends the analysis capacity by including special thermal hydraulic models for tight lattice core, CANDU, integral reactor, research reactor, and gas-cooled reactor.

One-dimensional features of MARS-KS have been employed for this analysis, while MARS-KS has a capacity to analyze three-dimensional problems as well as typical one-dimensional cases.

3.2. General Model Descriptions

In order to analyze APR1400 reliably, it is very important to describe the geometrical characteristics of APR1400 appropriately. Since it was actually impossible to collect all the data for APR1400, it is decided to collect geometrical information of APR1400 from a base input developed at KINS. The model for the scaling analysis has been developed with an idea where the experiment for DVI line guillotine break accident will be analyzed with APR1400 considering scaling parameters. Therefore, initial and boundary conditions at the experiment were applied to the APR1400 model after proper scaling.

The initial and boundary conditions as well as set points of reactor protection systems at the experiments were taken from the specifications for ATLAS DSP-01 [11]. The power given to ATLAS was 8.0 % of the nominal power. Because the power at the experiment included the compensation for heat loss during the experiment, the power without the heat loss compensation was given to the fuel rods in the APR1400 model.

Since the failure of an EDG was assumed as single failure, the safety injection from both DVI lines next to the broken line was assumed to be lost. In addition, the broken DVI line also lost the injection from the SIT and SIP. Thus, three SIT and one SIP were modeled at the APR1400 model as depicted in Figure 2. Differently from ordinary modeling practice with the accumulator model, both the SIT and surge line were described by using pipe components and a valve component has been used to simulate the fluid device which allows the transition from high to low flow modes. The initial pressure and temperature of the SIT were 4.2 MPa and 325 K, respectively, and the injection from the SIT starts at a pressure of 4.03 MPa. The SIP was modeled by using time dependent volume and time dependent junction components with the mass flow rate table. The SIP injection is actuated by low pressurizer pressure trip at a pressure of 10.72 MPa and a delay of 40.0 sec was assumed in order to consider delay due to the EDG start-up.

A quick-opening valve has been employed to model the break at the DVI line closed to loop 2a in Figure 2. The critical flow was described by using modified Henry-Fauske model. Since the APR1400 model was used to model the experiment at ATLAS, it is required to modify the discharge coefficient from a default value of 1.0 to a value suitable for the experiment. A previous study done by Ko and Kim [12] indicated that the proper value for the discharge coefficient was 0.75 based on sensitivity analyses done with MARS-KS calculations for the same ATLAS experiment. Since the scaling for the break mass flow rate was already done with the break flow area, it was decided to employ a discharge coefficient of 0.75 for this analysis.

The counter-current flow limitation (CCFL) can be present during accidents at the upper core tie plate or fuel alignment plate, downcomer annulus, steam generator tube support plates, and entrance to the tube sheet in the SG inlet plenum. In small-break LOCA analyses, it is very important to describe CCFL phenomena occur at the fuel alignment plate at the top of the reactor core. During the reflux condenser mode of SG, the condensate generated at SG flows back though the hot leg and finally to the fuel alignment plate. If the CCFL is not modeled appropriately, the condensate can directly fall into the reactor core and help the core cooling. However, CCFL actually occurs there due to the small flow path through the fuel alignment plate and, as a result, the reactor core has more chance to have a peak of the peak cladding temperature (PCT) due to less effective core cooling. Since CCFL phenomena are highly correlated to the geometry, the coefficients for CCFL models should be selected considering the geometry of the flow path. In MARS-KS, CCFL phenomena are modeled by using the Bankoff correlation, which allows an interpolation between Wallis and Kutateladze forms [13]. Since the flow path at the fuel alignment plate has a small hydraulic diameter, the Wallis form of the CCFL correlation is more appropriate to be employed. Sensitivity analyses to determine two coefficients in the CCFL model has been carried out and, as a result, optimal coefficients are obtained as 0.4 and 1.0 for slope m and gas intercept c, respectively.

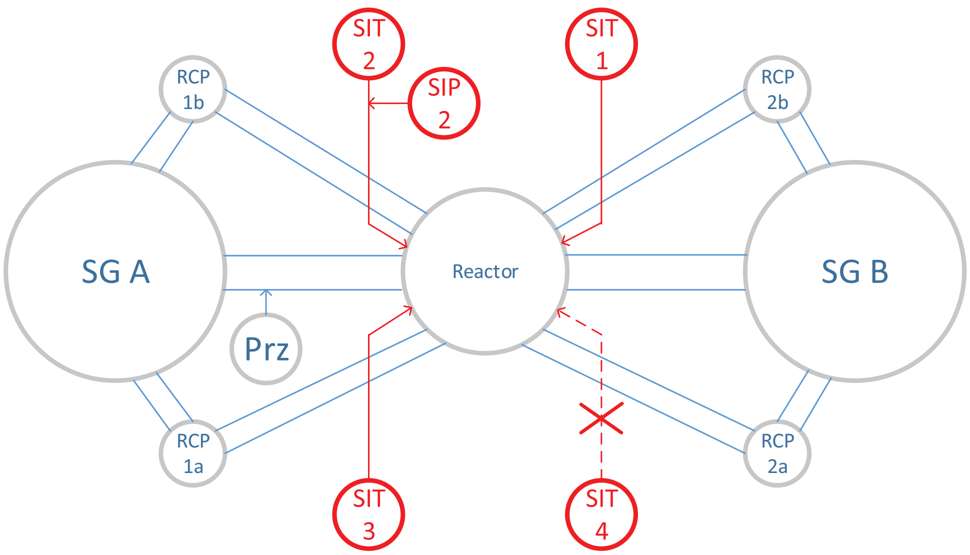

Figure 2. ECCS component arrangement.

4. DVI LINE BREAK ANALYSIS RESULTS

4.1. Steady State Calculation

Table II summarizes the steady state parameters for both experiment and APR1400 calculation. As indicated by Table II, the steady state parameters predicted by APR1400 calculation make good agreements with corresponding parameters from ATLAS.

Table II. Steady-State Parameters

Parameter	Target Value (ATLAS)	APR1400 (MARS-KS)	Equivalent Value
Primary System			
Core power (MW)	1.566	318.83	1.566 equivalent
Pressurizer press. (MPa)	15.55	15.55	-
Core inlet temp. (K)	563.85	562.39	-
Core outlet temp. (K)	597.35	597.35	-
Cold leg flow rate (kg/s)	2.0	396.58	1.95 equivalent
Secondary System			
Secondary press. (MPa)	7.83	7.829	-
Feedwater temp. (K)	505.35	505.37	-
Feedwater flow (kg/s)	0.44	90.634	0.445 equivalent
ECCS			
SIT pressure (MPa)	4.2	4.2	-
SIT temperature (K)	323.15	323.95	-
SIT level (%)	95.1/94.9/94.2	95.1/94.9/94.2	-

Table III. Chronology of the accident

Events	ATLAS (time*, sec)	APR1400 (time sec)	Remarks
Break open	0.0	0.0	
Low pressurizer pressure trip (LPP)	28.28	27.18	P < 10.72 MPa
Pressurizer heater trip	LPP + 0.0		
Reactor scram & RCP trip	LPP + 0.5		
Turbine Isolation	LPP + 0.1		
Main feedwater isolation	LPP + 10.0		
Safety injection pump start	LPP + 40.0		
SIT starts	328.0	285.0	P < 4.03 MPa

* Time of ATLAS is scaled to time of Apr1400 by multiplying a scaling ratio of 1.414.

4.2. Transient Results

4.2.1. Chronology

Because of the scaling with the reduced height, the transient at ATLAS occur 1.414 times faster than one at APR1400. The accident was initiated at 200.0 sec at the experiment which is equivalent to 282.8 sec at APR1400 and thus, the DVI line guillotine break at APR1400 model was initiated at 282.8 sec in order to compare results from the experiment and calculation more conveniently. From this point, the standard time is the APR1400 time.

As mentioned before, the DVI line guillotine break occurred at 282.8 sec by opening a quick-opening valve at the upper downcomer. As soon as opening the break valve, the primary pressure began to decrease and reached the set point of the low pressurizer pressure (LPP) trip, 10.72 MPa, at 310.0 sec. The scram signal was generated in 0.5 sec from the LPP signal. The main steam line and secondary feedwater were isolated after the LPP signal with delays of 0.1 sec and 10.0 sec, respectively. The core power was maintained constant for 5.7 seconds from the LPP signal and started to follow the programmed decay heat curve at 315.7 sec. At 350.0 sec, the SIP was triggered after a delay of 40.0 sec from the LPP signal. Three SITs started to deliver the ECC water at 567.8 seconds when the upper downcomer pressure was 4.03 MPa. The calculation was finished at 2,000 sec. The prediction of the chronology of the major events by MARS calculation was consistent with the experimental results. However, the SIT injection started earlier in APR1400 calculation due to relatively faster depressurization of the primary system. The chronology is summarized in Table III.

4.2.2. Pressure

The time-traces of the primary pressures of both experiment and APR1400 calculation are depicted in Figure 3. As soon as opening the break valve, the primary pressure decreased rapidly due to the sudden loss of coolant inventory. Rapid depressurization continued until the flashing of the coolant into steam was started. After the depressurization rate was changed, the primary pressure formed a plateau at a certain level until the loop seal clearing occurred. When the circulation flow path of the two-phase mixture in the primary system was secured by the loop seal clearing, the plateau was finished and the primary pressure started decreasing rapidly. In this stage, the APR1400 calculation revealed very high depressurization rate in pressure, comparing to the ATLAS experiment. This is because of high stored heat and thermal inertia number at ATLAS [7]. As a result of component scaling applied for ATLAS, it was indicated that the reactor pressure vessel had higher stored heat than APR1400 and the corresponding scaling factor was 2.6. In addition, thermal inertia number, defined by a ratio of the thermal inertia of solid and liquid, of ATLAS was 1.28 which reveals that ATLAS has 30 % higher thermal inertia than APR1400. This scaling analysis indicated that the depressurization of the primary system at ATLAS occurs slower than that at APR1400, and the calculation results revealed that the phenomena expected by scaling analysis actually occurred at the experimental facility.

4.2.3. Break Flow

Figure 4 compares the break flow from the experiment and MARS-KS calculation. Since there is a substantial pressure difference between the reactor pressure vessel and a tank simulates the containment, the critical flow condition was maintained for whole calculation time. The plot of the break flow shows a very clear transition of flow regime at the break from single-phase liquid, two-phase flow, and finally to single-phase vapor. The transition from two-phase flow to single-phase vapor flow occurred by the depressurization followed by loop seal clearing. The default critical flow model of MARS-KS, modified Henry-Fauske model [14], was employed for the break flow modeling and Figure 4 reveals that the characteristics of the break flow could be captured by the critical flow model with a discharge coefficient of 0.75.

4.2.4. Phenomena regarding Loop Seal Behavior

The variation of the collapsed water level in the vertical intermediate legs is presented in Figure 5. The condensate was generated at the SG during the reflux condenser mode and accumulated in the intermediate legs. Due to the accumulation of the condensate, the natural circulation flow path between the upper plenum and cold leg nozzle at the downcomer could not be established successfully. Thus, the pressure difference between the upper plenum and downcomer increased. When the pressure difference became big enough to push out the accumulated condensate at the intermediate leg, the condensate was removed at once and then a stable natural circulation path was established. Figure 5 indicates that the APR1400 calculation could capture the loop seal clearing phenomena at the same time as in the experiment. In addition, the primary pressure decreased when the loop seal clearing occurred because of no more pressure build-up in the system. Figure 6 reveals that the depressurization of the primary system started again right after the loop seal clearing.

During the pressure build-up at the upper plenum, the water levels at downcomer and core were totally different with each other due to the different pressure at downcomer and upper plenum. Since the pressure at the upper plenum was higher than that of the downcomer, the core had a lower water level than the downcomer. Such an inequality in the water level became more severe because of the continuous pressure build-up at the upper plenum. As a result, the core started to be uncovered and the cladding temperature of the uncovered fuel rods increased. In this stage, the loop seal clearing plays very important role in cooling down the uncovered fuel rods by flooding the core. The heat-up of the uncovered fuel rods continued until the core level was brought above the top of the active fuel as a result of the loop seal clearing. When the loop seal clearing occurred, the pressure difference between the downcomer and the upper plenum decreased substantially by establishing the natural circulation path between them. Because of the equilibrium in pressure, the water level at the core increased, whereas the water level in the downcomer decreased as shown in Figure 7. The water level increase at the core helped flooding the uncovered fuel rods and prevented the cladding temperature from increasing. As a result, the cladding temperature made a peak and decreased again, as depicted in Figure 8. The PCT decreased little faster in the APR1400 calculation. This is because of the scaling distortion in thermal inertia discussed in section 4.2.2.

In general, the phenomena at ATLAS related to the loop seal behavior were reproduced appropriately in the MARS-KS calculation for APR1400.

5. CONCLUSIONS

A scaling analysis for a DVI line guillotine break accident has been carried out in order to address similarity between APR1400 and its scaled-down experimental facility, ATLAS. The analysis was conducted by simulating an integral effect test for the DVI line break at ATALS using the MARS-KS calculation with the APR1400 model. The result indicates that the general thermal hydraulic behavior at ATLAS during the experiment was well reproduced by the APR1400 calculation. Especially, the loop seal clearing, one of the most important phenomena in determining the PCT, was well predicted by APR1400 calculation. Although the ATLAS experiment indicated slower depressurization of the primary system, the slower depressurization had been predicted from higher thermal inertia of ATLAS and such a scaling distortion could be analyzed by using scaling law applied for the experimental facility. In order to address the similarity between ATLAS and APR1400 in more general manner, it is expected to conduct more scaling analyses for different experiments.

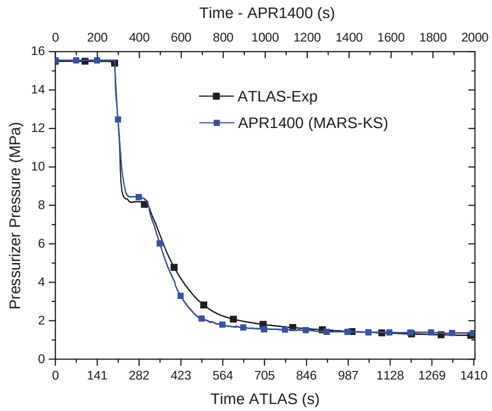

Figure 3. Primary pressure.

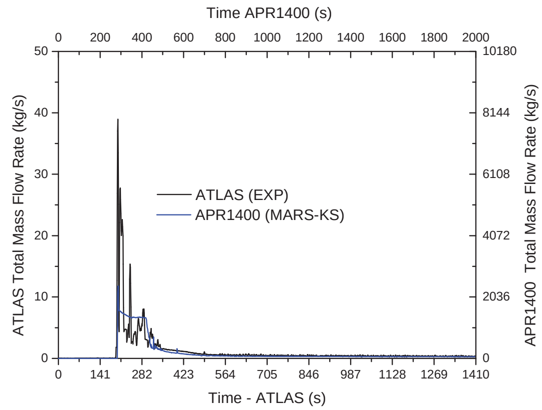

Figure 4. Break flow.

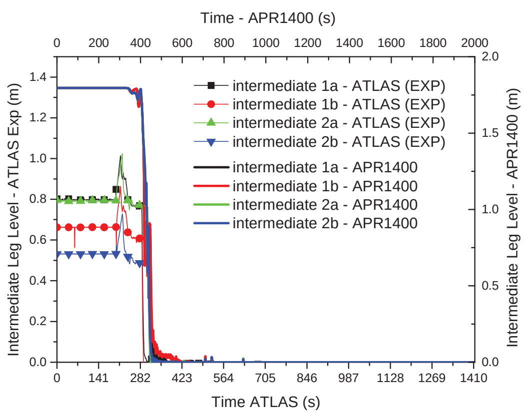

Figure 5. Collapsed water level in loop seal.

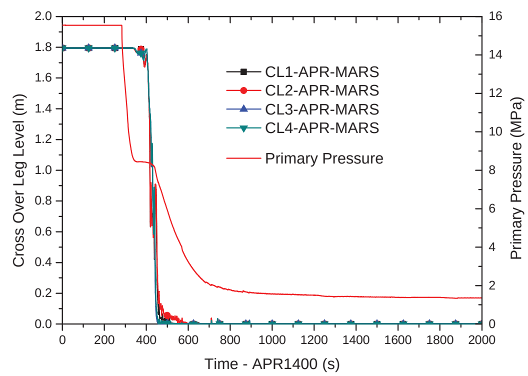

Figure 6. Primary pressure at loop seal clearing

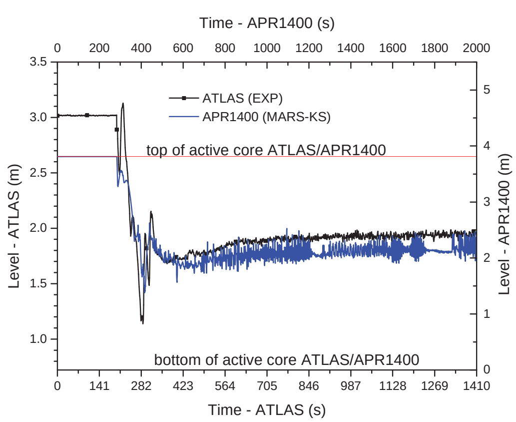

Figure 7. Active core level

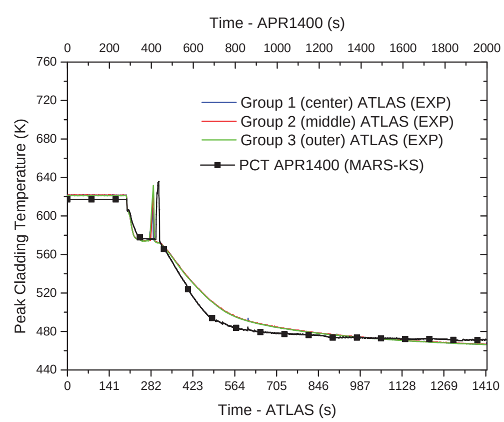

Figure 8. Peak cladding temperature

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