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International Agreement Report

Investigation of the Loop Seal Clearing Phenomena for the ATLAS DVI Line and Cold Leg SBLOCA Tests Using MARS-KS and RELAP5/MOD3.3

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ABSTRACT

In the framework of the ATLAS Domestic Standard Problem (DSP), the loop seal clearing phenomena of the ATLAS Direct Vessel Injection (DVI) line and cold leg Small Break Loss of Coolant Accident (SBLOCA) tests were investigated. MARS-KS and RELAP5/MOD3.3 codes were used to predict the transient thermal hydraulic behavior of the DVI line and cold leg SBLOCA and compared with the ATLAS test data. MARS-KS and RELAP5/MOD3.3 calculations show that both codes predict the sequence of events and major thermal hydraulic behaviors of the tests with reasonable agreement. However, both codes calculate some discrepancies in predicting core collapsed water level, loop seal clearing and thus show large differences in the maximum PCT. Further R&D is required specifically to investigate the loop seal clearing phenomena and its effects on the safety during a postulated SBLOCA.

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EXECUTIVE SUMMARY

ATLAS integral test facility was constructed at KAERI in 2006 as a part of the national long-term nuclear R&D program of the Ministry of Science and Technology. APR1400 was the reference plant of the ATLAS with DVI ECCS. ATLAS has been used for the validation of the thermal-hydraulic models and codes as well as for the performance and safety evaluations of the advanced safety systems of the operating OPR1000, APR1400 and advanced PWRs under development in Korea. ATLAS also has been used to simulate a wide range of transient and accident conditions of the BDEs and BDBEs including SBLOCAs and LBLOCAs. International cooperation has been developed through OECD/NEA CSNI ISP-50 for the 50% DVI line break SBLOCA database. KAERI and JAEA are also collaborating for a counterpart test program of the IET and 8” SBLOCA using ATLAS and LSTF. Currently, Using ATLAS test facility, KAERI is participating in the OECD-ATLAS program for the prolonged SBO and prolonged SBO with multiple steam generator tube ruptures.

This study has been performed in the framework of the DSP exercise program using the ATLAS test facility organized by KAERI and KINS since 2008. The objective of the ATLAS DSP exercise is to contribute to improving safety analysis methodologies for the PWRs with participating domestic entities in Korea. Currently, 23 organizations are participating in the ATLAS DSP program including Universities, nuclear industries, consulting firms and regulatory body. Various system codes were used from different organizations to simulate ATLAS tests and compare with the test data as well as other code results such as those of the MARS-KS, SPACE, RELAP5/MOD3.3, and TRACE..

In this study, ATLAS 100% DVI line and 6” cold leg SBLOCA tests were analyzed using the best estimate MRS-KS and RELAP5/MOD3.3 codes and compared with the ATLAS DSP experimental data. Especially, loop seal clearing phenomena during the postulated SBLOCA and its effects on the collapsed core water level and thus on the PCT were investigated in this study.

MAR-KS Version 1.2 and RELAP5/MOD3.3 Patch 4 were used to predict the ATLAS DVI line and cold leg SBLOCA experiments and the results were compared with the experiments. Both MARS-KS and RELAP5/MOD3.3 codes well predict major thermal hydraulic parameters and chronology during the transients with reasonable agreement. However, both MARS-KS and RELAP5/MOD3.3 have deficiencies in predicting loop seal clearing phenomena and thus the primary core pressure, core water level, and the PCT compared to the experiments performed through the ATLAS DSP program. Therefore, the loop seal clearing phenomena during SBLOCA and its impact on the safety should be further evaluated for the commercial nuclear power plants. .

ACKNOWLEDGMENTS

The authors acknowledge the financial support from the Ministry of Science (MOST) of Korea for this ATLAS Domestic Standard Problem (DSP) exercise program and the support of Korea Atomic Energy Research Institute (KAERI) and Korea Institute of Nuclear Safety (KINS) for the integrated coordination of the ATLAS DSP exercise program in Korea.

ABBREVIATIONS AND ACRONYMS

ALWR	Advanced Light Water Reactor
APR1400	Advanced Pressurized Reactor with 1400 MWe Electric Power
APR+	Advanced Power Reactor Plus
ATLAS	Advanced Thermal-hydraulic test Loop for Accident Simulation
BDBE	Beyond Design Basis Event
CCFL	Counter Current Flow Limit
CL	Cold Leg
CLI	Cold Leg Injection
DAS	Data Acquisition System
DBE	Design Basis Event
DC	Downcomer
DSP	Domestic Standard Problem
DVI	Direct Vessel Injection
ECCS	Emergency Core Cooling System
EPRI	Electric Power Research Institute
FAP	Fuel Alignment Plate
FLB	Feedwater Line Break
GUI	Graphic User Interface
HTGCR	High Temperature Gas Cooled Reactor
IET	Integral Effect Test
ISP	International Standard Problem
ITL	Integral Test Loop
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
LBLOCA	Large Break Loss of Coolant Accident
LOOP	Loss of Off-site Power
LPPT	Low Pressurizer Pressure Trip
LSTF	Large Scale Test Facility
MARS-KS	Multi-dimensional Advanced Reactor Safety Program- Korea Standard
MOST	Ministry of Science and Technology
MSSV	Main Steam Safety Valve
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OPR1000	Optimized Pressurized Reactor with 1000 MWe
PWR	Pressurized Water Reactor
RELAP5	Reactor Excursion and Leak Analysis Program
RCP	Reactor Coolant Pump
RPV	Reactor Pressure Vessel
SBLOCA	Small Break Loss of Coolant Accident
SBO	Station Black-Out
SIP	Safety Injection Pump
SIT	Safety Injection Tank
SIS	Safety Injection System
SET	Separate Effect Test
SFR	Sodium Fast Breeder Reactor
SGTR	Steam Generator Tube Rupture
SLB	Steam Line Break

SMART	Small and Medium Advanced Reactor
System80	ABB-CE PWR
System80+	Advanced ABB-CE PWR
TDJ	Time Dependent Junction
TDV	Time Dependent Volume
UAE	United Arab Emirates
URD	User Requirement Document
USNRC	United States Nuclear Regulatory Commission

1 INTRODUCTION

Nuclear regulatory safety criteria for the postulated Loss of Coolant Accident (LOCA) such as 10CFR50.46 Appendix K (Ref. 1) are applicable both for the SBLOCA and Large Break Loss of Coolant Accident (LBLOCA). Thus, the maximum Peak Cladding Temperature (PCT), cladding oxidation and hydrogen generation must not exceed the safety limits specified for the LOCA Design Basis Accidents (DBA). SBLOCA is generally defined a LOCA of the primary system inventory with a break size less than 0.5 ft^2 (0.4645^{-2} m^2) since the thermal hydraulic phenomena during a postulated SBLOCA are quite different from those of the LBLOCA. For most of the safety analyses as well as the Emergency Core Cooling System (ECCS) performance analyses, LBLOCA is more limiting than the SBLOCA due to inherent characteristics of the accident. However, due to best estimate assumptions and uncertainties of the LBLOCA analysis methodology, SBLOCA may results in a limiting case depending on the accident scenarios.

SBLOCA became an emerging safety issue since TMI-2 Nuclear Power Plant (NPP) accident in 1979 and various international researches on the SBLOCA predictions and experiments have been performed. Especially, loop seal formation, clearing, and reformation phenomena during the SBLOCA have been investigated through various experiments and analyses, and identified as a major cause of the core heat-up during the SBLOCA (Ref. 2) and thus increasing the PCT. Randomness of the loop seal clearing and its sequences was suggested (Ref. 3) for the cold leg SBLOCA even though it is the results of the thermal hydraulic flow resistances of the loop and manometric head across the core. Randomness of the loop seal clearing sequences also has been the US Nuclear Regulatory Commission (USNRC) regulatory position on the loop seal clearing during a postulated SBLOCA. Electric Power Research Institute (EPRI) published its design guidelines for the advanced LWRs as EPRI Utility Requirements Document (URD) (Ref. 4) and specified that reactor core should be covered during SBLOCA with break size less than 6 inch diameter of the pipe as a design requirement.

Due to the complexity in thermal hydraulics of the loop seal clearing phenomena and its impact on the PCT during SBLOCA, a set of SBLOCA tests were performed using Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) Integral Effect Test (IET) facility at KAERI. ATLAS Integral Test Loop (ITL) was constructed at KAERI in 2006 as a scaled model of the APR1400 reference plant with DVI Safety Injection System (SIS). ATLAS has been used for the validation of the thermal-hydraulic models and codes, and for the performance and safety evaluations for the advanced safety systems of the advanced PWRs under development in Korea. ATLAS was designed as a reduced height scaled model with volume scale of 1/288 (= 1/2 x 1/12 x 1/12) following Ishii and Kataoka (Ref. 5) reduced height and 3-level scaling methodology. ATLAS has been used to simulate a wide range of the transient and accident conditions of the BDEs and Beyond DBEs (BDBEs) including SBLOCA and LBLOCA. ATLAS test facility is described in detail in Chapter 3 of this report.

This study was performed in the framework of the DSP exercise program using ATLAS. The objective of the ATLAS DSP exercise is to contribute to improving safety analysis methodologies for the PWRs with domestic entities in Korea. Currently, 23 organizations are participating in the ATLAS DSP exercise program such as Universities, nuclear industries, consulting firms and regulatory body. Various system codes were used from different organizations to simulate ATLAS tests and compare with test data as well as other code results such as those of the MARS-KS, SPACE, RELAP5/MOD3.3, and TRACE codes.

This study is the results of the ATLAS DSP-01 (SB-DVI-08 test, 100% DVI Line SBLOCA) and DSP-02 (SB-CI-09 test, 6” Cold Leg SBLOCA) using MARS-KS (Ref. 7) performed by Environment and Energy Technology, Inc. RELAP5/MOD3.3 (Ref. 8) was also used to compare the results with those of the MARS-KS. This study is especially focused on the loop seal clearing behavior during DVI line and cold leg SBLOCA and its impact on the PCT.

2 ATLAS INTEGRAL EFFECT TEST FACILITY

2.1 Overview of the ATLAS Integral Effect Test Facility

KAERI has been operating ATLAS IET facility for transient and accident simulations for the OPR1000 and APR1400 nuclear power plants which are currently in operation in Korea. APR1400 is a DVI SIS plant compared to the OPR1000 with cold leg injection SIS and thus ATLAS is equipped with both DVI line and cold leg small break LOCA simulators (Ref. 6).

The ATLAS test program was started in 1997 under long-term nuclear R&D program funded by the Ministry of Science and Technology (MOST) of Korean government. In 2005, ATLAS was completely installed and after several commissioning tests, the first IET test was performed in 2006 for a cold leg SBLOCA with a break size equivalent to 3 inch in diameter.

Since 2007, ATLAS has been extensively used to resolve the safety issues related to the DVI line SBLOCA, which were raised by the KINS during its licensing process for the APR1400. The thermal hydraulic phenomena in the Reactor Pressure Vessel (RPV) Downcomer (DC) during the DVI line and cold leg SBLOCAs are expected to be different due to the DVI and cold leg injection SIS. ATLAS sensitivity tests for different DVI line break sizes were performed for four break sizes: 5%, 25%, 50%, and 100%. ATLAS has been used to provide unique test data for the 2(hot legs) x 4(cold legs) reactor coolant system with DVI SIS of ECCS; this ATLAS tests significantly expanded the currently available thermal hydraulic data base for code validation.

After a series of DVI line SBLOCA tests, ATLAS sensitivity tests for different cold leg break sizes and different break locations have been conducted. KAERI is also collaborating with Japan Atomic Energy Agency (JAEA) for the IET counterpart tests using Large Scale Test Facility (LSTF) for 6" SBLOCA, Steam Generator Tube Rupture (SGTR), Feed Line Break (FLB), Steam Line Break (SLB) and other transients of mutually agreed. Currently, ATLAS is also performing OECD-ATLAS International Standard Problem Exercise (ISP-50) tests for a prolonged Station Black-Out (SBO) with multiple SGTR failures.

ATLAS integral effect test facility is a two-loop scaled model of the APR1400 operating in Korea and under construction in United Arab Emirates (UAE). ATLAS has been operated to investigate and validate major operational transients and design basis accidents for the APR1400. In order to evaluate the performance and thermal hydraulic phenomena of the safety systems of the OPR1000 operating in Korea, ATLAS also incorporated specific design features of the OPR1000 such as cold leg SIS ECCS. ATLAS was designed with reduced height 3-level scaling methodology following Ishii and Kataoka scaling method (Ref. 5). Table 1 shows major scaling parameters. Tables 2 and 3 show the global scaling ratios for the single-phase and two-phase natural circulation of the reactor core, respectively (Ref. 6). Except the heat transfer due to turbulence and superficial velocity due to reduced height and increased surface area, most of the thermal hydraulic dimensionless parameters are scaled with reasonable agreement. ATLAS is a full pressure, half-height and 1/288 volume (1/2 x 1/12 x 1/12) and 10% of scaled power (1.96 MWe) integral test facility with respect to the APR1400 reference plant. Scaled (1/144) heated rods were used to simulate the core power. Fluidic system of the ATLAS integral test loop consists of the primary system, secondary system, four-train safety injection systems, break simulating system, containment simulating system, auxiliary feedwater systems and engineered safety featured system. Primary system includes reactor vessel, two hot legs, four cold legs, pressurizer, four reactor coolant pumps, and two steam generators. Secondary system of the ATLAS is simplified as a circulating loop configuration. Figures 1 and 2 show the ATLAS schematic design configuration and corresponding flow diagram, respectively. Both DVI and CLI for the APR1400 and OPR1000 were incorporated in the ATLAS SIS and Figure 3 shows arrangement of the primary loop and DVI SIS of the APR1400. More than 1300 instruments are installed to measure major transient thermal hydraulic parameters using ATLAS instrumentation and Data Acquisition System (DAS).   .

Table 1   Major Scaling Parameters of ATLAS

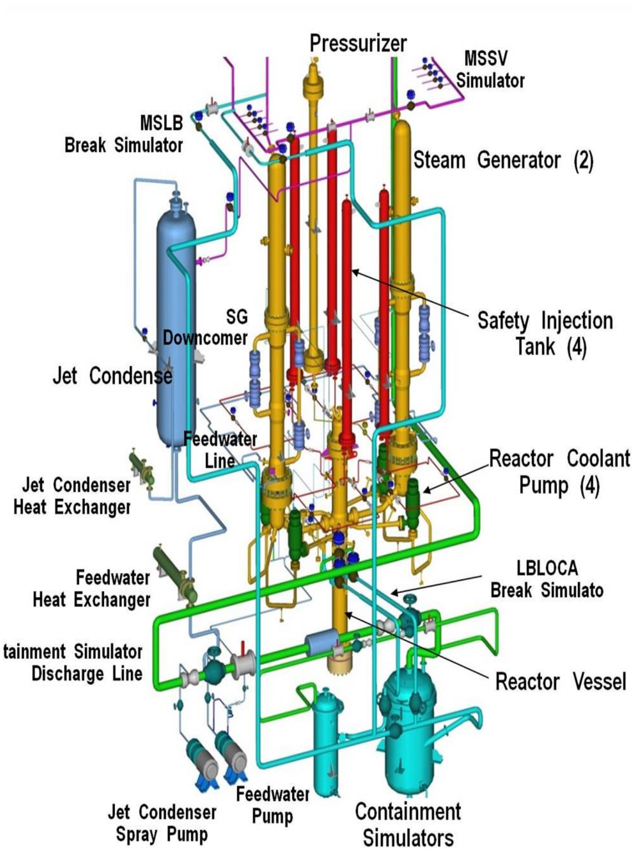
Parameters	Scaling ratio	ATLAS design
Length (height)	l_{oR}	1/2
Diameter	d_{oR}	1/12
Area	d_{oR}^2	1/144
Volume	$l_{oR}\, d_{oR}^2$	1/288
Core temperature rise	T_{oR}	1
Velocity	$l_{oR}^{1/2}$	1/1.414
Time	$l_{oR}^{1/2}$	1/1.414
Power/volume	$l_{oR}^{-1/2}$	1.414
Heat flux	$l_{oR}^{-1/2}$	1.414
Core power	$l_{oR}^{1/2}\ d_{oR}^2$	1/203.6
Rod diameter (core)	1	1
U-Tube diameter (steam generator)	$l_{oR}^{1/2}$	1/1.414
Number of rods (core)	d_{oR}^2	1/144
Number of U-tubes (steam generator)		1/72
Flow rate	$l_{oR}^{1/2}\ d_{oR}^2$	1/203.6
Pressure drop	l_{oR}	1/2

Table 2 Global Scaling Results for Single Phase Natural Circulation of the Reactor Core

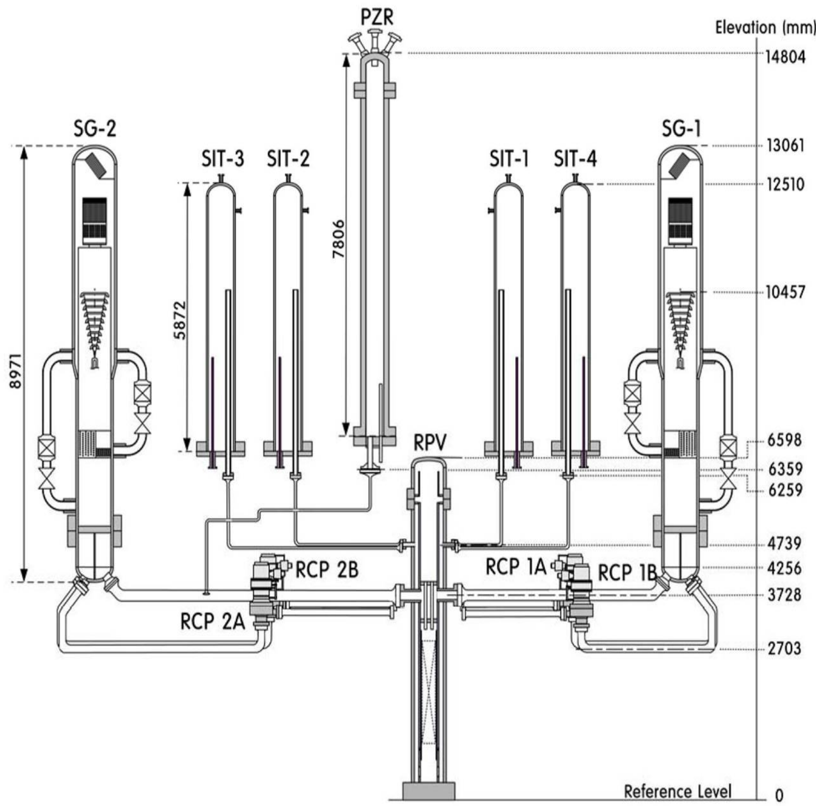
Design parameter	ATLAS scaling ratio
Richardson number	1.00
Friction number	1.00
Axial length scale	1.00
Flow area scale	1.00
Heat transfer coefficient (laminar)	1.00
Heat transfer coefficient (turbulent)	0.76
Modified Stanton number (laminar)	0.71
Modified Stanton number (turbulent)	0.54
Time ratio number	0.94
Biot number (laminar)	0.90
Biot number (turbulent)	0.68
Heat source number	0.78

Table 3 Global Scaling Results for Two-Phase Natural Circulation of the Reactor Core

Design parameter	ATLAS scaling ratio
Phase change number	1.00
Subcooling number	1.00
Froude number	1.00
Time ratio number	0.94
Thermal inertia number	1.28
Inlet subcooling	1.00
Exit quality	1.00
Friction number	0.71
Orifice number	1.00
Superficial velocity	0.71
Drift flux number (Bubbly-slug)	1.40 ~ 1.05
Drift flux number (Turbulent slug)	1.40 ~ 1.05
Heat transfer coefficient	~ 1
Modified Stanton number	0.71
Biot number	0.90



(a)Schematic Diagram of ATLAS Test Facility



(b) Relative Elevation

Figure 1 Schematic Diagram of ATLAS Loop Configuration

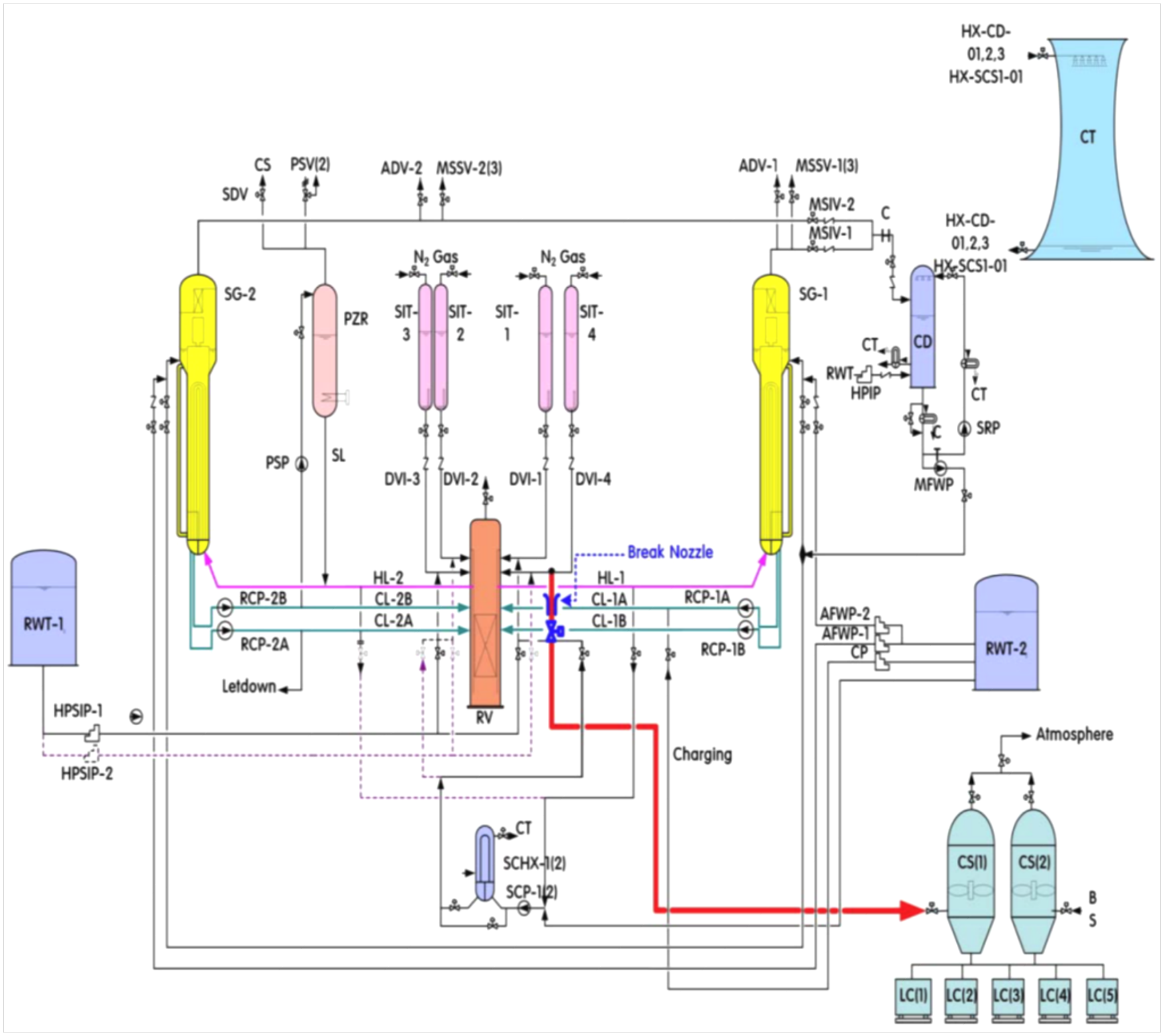


Figure 2 ATLAS Flow Diagram

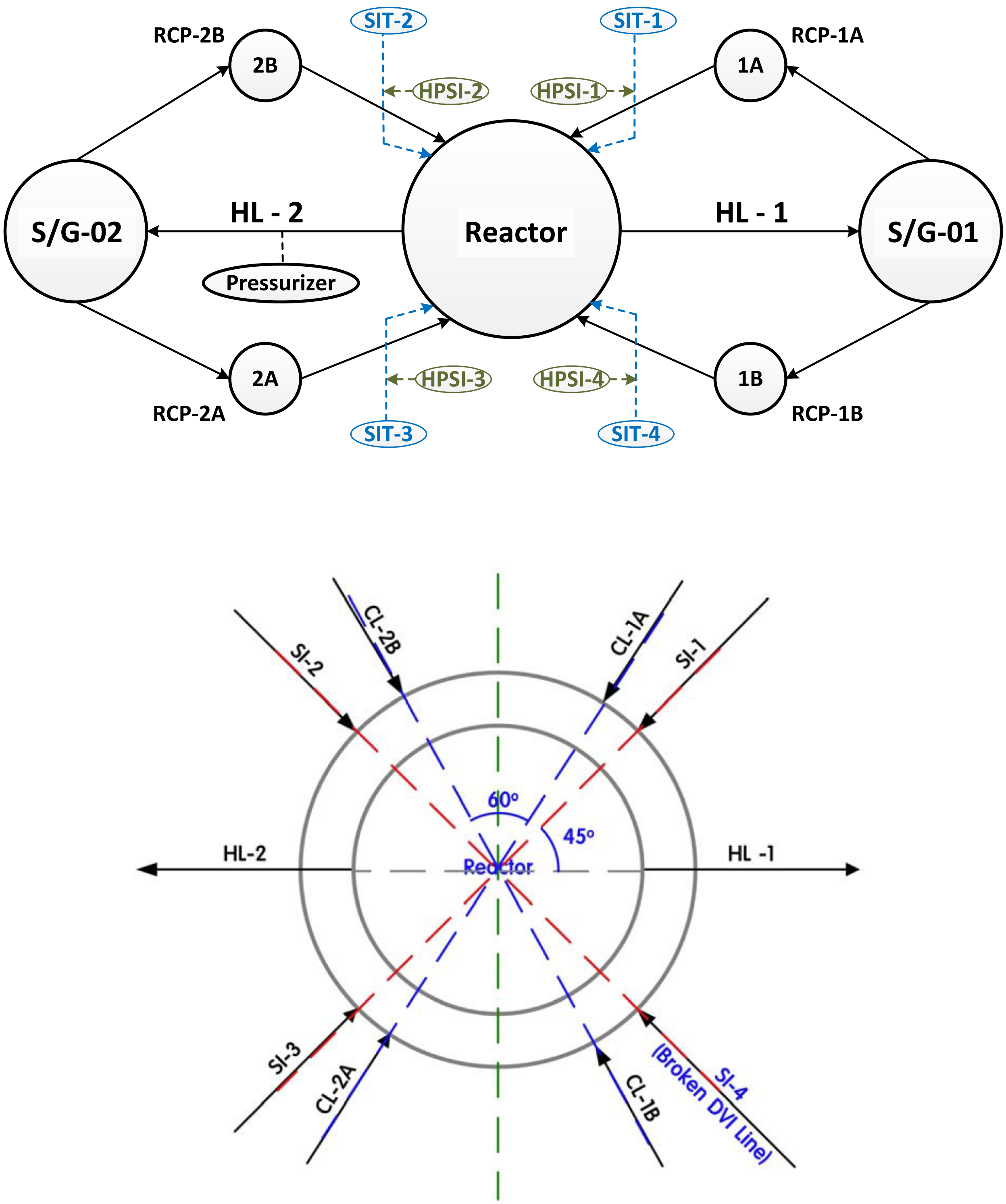


Figure 3 ATLAS Loop and DVI SIS Arrangement

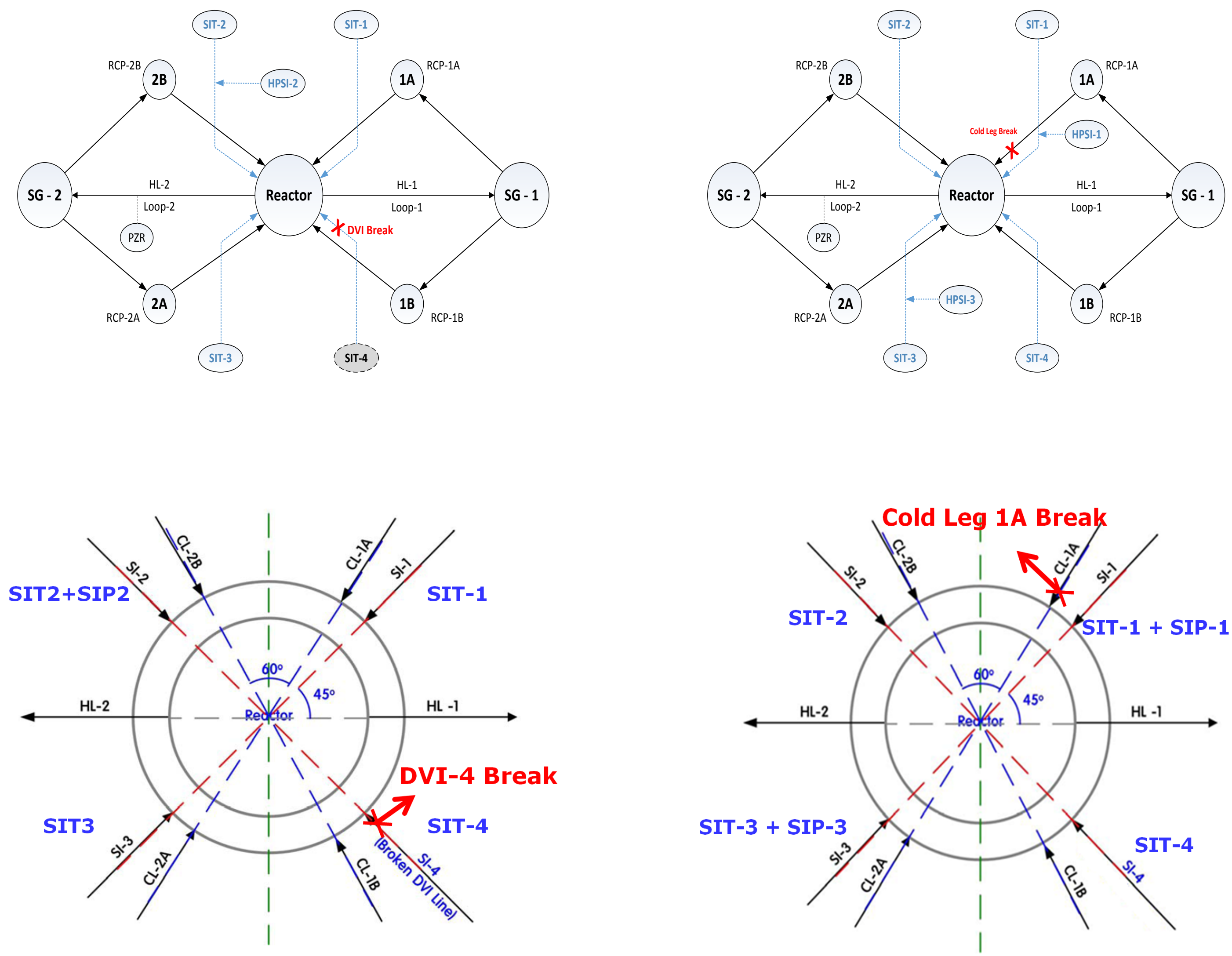
2.2 DVI Line and Cold Leg Break Simulation

For the APR1400 system design, each Safety Injection Tank (SIT) outlet pipe is connected to the DVI line and the DVI lines are located at 8ft above the cold leg centerline with an azimuthal angle of 15^{o}. Figures 4(a) and 4(b) show the DVI line and cold leg break locations for the DVI line and cold leg SBLOCA simulations as well as the SIT and HPSI arrangement with respect to the primary loop of the ATLAS ITL facility.

For the 100% DVI line SBLOCA test, break size of the DVI line was 0.59” diameter scaled from a 8.5” prototype diameter of the APR1400 DVI line (Ref. 9). Both DVI line and cold leg SBLOCA simulations, only one High Pressure Safety Injection (HPSI) pump opposite of the break is conservatively credited due to Loss of Off-site Power (LOOP) assuming two-trains of the plant electric system of the APR1400 design. Three SITs are assumed operable through the DVI lines for the DVI line SBLOCA and all 4 SITs are assumed operable for the cold leg SBLOCA. For the DVI line SBLOCA and cold leg SBLOCA, DVI line 4 (DVI-4) and cold leg 1A (CL-1A) are assumed as the break locations as shown in Figures 4(a) and 4(b), respectively.

DVI line break was simulated using a break spool piece at the broken DVI nozzle. DVI line break simulator consisted of a quick opening valve, a break nozzle, a case holding the break nozzle, and the instruments. A pressure transducer and two thermocouples were installed at both upstream and downstream of the break nozzle. Figure 5 shows geometric configuration of the break nozzle simulator for the DVI line break test SB-DVI-08 (Ref. 10).

Cold leg break simulator also consists of quick opening valve, break nozzle and its housing, and its related instruments. Figure 6 shows detailed geometry of the break nozzle of the cold leg SBLOCA simulator of the ALTAS-SB-CL-09 test (Ref. 11, 12). The inner diameter of the break nozzle is determined as 10.0 mm from the scaling of the 6” cold leg break area which corresponds to the Electric Power Research Institute (EPRI) User Requirement Document (URD) criteria of the core uncovery during SBLOCA for the Advanced Light Water Reactors (ALWRSs).



(a) DVI Line SBLOCA **(b) Cold Leg SBLOCA**

Figure 4 Break Locations for the DVI Line and Cold Leg SBLOCA Simulation

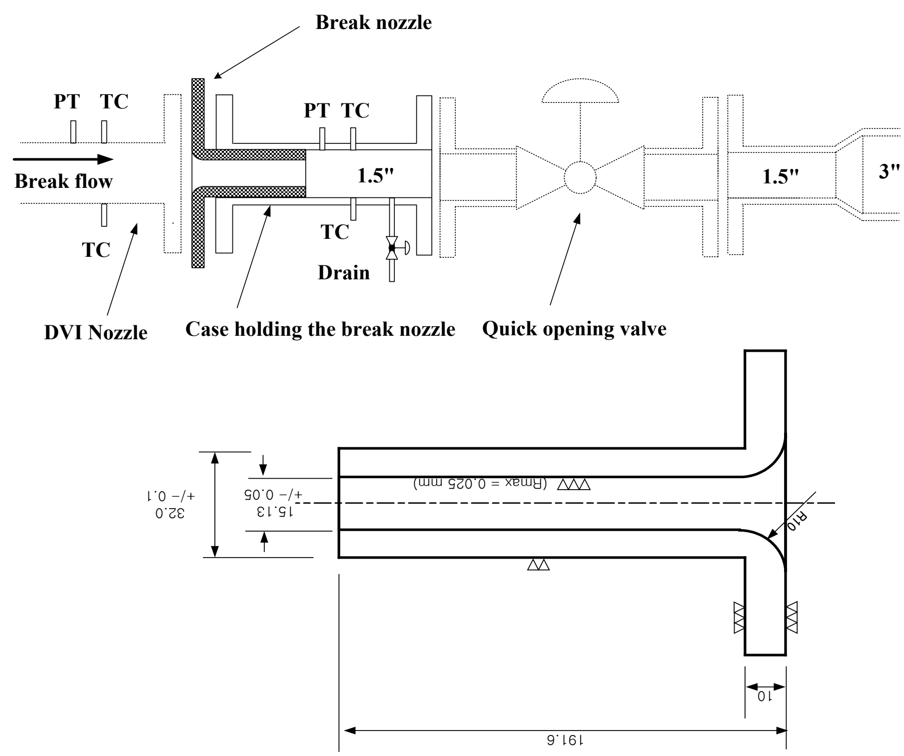


Figure 5 Configuration of DVI Line Break Simulator for ATLAS SB-DVI-08 Test

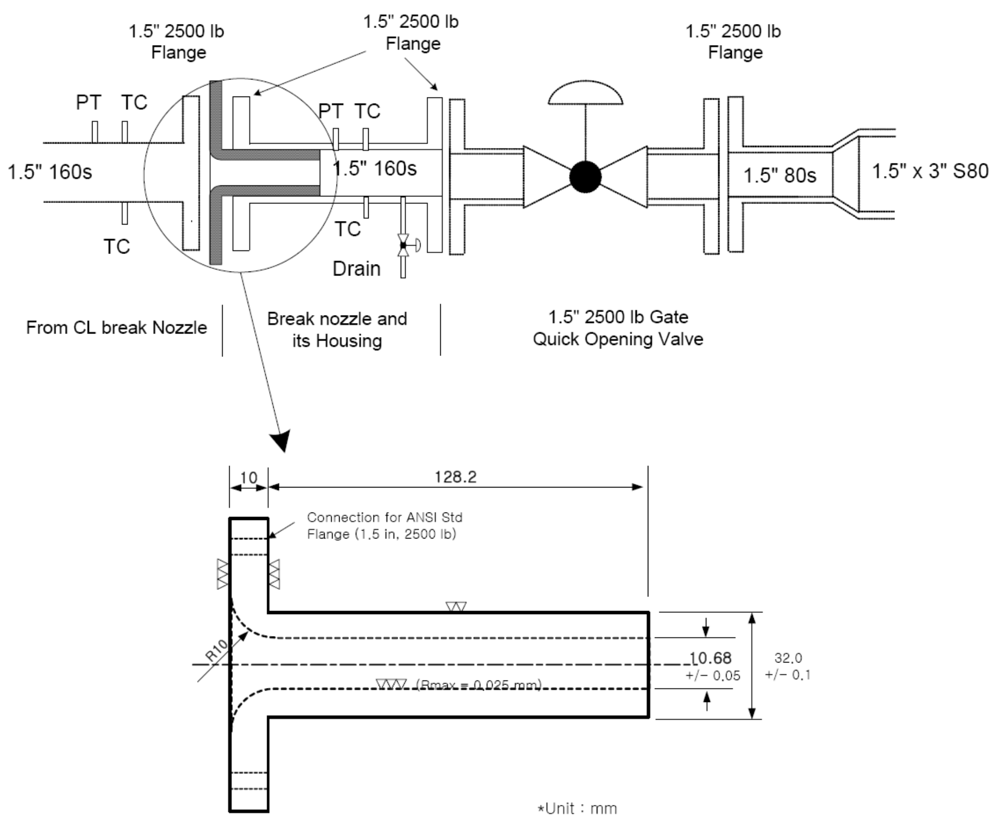


Figure 6 Configuration of Cold Leg Break Simulator for ATLAS SB-CL-09 Test

3 ATLAS DVI LINE AND COLD LEG SBLOCA TESTS

3.1 ATLAS 100% DVI Line SBLOCA SB-DVI-08 Test

ATLAS SB-DVI-08 DVI line break SBLOCA test was performed with the test initial and boundary conditions obtained from the MARS-KS best estimate pretest analysis of the 100% DVI line SBLOCA of the ARR1400 reference plant.

Following assumptions are used for the ATLAS SB-DVI-08 test;

- Simultaneous LOOP with the break
- Single Failure : Loss of one diesel generator to minimize SIP flow
- Conservative Decay Heat Power : 1.2 x ANS 1973 Decay Heat Curve
- Core Power : 8% of scaled core power
- Core Flow : 8% of scaled core flow
- Containment Back Pressure : Neglected due to negligible impact on the transient progress
- Signal Delay Time : Reduced by the ATLAS scaling ratio
- Steady state condition was maintained for 10 minutes after the heatup of the primary inventory by core heater, secondary heatup to balance heat removal and pressurization by pressurizer to achieve steady state thermal hydraulic initial conditions
- DVI line SBLOCA initiated by opening the quick opening valve of the DVI line break simulator. .

Table 4 shows the initial and boundary conditions of the ATLAS SB-DVI-08 DVI line SBLOCA test (Ref. 13).

Table 4 Initial and Boundary Conditions of ATLAS DVI Line SBLOCA SB-DVI-08 Test

Parameter	Measured value	Remarks
Primary system		
Core power (MW)	1.647	8% scaled core power
PZR Pressure (MPa)	15.49	
Core inlet temp. (K)	563.2	
Core exit temp.(K)	598.9	
RCS flow rate (kg/s)	2.2±5% 2.2±5% 2.3±5% 2.2±5%	Cold leg 1A Cold leg 1B Cold leg 2A Cold leg 2B
Secondary system		
Pressure (MPa)	7.85 / 7.85	SG1 / SG2
Steam temp. (K)	566.9 / 566.3 568.6 / 569.3	Steam pipe line Steam dome
FW temp. (K)	505.8 / 507.6 501.8 / 499.4	Economizer Down-comer
FW flow rate (kg/s)	0.33 / 0.35 0.0 / 0.0	Economizer Down-comer
Water level (m)	2.39 / 2.50	
ECCS		
SIT pressure (MPa)	4.23 / 4.26 / 4.22	SIT 1 / SIT 2 / SIT3
SIT temp. (K)	314.2 ~ 314.8	
SIT level (%)	92.0 / 91.3 / 90.4	
RWT temp. (K)	321.2	Storage tank
Containment		
Pressure (MPa)	0.1013	Atmospheric condition / open

3.2 ATLAS 6" Cold Leg SBLOCA SB-CL-09 Test

Initial and boundary conditions of the ATLAS 6” cold leg SBLOCA SB-CL-09 test were determined through the best estimate pretest analysis performed for the 6” cold leg SBLOCA of the APR1400 reference plant using MARS-KS best estimate code.

Following assumptions were used for the ATLAS SB-CL-09 test;

- Simultaneous LOOP with the break
- Single Failure : Loss of one diesel generator to minimize SIP flow
- Conservative Decay Heat Power : 1.2 x ANS 1973 Decay Heat Curve
- Core Power : 8% of scaled core power and heat loss of the primary system

- Core Flow : 8% of scaled core flow
- Containment Back Pressure : Neglected due to negligible impact on the transient progress
- Signal Delay Time : Reduced by the ATLAS scaling ratio
- Steady state condition was maintained for 30 minutes after heatup of the primary inventory by core heater, secondary heatup to balance heat removal and pressurization by pressurizer to achieve steady state thermal hydraulic initial conditions
- Cold leg SBLOCA initiated by opening the quick opening valve of the cold leg break simulator.

Table 5 shows the initial and boundary conditions of the ATLAS SB-DVI-08 DVI line SBLOCA test (Ref. 13).

Table 5 Initial and Boundary Conditions of ATLAS Cold Leg SBLOCA SB-CL-09 Test

Parameter	Measured value	Remarks
Primary system		
Core power (MW)	1.633	8% scaled core power
PZR Pressure (MPa)	15.5	
Core inlet temp. (K)	563.2	
Core exit temp.(K)	598.8	
RCS flow rate (kg/s)	2.2±5% 2.2±5% 2.2±5% 2.2±5%	Cold leg 1A Cold leg 1B Cold leg 2A Cold leg 2B
Secondary system		
Pressure (MPa)	7.82 / 7.82	SG1 / SG2
Steam temp. (K)	566.9 / 566.7 567.8 / 568.1	Steam pipe line Steam dome
FW temp. (K)	505.4 / 506.4 496.5 / 495.7	Economizer Down-comer
FW flow rate (kg/s)	0.373 / 0.382 0.044 / 0.042	Economizer Down-comer
Water level (m)	1.95 / 2.0	
ECCS		
SIT pressure (MPa)	4.24 / 4.15 / 4.01 / 4.17	SIT 1 / SIT 2 / SIT3 / SIT4
SIT temp. (K)	322.5 / 323.2 /323.2 / 325.4	
SIT level (%)	95.1 / 94.9 / 94.2 / 94.5	
RWT temp. (K)	323.2	Storage tank
Containment		
Pressure (MPa)	0.1013	Atmospheric condition / open

4 ATLAS MARS-KS AND RELAP5/MOD3.3 INPUT MODELS

4.1 MARS-KS and RELAP5/MOD3.3 Codes

This study was initiated as an ATLAS DSP exercise program organized by KAERI and KINS since 2008 in Korea. Among the participating members, Environment & Energy Technology, Inc. (en^{2}t), participated in the ATLAS DSP exercise program using MARS-KS Version 1.2 best estimate licensing regulatory safety review code of the KINS.

MARS-KS best estimate code (Ref. 7)has been developed by improving COBRA/RELAP5 code (Ref. 14) by numerically coupling the COBRA-TF subchannel analysis model (Ref. 15) with RELAP5/MOD3 (Ref. 8) best estimate system code using implicit pressure matrix coupling method in 2009 (Ref. 16). MARS-KS has been restructured using FORTRAN90 and its characteristic features of modular data structure and Dynamic Link Library (DLL). After verification and validation, MARS-KS has been used as a best estimate regulatory safety review system code at KINS since 2010. KINS uses MARS-KS for its licensing safety review of the advanced reactors under development in Korea as well as the reload safety analyses of the operating plants. MARS-KS basically consists of 1-dimensional RELAP5/MOD3 model and 3-dimensional COBRA-TF core subchannel model. However, since a MULTI-D model with turbulent mixing and conductivity models was also implemented in the MARS-KS, MARS-KS code is also used to predict multi-dimensional phenomena during operational transient and accident conditions. MARS-KS code has been linked with CONTAIN and CONTEMPT containment analysis codes, MASTER multi-dimensional core analysis code, and MIDAS severe accident code. MARS-KS also implemented various material properties such as H_2, H_2O, D_2O, Sodium, Pb-Bi, He, CO_2 to support licensing review for various advanced reactors such as CANDU, SMART, SFR, HTGCR, and research reactors. Thus MARS-KS provides various safety analysis and performance evaluation capabilities. User friendly on-line Graphic User Interface (GUI) is also developed for user-friendly interfaces and easy access from the users.

RELAP5/MOD3.3 Patch 4 code was also used in this study to compare the results with the results of the MARS-KS Version 1.2 calculations as well as the ATLAS test data.

4.2 ATLAS MARS-KS SBLOCA Input Model

4.2.1 MARS-KS Input Model for the ATLAS SB-DVI-08 Test

MARS-KS input for the ATLAS SB-DVI-08 DVI line SBLOCA test has been prepared based on the initial and boundary conditions as well as the analysis assumptions based on the SB-DVI-08 test specifications (Ref. 10).

The core power was used from the experimental data (Ref. 10). Since the experimental data indicated that the initial heat loss to the environment was 5.6 % of the total power, the reduced core power was employed to account for the heat loss in the calculation and thus the constant heat loss of 5.6 % was applied during entire period of the transient. Since the core power in the experiment was controlled to be constant until it switched to the scaled decay heat power, a delay of 4.0 sec was assumed when the decay heat curve is applied as was the experiment.

The DVI line break was modeled using the VALVE and TIME DEPENDENT VOLUME (TDV) components and connected to the upper downcomer, which is above cold leg B1, C597, as shown in Figure 7 of the MARS-KS nodalization. Henry-Fauske critical flow model was employed with a discharge coefficient of 0.77 based on the sensitivity analyses. Four train Safety Injection Tanks (SITs) and injection lines have been modeled using the PIPE and VALVE components in the MARS-KS code as depicted in Figure 8. Since three out of four SITs are available during the DVI line break accident, the SIT of the broken DVI line was not modeled. The nodalization of each SIT and the dimension of each injection line are slightly different from each other due to the difference in the initial water level of each SIT and the dimension of each injection line. The fluidic device in each SIT was modeled using a flow control valve and an orifice. The diameter of the orifice and the operation characteristics of the flow control valve were determined using the SB-DVI-08 test specifications. The initial pressure and temperature of the SITs were 4.2 MPa and 325 K, respectively.

The Safety Injection Pumps (SIPs) were modeled using TIME DEPENDENT JUNCTIONs (TDJ) and VOLUMEs (TDV) as shown in Figure 8, and the mass flow given in Table 4 was taken from the SIP flow curve. Since the SIP installed at the DVI nozzle opposite to the broken DVI nozzle is available during the transient, the TDJ for the SIP was connected to a volume in upper downcomer as shown in Figure 7. A delay of 28.28 seconds from the Low Pressurizer Pressure Trip (LPPT) signal was assumed for the SIP injection according to the test specifications. Scaled bypass flow between downcomer and hot leg was set to 0.057 kg/sec which is 8 % of nominal bypass flow of the APR1400. A bypass flow of 0.02 kg/sec was considered for the bypass between downcomer and upper head. The countercurrent flow limitation (CCFL) model was implemented for the fuel alignment plate in the RPV. The Wallis correlation was chosen to model the CCFL phenomena in the RPV and the gas intercept was set to 0.8 based on a sensitivity analysis.

4.2.2 MARS-KS Input Model for the ATLAS SB-CL-09 Test

The cold leg break was modeled using VALVE and TIME DEPENDENT VOLUME (TDV) components and connected to a cold leg in loop 1A, C396, as shown in Figure 7. Henry-Fauske critical flow model was employed as a break flow model and the discharge coefficient was set to 0.93 based on the sensitivity analyses.

Based on the isometric drawings provided by KAERI (Ref. 6), the Safety Injection Tank (SIT) and injection line has been modeled using PIPE and VALVE components in the MARS-KS code as shown in Figure 7. The operation of all four SITs was considered in this analysis. The nodalization of each SIT and the dimension of each injection line are slightly different from each other due to the difference in the initial water level of each SIT and the dimension of each injection line. The fluidic device in each SIT was modeled using a flow control valve and an orifice. The diameter of the orifice and the operation characteristics of the flow control valve were determined on the basis of the test specifications described in Reference 5. The initial pressure and temperature of the SITs were 4.18 MPa and 323.2 K, respectively.

The SIP was modeled using TDJ and TDV as shown in Figure 8, and the mass flow of the SIP was obtained from Table 5. Since the LOOP was assumed as a coincident event and the pretest calculation indicted a loss of one diesel generator as the worst single failure, it was assumed that the safety injection from the HIPs via DVI-1 and 3 were available during the transient. A delay of 28.28 seconds from the LPPT signal was assumed according to the ATLAS-SB-CL-09 test specifications.

CCFL model was assumed for the Fuel Alignment Plate (FAP) to better simulate the flow behavior in the upper plenum and core exits.

The Main Steam Safety Valve (MSSV) actuation characteristics were modeled according to the ATLAS SB-CL-09 DSP-02 test specifications. The secondary heat loss of the steam generators to the environment was modeled through the heat structure modeling of the steam generator assuming convective heat transfer at ambient temperature.

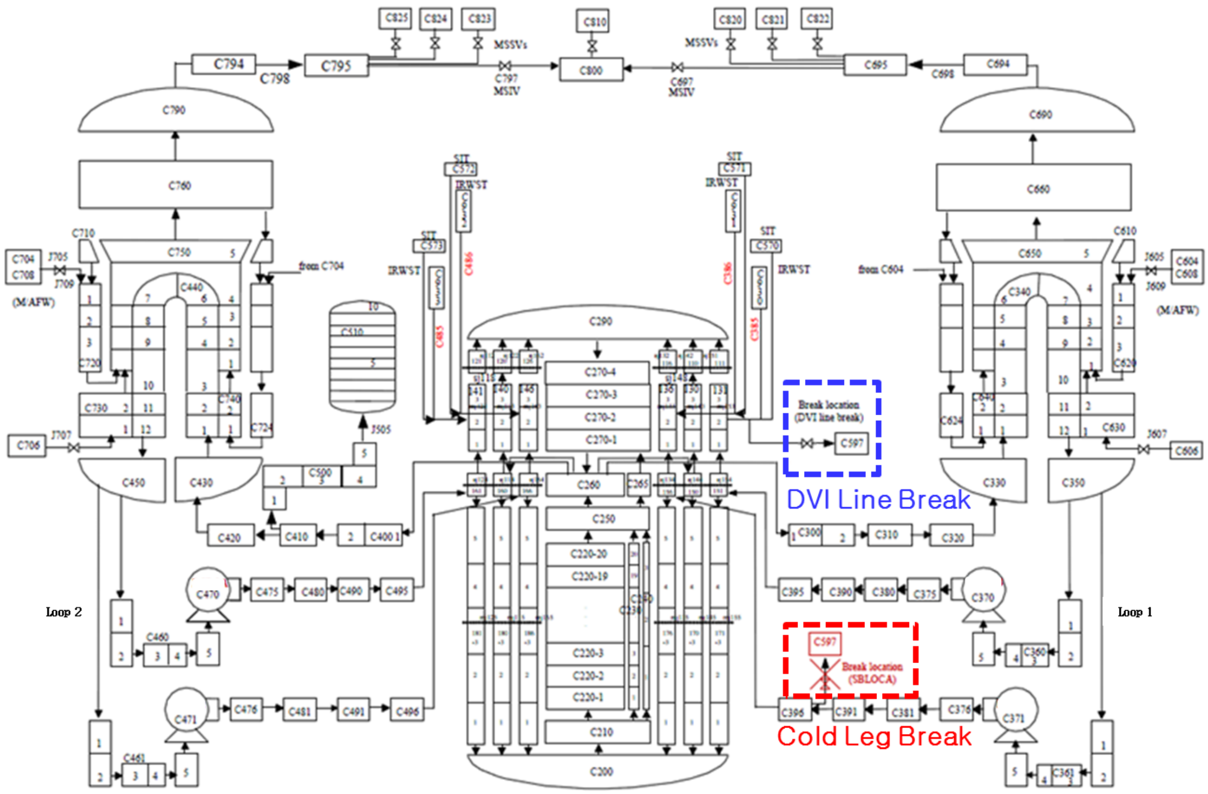


Figure 7 MARS-KS Nodalization for ATLAS DVI Line and CL SBLOCA Tests

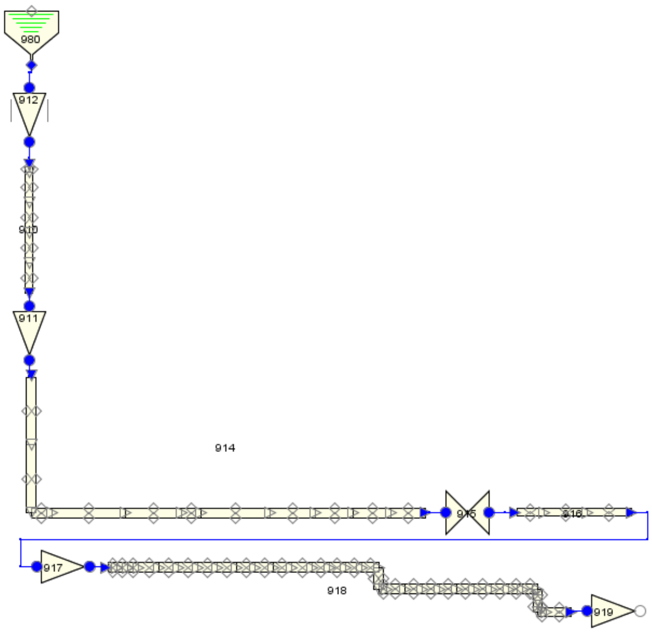


Figure 8 MARS-KS SIT Nodalization for ATLAS DVI Line and CL SBLOCA Tests

4.3 <u>RELAP5/MOD3.3 SBLOCA Input Model</u>

Since MARS-KS 1-D model was used in this study, identical nodalization and input model were used for the RELAP5/MO3.3 SBLOCA simulations. This ensures that the uncertainties due to differences in the nodalization and input of the two codes are eliminated for the comparison of the thermal hydraulic transient behaviors as well as the loop seal clearing phenomena during the DVI line and cold leg SBLOCA.

5 MARS-KS AND RELAP5/MOD3.3 PREDICTIONS

5.1 ATLAS 100% DVI Line SBLOCA

ATLAS 100% DVI line SBLOCA transient was initiated by opening the break valve at 199 seconds after the steady state run. As soon as the break valve opened, the primary pressure began to decrease due to the depletion of the primary coolant to the break and reached LPPT setpoint signal of 10.72 MPa at 219.7 seconds. The scram signal was generated 0.35 second later after the LPPT signal. The main steamline and feedwater were isolated after the LPPT signal with delays of 0.07 and 7.07 seconds, respectively. The core power kept constant for 4.0 seconds from the LPPT signal and started to follow the programmed 120% of the 1973 ANS decay heat curve at 223.7 seconds. At 247.28 seconds, the SIP was triggered after a delay of 28.28 seconds from the LPPT signal. Three SITs started to deliver the ECC water at 430.6 seconds when the downcomer upper node pressure reached 4.03 MPa. The test was finished at 2,000 seconds. The predictions of the sequence of the major events by the MARS-KS and RELAP5/MOD3.3 calculations were consistent with the ATLAS SB-DVI-08 test data as shown in Table 6 for the sequence of events of the ATLAS SB-DVI-08 test. However, predicted time of the MARS-KS and RELAP5/MOD3.3 codes for the loop seal clearing and the sequences were quite different from the test data as shown in Table 6. This loop seal clearing phenomena is further discussed in detail in Chapter 6 of this report.

5.1.1 Pressure

The transient behaviors of the primary pressures predicted by the MARS-KS and RELAP5/MOD3.3 calculations are compared with the test data as depicted in Figure 9. As soon as the break valve opens, the primary pressure decreases rapidly due to a sudden loss of primary coolant inventory to the break. Such rapid depressurization continues until the flashing of the coolant and boiling in the core were started. After the initial rapid depressurization, the primary pressure is maintained at a certain level of pressure plateau until the loop seal clearing occurred due to thermal equilibrium between the primary loop and secondary steam generator system. The plateau of the primary pressure lasts less than 100 seconds during the transient and both MARS-KS and RELAP5/MOD3.3 codes well predict the pressure behavior as shown in the Figure 9. As shown in Figure 10, MARS-KS and RELAP5.MOD3.3 predicted break flows are less than the experiment at the beginning of the transient, and thus the MARS-K and RELAP5/MOD3.3 slightly over predict the test primary pressure during initial period of the transient.

As the steam in the upper plenum and hot legs flows to the steam generator, the condensate of the steam generators flows back to the upper plenum and establishes the countercurrent reflux flow in the hot legs. As the secondary pressure exceeds the primary pressure, the heat transfer at the steam generator is reversed and the primary pressure remains at the pressure plateau until the loop seal clearing. As the water in the loop seal nodes blocks the steam venting through the loop seal, the steam builds up at the steam generators and thus the pressure, and then the core water level is depressed until the first loop seal clearing. After the loop seal clearing, the primary and secondary pressures decrease gradually and maintain at almost constant pressure as the break flow decreases and the safety injection flow increases.

Overall, it was concluded both MARS-KS and RELAP5/MOD3.3 calculations well predict the primary pressure behavior of the ATLAS SB-DVI-08 experiment.

5.1.2 Break Flow

Figure 10 compares the break flow of the experiment with the MARS-KS and RELAP5/MOD3.3 predictions. Since there is a substantial pressure difference between the reactor pressure vessel and the atmosphere, the critical flow condition was maintained during the transient. Henry-Fauske critical flow model was employed for the break flow in the MARS-KS and RELAP5/MOD3.3 analyses with a discharge coefficient of 0.77 after the sensitivity analyses. Initially, subcooled water discharges through the break followed by the two-phase flow and the steam. The break flow decreases significantly after the loop seal clearing due to the decrease in the primary pressure. However, both MARS-KS and RELAP5/MOD3.3 codes failed to predict the initial peak of the measured test break flow. Measured break flow of the test could be over-estimated due to abrupt pressure increase in the break simulator system during initiation of the break as described in the test report (Ref. 11). Thus, it can be concluded that, overall, both MARS-KS and RELAP5/MOD3.3 codes reasonably predict the test break flow. This conclusion is supported by the accumulated break flow as depicted in Figure 11 which shows good agreement between the experiment and the MARS-KS and RELAP5/MOD3.3 code calculations.

5.1.3 Safety Injection Flow

SI flows are presented in Figure 12 for the ATLAS test data and predicted SI flows from the MARS-KS and RELAP5/MOD3.3 codes. As shown from Figure 12, at the beginning of the transient, MARS-KS and RELAP5/MOD3.3 predict a little higher SI flow than the test SI flow. During the SIT injection under high flow condition, both MARS-KS and RELAP5/MOD3.3 predict similar flow but a little higher flow than the test data. However, overall, the predictions by the MAR-KS and RELAP5/MOD3.3 codes show reasonable agreement with the experimental data.

Table 6 Comparison of Sequence of Events for ATLAS DVI Line SBLOCA SB-DVI-08 Test

Event	100% 8.5"(0.59") DVI Break		
	SBLOCA Test	MARS-KS V1.2	RELAP5/MOD3.3
Break	199	199.1	199.1
LPPT Signal	219	219.8	218.9
Rx Trip	LPPT + 0.35 sec		
Turbine Isolation	LPPT + 0.07 sec		
FW Isolation	LPPT + 7.07 sec		
Decay Heat Starts	223.7	223.8	223.0
	LPPT + 4.0 sec		
SIP Starts	247.28	248.0	247.2
	LPPT + 28.28		
Loop Seal Clearing	293	392	406
SIT Starts	431	429.6	415.8

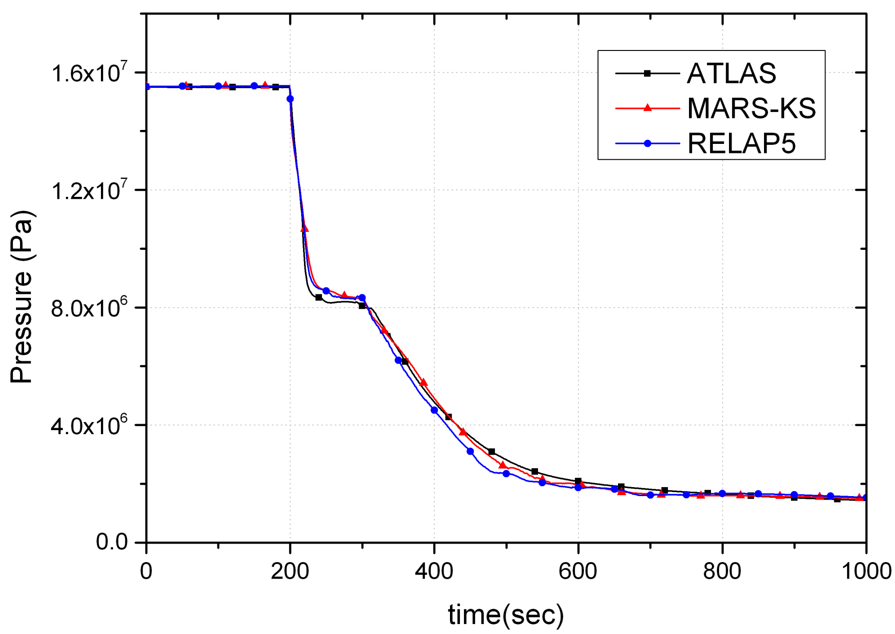


Figure 9 Primary Pressure of ATLAS DVI Line SBLOCA

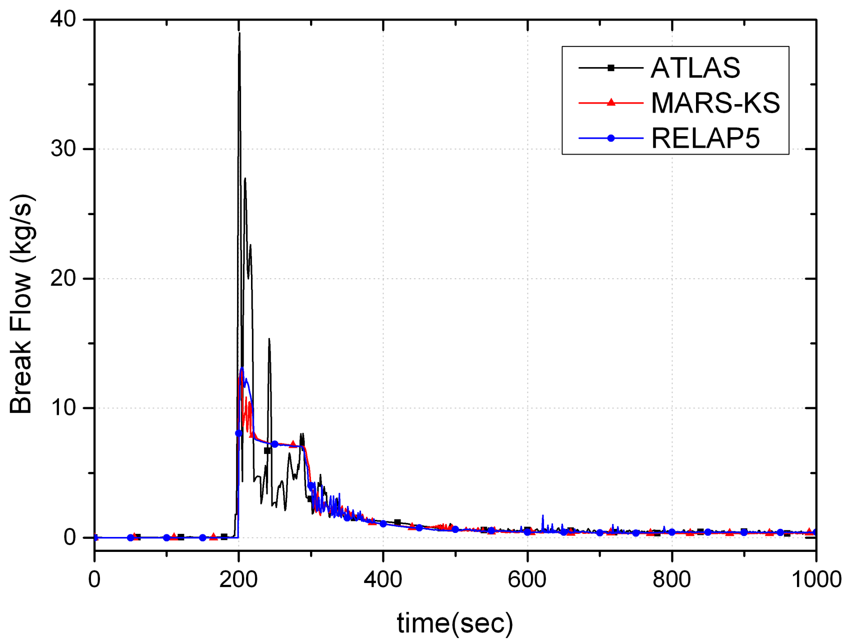


Figure 10 Break Flow Rate of ATLAS DVI Line SBLOCA

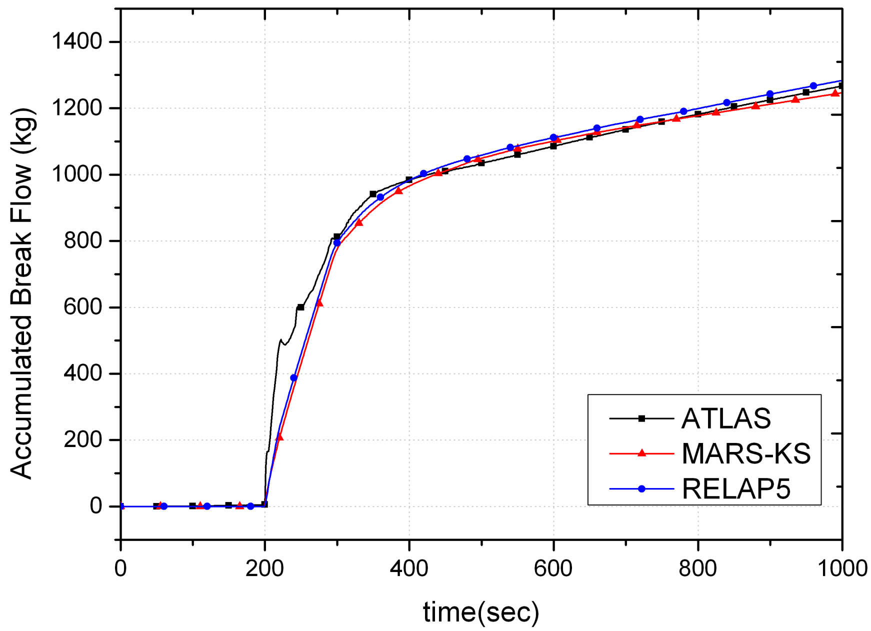


Figure 11 Accumulated Break Flow of ATLAS DVI Line SBLOCA

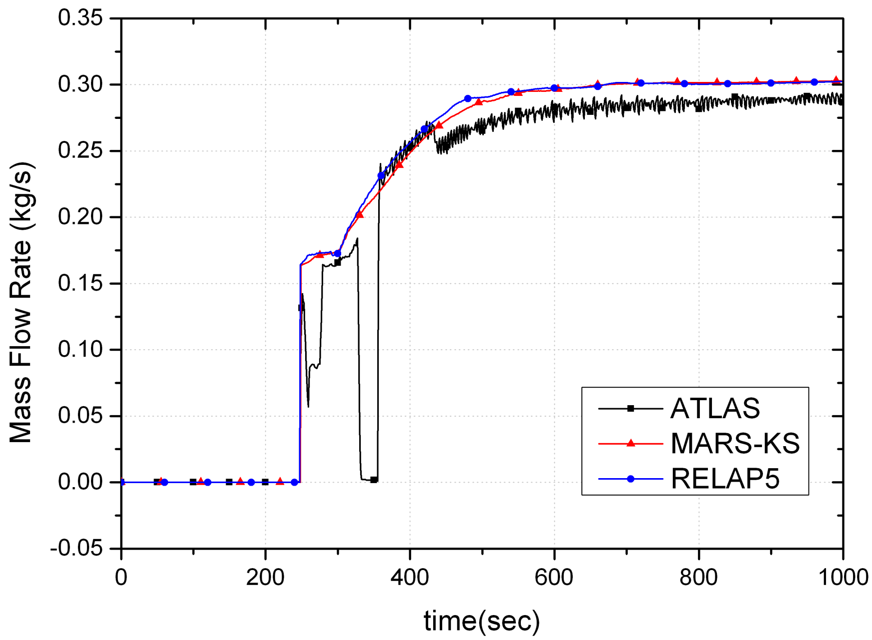


Figure 12 SIP Flow Rate of ATLAS DVI Line SBLOCA

5.1.4 Collapsed Core Water Level

The variation of the measured collapsed core water level of the test data is presented in Figure 13 together with the predicted collapsed core water level of the MARS-KS and RELAP5/MOD3.3 codes. At the beginning of the transient, the collapsed core water level decreases due to the loss of coolant inventory through the break. In the experiment, the collapsed water level decreases continuously before the loop seal clearing and consequently the active core water level is highly depressed. Then the core water level starts increasing as soon as the loop seal is cleared at 293 seconds after the transient. In the MARS-KS and RELAP5/MOD3.3 predictions, the collapsed core water level decrease at the beginning of the transient as was the experiment. However, at around 250 seconds, the collapsed core water level stops decreasing and maintains at a certain level for a while and then decreases rapidly. This delayed decrease of the core water level seems due to the primary pressure plateau during the CCF in the hot legs through the reflux condensation in the SGs. For the time between 250 and 330 seconds when the core water level is maintained at a certain level, relatively high reverse mass flow from the SG to the RPV can be observed at both hot legs. Such countercurrent reflux flow is established by the condensate flow from the SG to the upper plenum and steam form the upper plenum to the SGs through the hot legs during the period of the primary pressure plateau. The collapsed core water level increases a little when the loop seal is cleared and then starts decreasing again until the safety injections from the SITs begin. Larger break flow than the SIP ECC flow causes such a continuous water level decrease. The core water level then begins to increase when the ECC flow is increased by the SI from the SITs. This delayed decrease of the collapsed core water level results in a later and higher maximum PCTs of the MARS-KS and RELAP5/MOD3.3 predictions than the experiment.

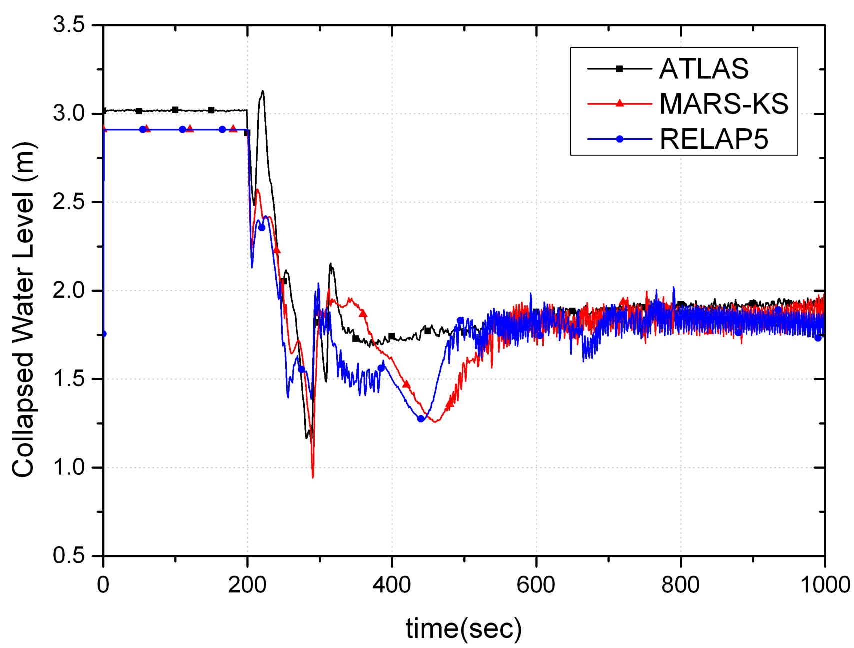


Figure 13 Collapsed Core Water Level of ATLAS DVI Line SBLOCA

5.1.5 Peak Cladding Temperature

Figure 14 shows the measured PCT from the experiment and the PCTs predicted by the MARS-KS and RELAP5/MOD3.3 codes. In the experiment, the PCT initially decreases slightly during the pressure plateau and then begins to rapidly increase due to the depressed collapsed core water level until the loop seal is cleared. PCT of 632 K can be observed during the experiment at around 290 seconds when the loop seal is just cleared. Due to the rise of the core water level by the decreased core pressure after the loop seal clearing, the PCT decreases after the loop seal clearing. Implementation of the CCFL model for the fuel alignment plate allows the MARS-KS code to predict the PCT at loop seal clearing as similar to the experiment. However, MARS-KS code predicts higher PCT than the experiment and the PCT is predicted much later than the experiment. MARS-K predicts PCT of 730 K at around 489 seconds after the transient which corresponds to the loop seal clearing at about 200 seconds later than the experiment. It is because of the differences in the MARS-KS prediction of later loop seal clearing including partial loop seal clearing of the loop A1 and thus later and lower core water level during the initial period of the transient. Figure 14 also shows that the PCT prediction of the RELAP5/MOD3.3 code is quite different from the PCTS of the experiment as well as the MARS-KS prediction. Collapsed core water level predicted by the RELAP5/MOD3.3 code is slightly lower than the collapsed core water level of the experiment and MATS-KS during the primary pressure plateau and before loop seal clearing as shown in Figure 13. As shown in Figure 14, this behavior of the lower collapsed core water level results in the transient PCT behavior, which is earlier and higher PCT compared to the PCT predicted by the MARS-KS. However, the PCTs are well below the acceptance criteria of the SBLOCA.

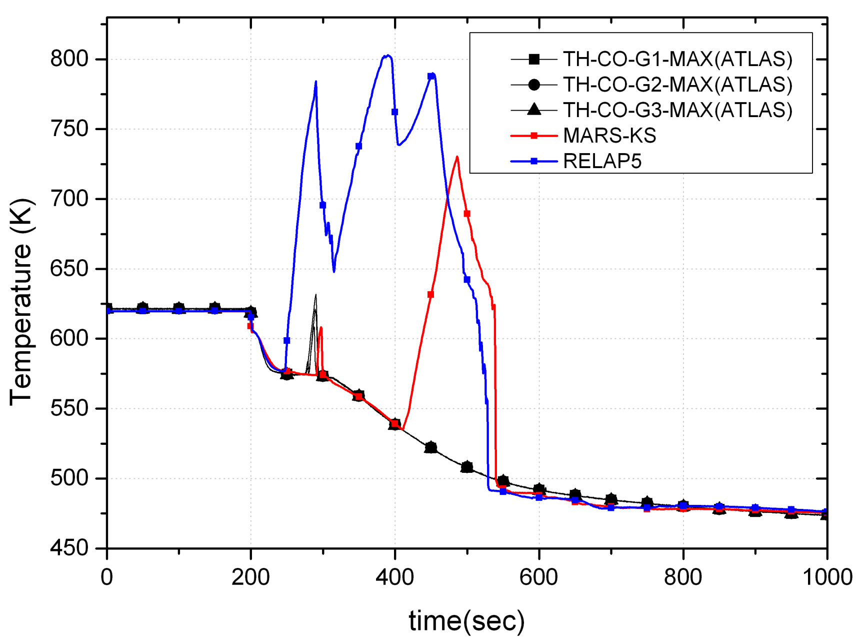


Figure 14 Peak Cladding Temperature of ATLAS DVI Line SBLOCA

5.2 ATLAS 6" Cold Leg SBLOCA

ATLAS 6” cold leg SBLOCA test was initiated by opening the break valve at 204 seconds. As soon as the break valve opened, the primary pressure began to decrease and reached the setpoint of LPPT, 10.72 MPa, at 228 seconds. The scram signal was generated 0.354 second after the LPPT signal. The main steam and feedwater lines were isolated after the LPPT signal with delays of 0.07 second and 7.08 seconds, respectively. The core power kept constant for 31.7 seconds after the initiation of the transient and started to follow the programmed conservative decay heat curve at 259.7 seconds. At 256 seconds, the SIP was triggered after a delay of 28.28 seconds from the LPPT signal. MARS-KS and RELAP5/MOD3.3 predicted the loop seal clearing 250 and 2466 seconds later than the experiment of 399 seconds. Four SITs started to deliver the Emergency Core Cooling (ECC) water at 649 seconds when the downcomer pressure reached 4.03 MPa. Both MARS-KS and RELAP5MOD3.3 predicted 1.7 and 34.2 seconds earlier SIT SI that the experiment of 649 seconds. The calculation was finished at 1,000 seconds. The predictions of the chronology of the major events by the MARS-KS and RELAP5/MOD3.3 codes were summarized in Table 7.

Table 7 Comparison of Sequence of Events for ATLAS Cold Leg SBLOCA SB-CL-09 Test

Event	6” Cold Leg Break		
	SBLOCA Test	MARS-KS V1.2	RELAP5/MOD3.3
Break	204	204.1	204.1
LPPT Signal	228	232.1	231.5
Rx Trip	LPPT + 0.354 sec		
Turbine Isolation	LPPT + 0.07 sec		
FW Isolation	LPPT + 7.08 sec		
SIP Starts	256	260.4	259.9
	LPPT + 28.28		
Decay Heat Starts	259.7	263.8	263.2
	Break + 31.7 sec		
Loop Seal Clearing	399	649	645
SIT Starts	649	647.3	614.8

5.2.1 Pressure

The behavior of the primary pressures of the ATLAS cold leg SBLOCA experiment as well as the MARS-KS and RELAP5/MOD3.3 predictions is shown in Figure 15. As soon as the break valve opens, the primary pressure decreases rapidly due to the sudden loss of coolant inventory to the break. Such a rapid depressurization continues until the flashing of the coolant during the depressurization. Both MARS-KS and RELAP5/MOD3.3 predict higher pressure during this initial depressurization due to the calculated lower break flows than the experiment. After the depressurization of the primary pressure, a pressure plateau of the primary pressure is established until the loop seal clearing. After the primary pressure plateau, the break flow of the experiment still remains higher than the MARS-KS and RELAP5/MOD3.3 predictions of the break flows and thus results in lower pressure. The primary pressures predicted by the MARS-KS and RELAP5/MOD3.3 codes then switch to lower pressures due to higher break flow and injection of the SITs earlier than the experiment. As soon as the loop seal clears, the primary pressure decreases gradually. Overall, it can be concluded that the MARS-KS and RELAP5/MOD3.3 codes well predict the primary pressure behavior of the ATLAS experiment.

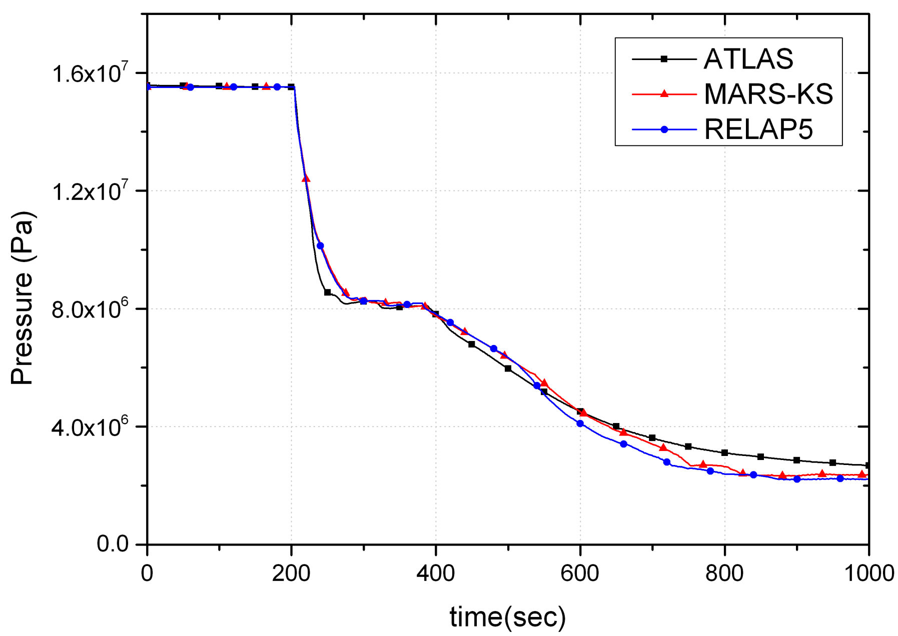


Figure 15 Primary Pressure of ATLAS Cold Leg SBLOCA

5.2.2 Break flow

Figure 16 compares the break flow of the experiment with the MARS-KS and RELAP5/MOD3.3 predictions of the break flow. As shown in Figure 16, large fluctuations of the break flow is observed in the ATLAS experiment from the beginning of the transient until the loop seal clearing. The measured break flow in Figure 16 was estimated using hybrid method and it was noticed in the references 11 and 12 that the hybrid method results in a poor prediction during the blowdown phase of the transient and better prediction during the later phase. Assuming that the measured break flow of the experiment during the later phase of the transient is correct, the MARS-KS and RELAP5/MOD3.3 codes reasonably predict the measured break flow during the later phase of the transient. Even though, the RELAP5/MOD3.3 predicts slightly higher break flow than the MARS-KS and the measured break flow as shown in Figure 17 for the accumulated break flow. In this study, Henry-Fauske critical flow model were employed both for the MARS-KS and RELAP5/MOD3.3 codes with adjusted discharge coefficient of 0.93 after the sensitivity analyses.

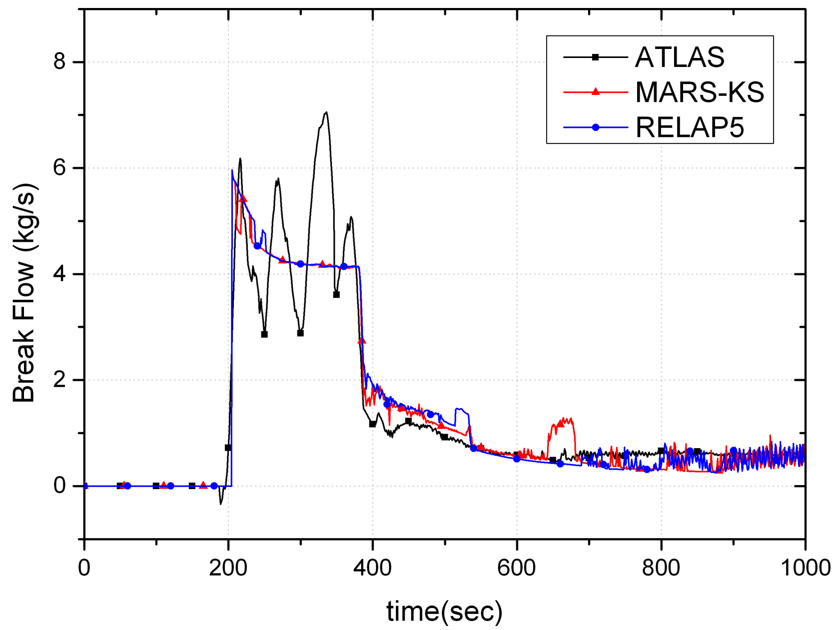


Figure 16 Break Flow Rate of ATLAS LAS Cold Leg SBLOCA

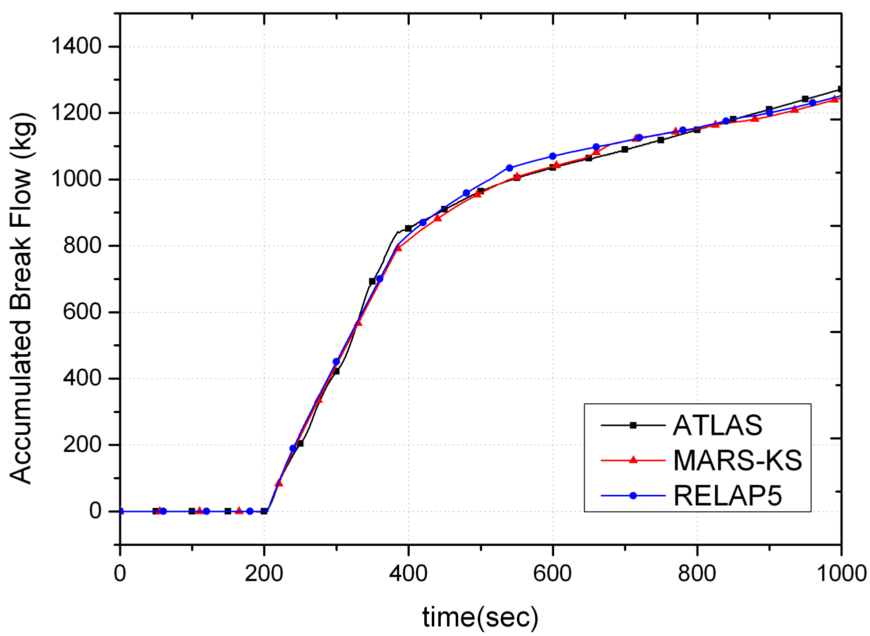


Figure 17 Accumulated Break Flow of ATLAS LAS Cold Leg SBLOCA

5.2.3 Safety Injection Flow

SI is presented in Figure 18 for the ATLAS test data and predicted SI flows from the MARS-KS and RELAP5/MOD3.3 codes. Figure 18 shows that the ECC SI flow from the SIP was well predicted by both MARS-KS and RELAP5/MOD3.3 codes. However, SIP SI flows show different behavior at around 550 seconds especially when SIP SI flows from the SIP-3 opposite of the break. This is because of the difference in the SIP operation. After the primary pressure plateau, the primary pressures predicted by the MARS-KS and RELAP5/MOD3.3 codes are lower than the measured pressure and thus resulting in higher SIP SI flows than the experiment as shown in Figure 18. This lower primary pressures predicted by the MARS-KS and RELAP5/MOD3.3 codes during later phase of the transient then also cause earlier and higher SIT SI flows.

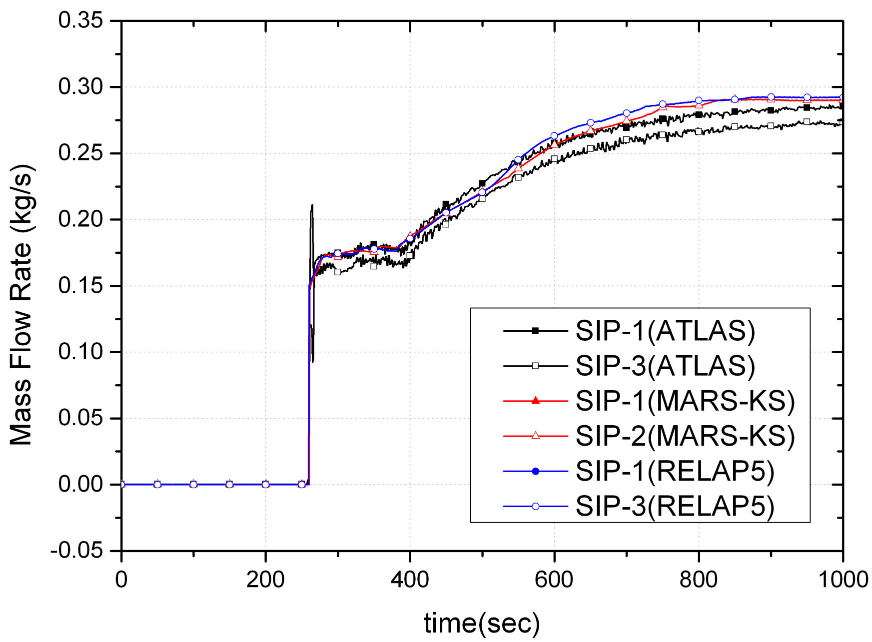


Figure 18 SIP Flow Rate of ATLAS LAS Cold Leg SBLOCA

5.2.4 Collapsed Core Water Level

The transient behavior of the collapsed core water level during the cold leg SBLOCA is shown in Figure 19 for the ATLAS experiment and code predictions of the MARS-KS and RELAP5/MOD3.3 codes. At the beginning of the transient, the collapsed core water level decreases due to the loss of core inventory through the break. The collapsed core water level decreases continuously until the loop seal clearing due to the pressure build up at the upper plenum through the upstream of the loop seals SGs and hot legs. Consequently the collapsed core water level at the active core is depressed and may be uncovered and partially exposed to the steam. This phenomena cause the PCTs in the experiment as well as the MARS-KA and RELAP5/MOD3.3 code predictions of the PCTs. Then, the collapsed core water level starts increasing as soon as the loop seal is cleared.

As shown in Figure 19, after initial decrease of the collapsed water level, the collapsed core water level is increased compared to the code predictions probably due to flashing in the liquid and less break flow due to lower pressure. The lower and depressed collapsed core water level of the RELAP5/MOD3.3 between 520 and 700 seconds seems due to higher break flow than the experiment and MARS-KS calculated break flows. Predicted collapsed core water level of the RELAP5/MOD3.3 is then increasing after the SIT safety injection to the core. In general, MARS-KS better predicts the collapsed core water level of the ATLAS experiment than the RELAP5/MOD.3.3. It is also shown in Figure 19 that, due to a large SIT SI flow, the collapsed core water level increases more rapidly than that of the experiment.

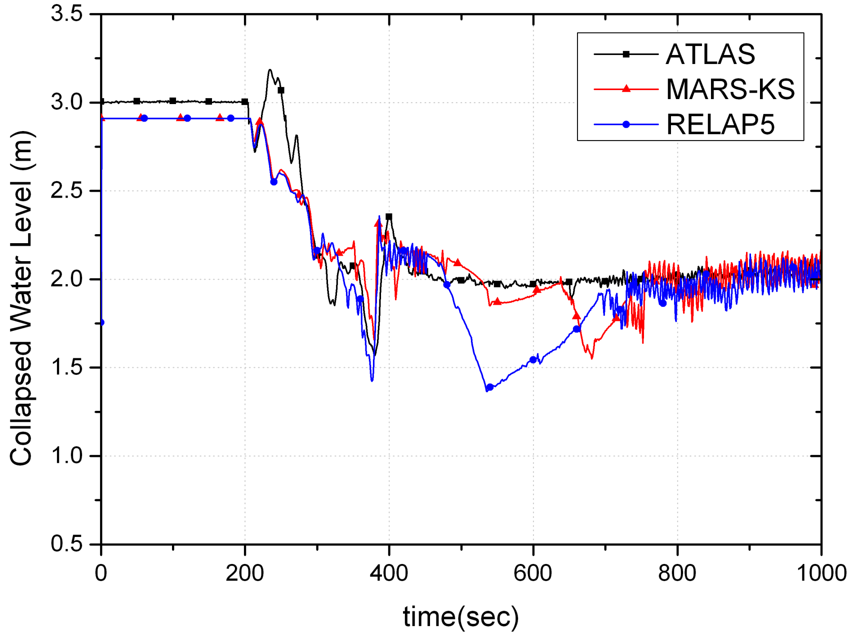


Figure 19 Collapsed Core Water Level of ATLAS LAS Cold Leg SBLOCA

5.2.5 Peak Cladding Temperature

Figure 20 shows the measured PCT from the ATLAS experiment and the PCTs predicted from the MARS-KS and RELAP5/MOD3.3 codes. The PCTs predicted by the MARS-KS and RELAP5/MOD3.3 codes are increased at around 348 seconds, whereas the PCT measured from the ATLAS experiment is not increased. It is due to the CCFL model employed at the FAP for the MARS-KS and RELAP5/MOD3.3 codes. The CCFL model was applied to the FAP in the analyses and thus, the water downflow to the core from the upper plenum was disturbed and limited by the upward steam flow from the core exit to the upper plenum. This results in a higher void fraction at the top of the core than the upper plenum and thus indicates that the active upper core was uncovered, so that the PCT increased for a while. The PCT stops increasing because of the core level increase by the loop seal clearing. Comparing with the measured PCT, MARS-KS and REALP5/MOD3.3 results reveal that the increased void fraction and thus the pressure build up at the top of the core and thus in the upper plenum may help the loop seal clearing during the transient. Figure 20 also shows the second and higher PCT of the RELAP5/MOD3.3 prediction due to the compressed collapsed core water level as shown in Figure 19.

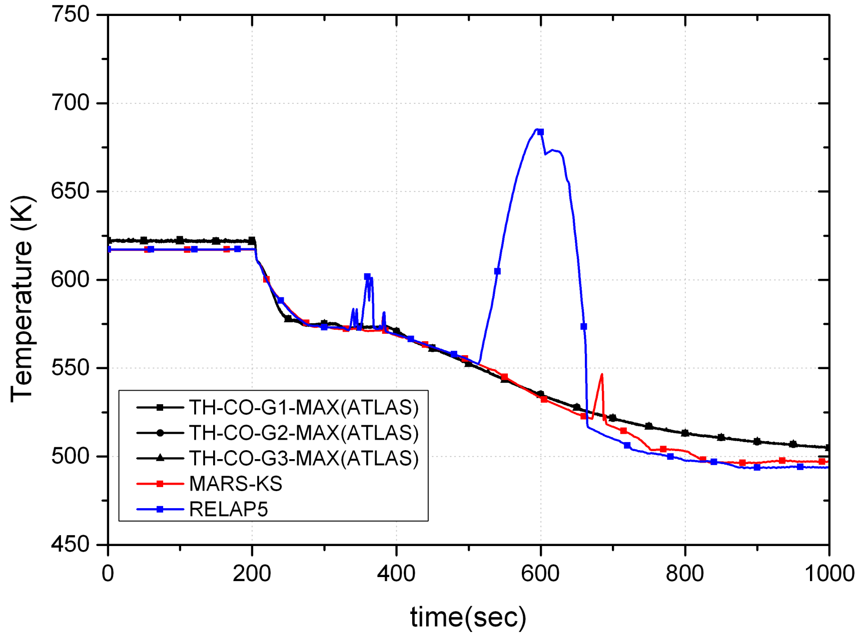


Figure 20 Peak Cladding Temperature of ATLAS LAS Cold Leg SBLOCA

5.3 Discussions

In the framework of the first ATLAS DSP exercise program, 100 % DVI line and 6” cold leg SBLOCA ATLAS experiments have been analyzed using MARS-KS and RELAP5/MOD3.3 codes. MARS-K and RELAP5/MOD3.3 code predictions were compared with the corresponding ATLAS experimental data. MARS-KS and RELAP5/MOD3.3 codes were employed for the transient thermal hydraulic analyses using test initial and boundary conditions as well as the assumptions used in the experiments. Overall, MARS-KS and RELAP5/MOD3.3 code predictions show that both codes can predict the sequence of events and major thermal hydraulic phenomena of the ATLAS experiments with reasonable agreement. However, compared to the experiment, the MARS-KS and RELAP5/MOD3.3 predictions show some discrepancies in predicting the collapsed core water level and loop seal clearing, and consequently large differences in the PCT predictions due to CCFL model at the FAP. Further analyses for the impact of the loop seal clearing phenomena on the PCT are required during SBLOCA. However, safety limit acceptance criteria of the PCT for the SBLOCA are satisfied during the SBLOCA transients.

6 LOOP SEAL CLEARING PHENOMENA

6.1 Loop Seal Clearing Phenomena during Postulated SBLOCA

Loop seal clearing is an important phenomenon of the SBLOCA and its timing significantly influences the core water and mixture level and thus the PCT. The water in the vertical loop seal nodes are trapped at the lowest pump suction volume and the steam in the steam generators cannot vent through the cold leg, rather it depresses the core water and mixture level due to pressure build up in the steam generators. Therefore, the loop seal clearing is important for the core mixture level and thus the core uncovery or core recovery, which is one of the design requirements of advanced nuclear reactors. It is known that the sequence of the loop seal clearing depends on the location of the break and the geometry of the cold legs. Thus, the loop seal formation, clearing, and reformation phenomena during the SBLOCA have been investigated through various experiments and analyses for the core heat-up during SBLOCA (Ref. 2). Randomness of the loop seal clearing and its sequences is suggested (Ref. 3) for the cold leg SBLOCA during the USNRC safety review of the SBLOCA. Randomness of the loop seal clearing sequences has been the US Nuclear Regulatory Commission (USNRC) regulatory position on the loop seal clearing during the SBLOCA.

In this study, loop seal clearing phenomena are further discussed with respect to the MARS-KS and RELAP5/MOD3.3 predictions of the ATLAS 100% DVI line SBLOCA and cold leg SBLOCA experiments in the framework of the ATLAS DSP.

Figure 4 shows the ATLAS geometric arrangement of the cold legs and DVI lines including the DVI line and cold leg breaks. As shown in Figure 4, since the breaks occurred at DVI line 1B and at the cold leg 1A, cold legs 1B, 2A, 1A and 2B are the closest cold legs from the DVI line break, and 2B, 1B, 2A are the closest cold legs from the cold leg break. Figure 7 is the MARS-KS and RELAP5/MOD3.3 nodalization of the DVI line and cold leg SBLOCA analyses in this study, and show the loop seal nodalization.

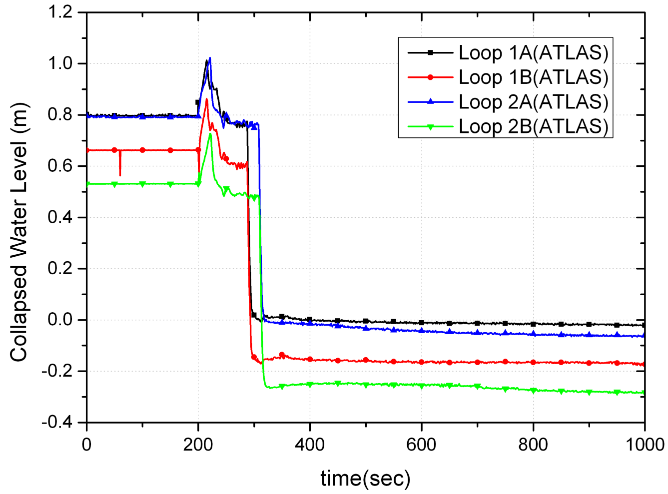
6.2 Loop Seal Clearing Phenomena during 100% DVI Line SBLOCA

Transient behavior of the collapsed core water levels in the vertical loop seals is presented in Figure 21 for the ATLAS experiment and predictions for the DVI line SBLOCA. In the DVI line SBLOCA experiment, the loop seals of loops 1A and 2A were cleared at around 280 seconds followed by the clearing for two other loop seals, 1B and 2B, occurred 10 seconds later as shown in Figure 21. For the MARS-KS calculation, three loop seals except for the cold leg 1A were cleared at about 392, 408 and 416 seconds in the sequence of 1B, 2A and 2B as shown in Figure 22 and Table 8. Even though, the MARS-KS prediction correctly predicts the first cleared loo seal 1B of the experiment. The collapsed core water level of the 1A loop seal decreased gradually but this loop seal was not completely cleared during the transient. This can be also seen from the void fraction of the loop seal nodes in Figure 22. Due to the incomplete and partial loop seal clearing, Loop 1A had less mass flow rate than other loops after the loop seal clearing as shown in Figure 22. This partial loop seal clearing of the loop 1A also contributes to the depression of the core water level. The RELAP5/MOD3.3 predicts, however, quite different loop seal clearing sequence from the experiment as well as the MARS-KS predictions as shown in Table 8 and Figure 21. RELAP5/MOD3.3 predicts the loop seal clearing sequence rather simultaneously in the sequence of 2B, 2A, 1B and 1A as shown in Table 8 and Figure 23 for the void fraction of the loop seal nodes.

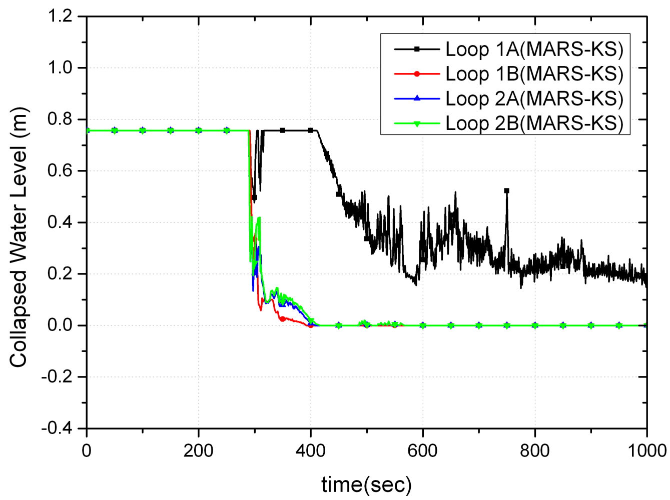
It should be noted that the sequences of the loop seal clearing from the MARS-KS and RELAP5/MOD3.3 predictions are different from that of the ATLAS experiment. Usually, the loop seal next to the break, 1B, clears first due to its less geometric resistance. Thus, the experiment showed reasonable loop seal clearing sequence, however, the MARS-KS could not correctly predict the timing of the first loop seal (1B) clearing as well as the sequence as shown in Table 8. RELAP5/MOD3.3 also failed to predict the first cleared loop seal and lop seal clearing as well as the sequence of the loop seal clearing. However, RELAP5/MOD3.3 predicts almost simultaneous lop seal clearing of the 4 loop seals at about 100 seconds later. These delayed loop seal clearing certainly impacted the primary pressure, lower and delayed collapsed core level. In order to calculate the core mixture level in the core and loop seal nodes, level tracking model of the MARS-KS and RELAP5/MOD3.3 codes was employed but it is found that the level tracking model needs improvement.

Table 8 Loop Seal Clearing Sequence of ATLAS DVI Line SBLOCA

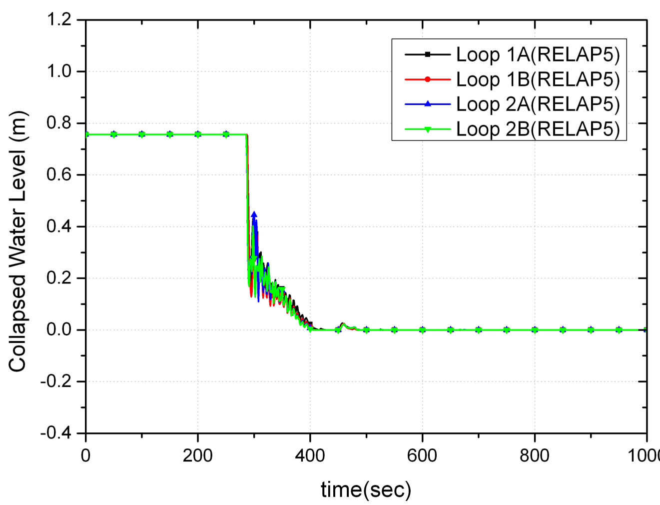
ATLAS 100% DVI line SBLOCA		
ATLAS Test	MARS-KS V1.2	RELAP5/MOD3.3
CL-1B/293	CL-1B/392	CL-2B/406
CL-1A/305	CL-2A/408	CL-2A/406
CL-2B/313	CL-2B/416	CL-1B/407
CL-2A/318	CL-1A	CL-1A/416
	CL-1A Not Cleared	
Geometrical Proximity of Loop Seal from the broken DVI Line : Cold Leg _1B, 2A, 1A, 2B		



a. **DVI Line SBLOCA SB-DVI-08 Test**



b. **MARS-KS**



c. **RELAP5**

Figure 21 Loop Seal Water Level of ATLAS DVI Line SBLOCA

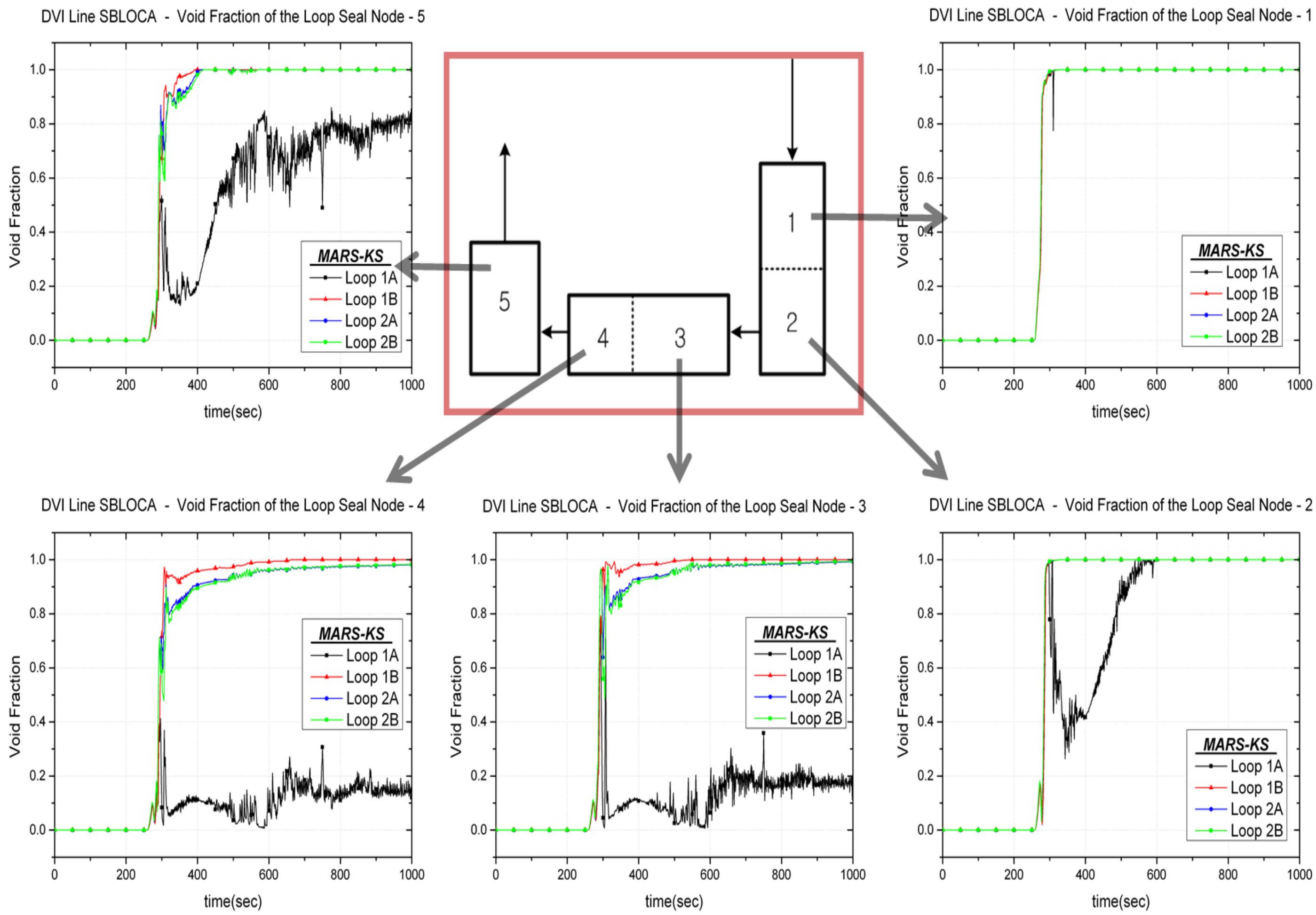


Figure 22 MARS-KS Loop Seal Node Void Fraction of ATLAS DVI Line SBLOCA

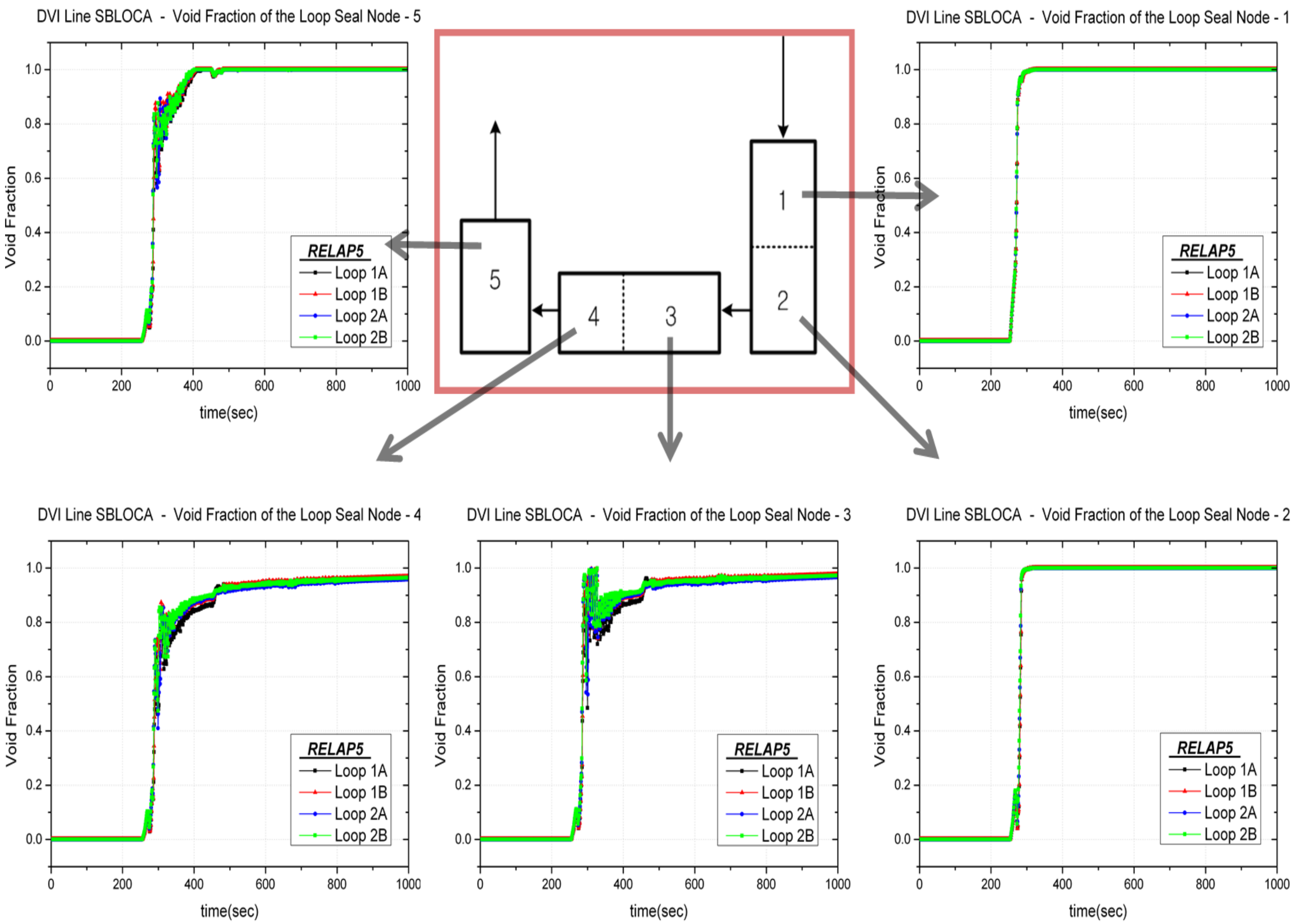


Figure 23 RELAP5 Loop Seal Node Void Fraction of ATLAS DVI Line SBLOCA

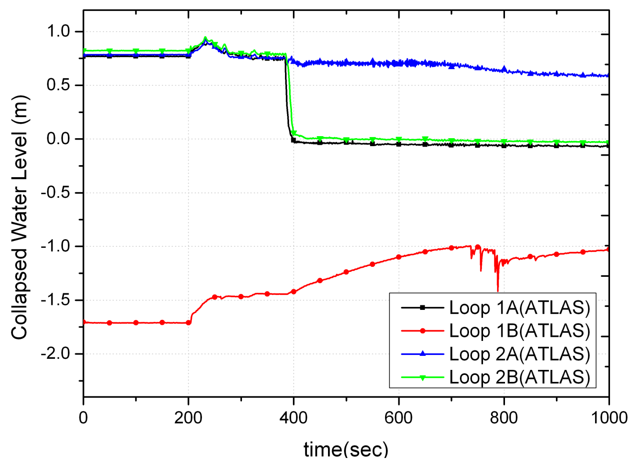
6.3 Loop Seal Clearing Phenomena during 6" Cold Leg SBLOCA

Transient behavior of the collapsed water level in the vertical loop seals of the ATLAS 6" cold leg SBLOCA experiment is presented in Figure 24. In the cold leg SBLOCA experiment, loop seals of loops 1A and 2B were cleared at 195 and 221 seconds after the transient. Loop seals of the cold legs 2A and 1B were not cleared and the collapsed water level data of the loop 1B seems erroneous measurement data as shown in Figure 24. The sequence of the loop seal clearing of the cold leg SBLOCA experiment is clearly shown in Figures 24 and 25. However, in the MARS-KS calculation, two loop seals 2A and 1A were cleared sequentially at 445 and 626 seconds in the transient as shown in Figure 24. The collapsed water level of the loop seals of loops1B and 2B decreased gradually but these loop seals were not completely cleared during the transient. This also can be clearly seen from the void fraction of the loop seal nodes in Figure 25. Figures 24 and 25 also show the collapsed core water level and void fraction of the lop seal nodes predicted by the RELAP5/MOD3.3 code. RELAP5/MOD3.3 predicts loop seal clearing of the loop seals 2A and 1A at 441 and 546 seconds in the transient. RELAP5/MOD3.3 also predicts that loop seals 1B and 2B were not cleared during the transients. Both MARS-KS and RELAP5/MOD3.3 codes failed to predict the first cleared loop seal, its clearing time and loop seal clearing sequences during the cold leg SBLOCA.

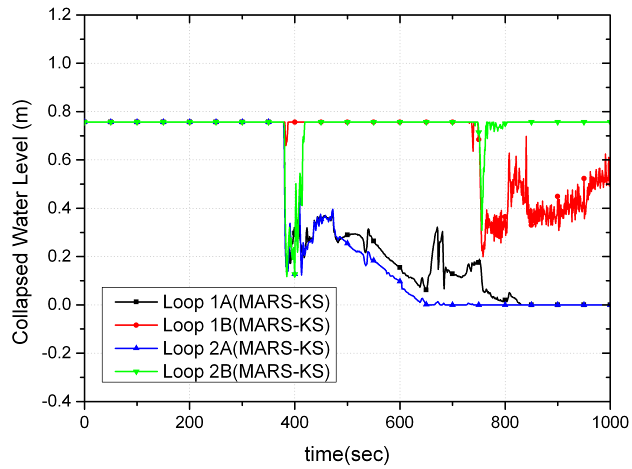
It should be noted that the sequences of the loop seal clearing predicted by the MARS-KS and RELAP5/MOD3.3 codes are different from that of the cold leg SBLOCA experiment. Usually, the loop seal next to the break clears first due to its less geometric resistance. Thus, the experiment showed reasonable loop seal clearing sequence, however, both MARS-KS and RELAP5/MOD3.3 codes could not correctly predict the timing of the first loop seal clearing as well as the sequence. Delayed loop seal clearing of the MARS-KS and RELAP5/MOD3.3 prediction certainly impacted the primary pressure, the core collapsed level and thus the PCT during SBLOCA.

Table 9 Loop Seal Clearing Sequence of ATLAS 6" Cold Leg SBLOCA

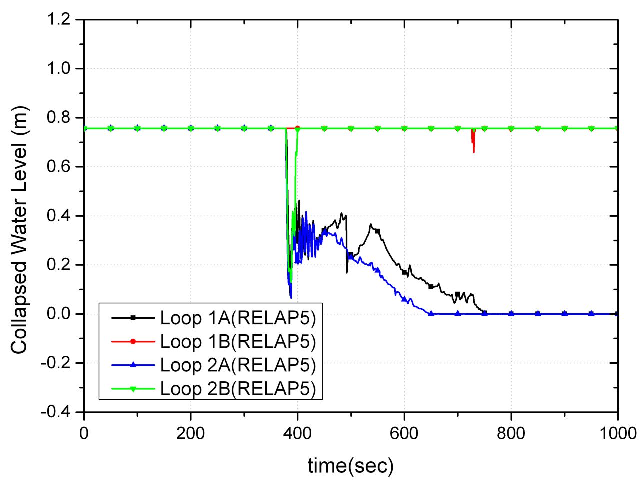
ATLAS 6" Cold Leg SBLOCA		
ATLAS Test	MARS-KS V1.2	RELAP5/MOD3.3
CL-1A/399	CL-2A/649	CL-2A/645
CL-2B/425	CL-1A/830	CL-1A/750
CL-2A	CL-1B	CL-1B
CL-1B	CL-2B	CL-2B
CL-2A : Not cleared CL-1B : error	CL-1B, CL-2B Not cleared	CL-1B, CL-2B Not cleared
Geometrical Proximity of Loop Seal from the Broken Cold Leg: Cold Leg _1A, 2B, 1 B, 2A		



a. DVI Line SBLOCA SB-DVI-08 Test



b. MARS-KS



c. RELAP5

Figure 24 Loop Seal Water Level of ATLAS Cold Leg SBLOCA

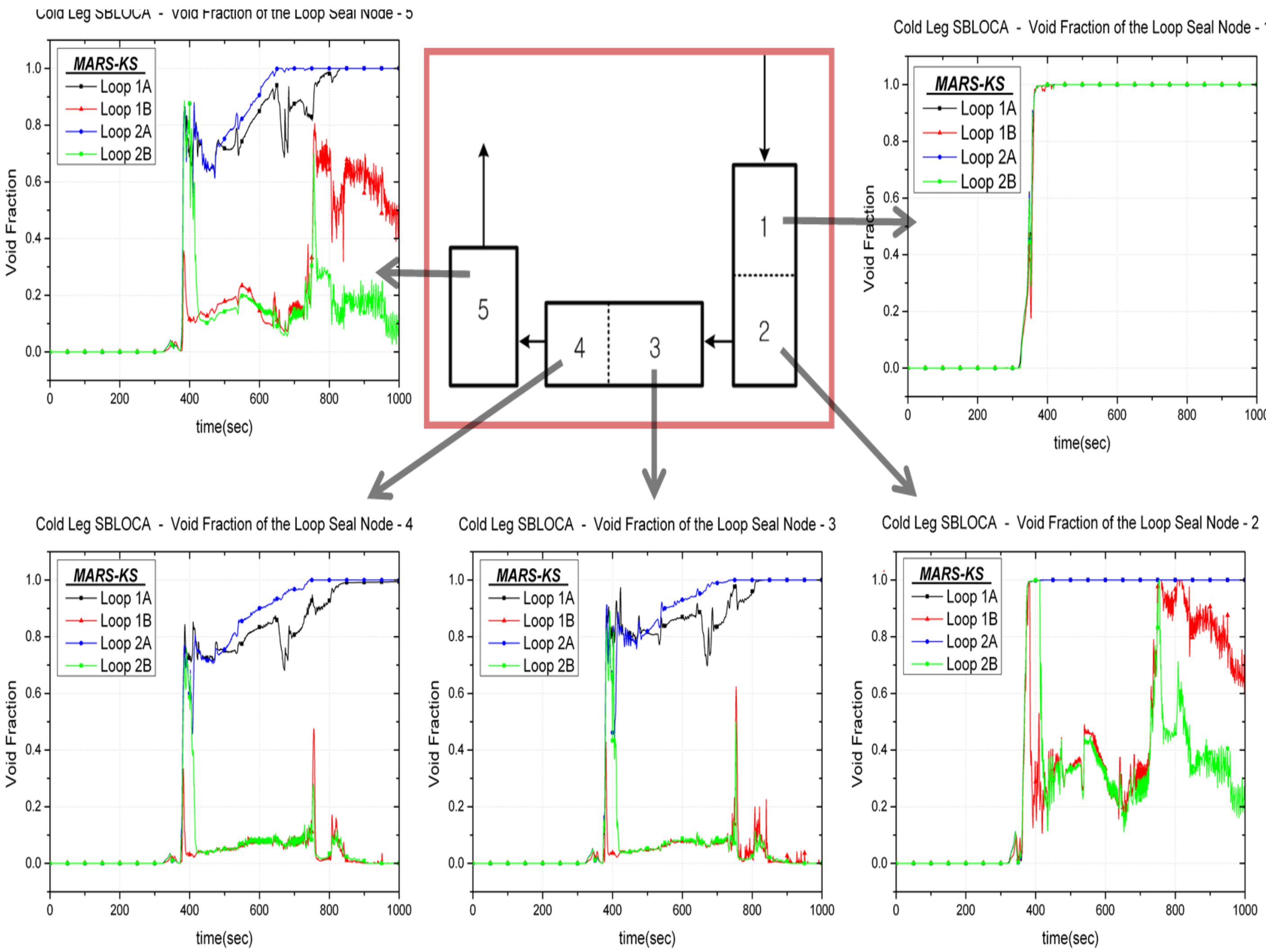


Figure 25 MARS-KS Loop Seal Node Void Fraction of ATLAS Cold Leg SBLOCA

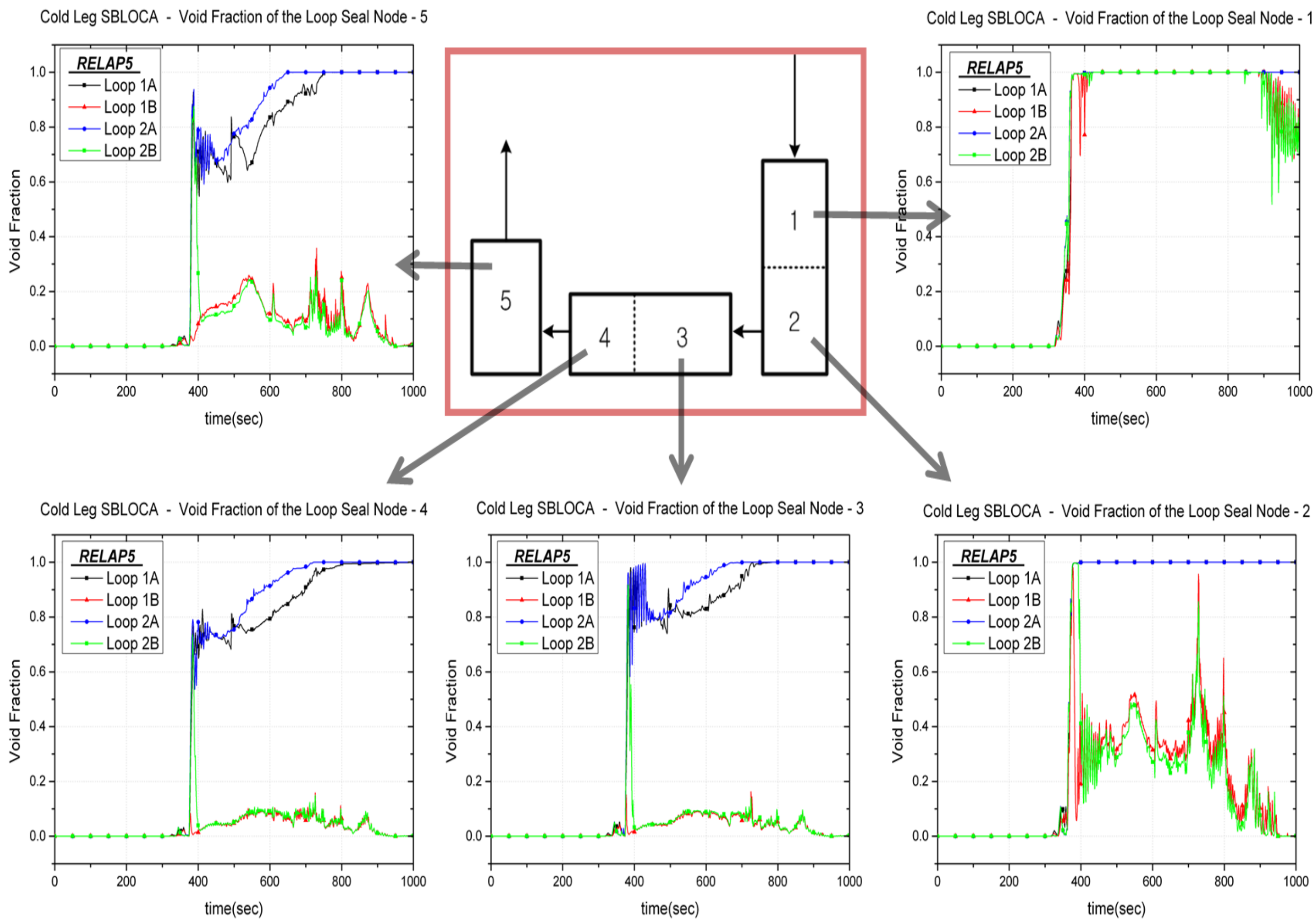


Figure 26 RELAP5 Loop Seal Node Void Fraction of ATLAS Cold Leg SBLOCA

7 RUN STATISTICS

The calculations in this study were performed using Intel® Core™ i5 750 @ 2.676 GHz processor. The operating system is Microsoft Windows 7 Professional.

Table 10 shows the run statistics for the MARS-KS Version 1.2 and RELAP5/MOD3.3 Patch 4 code calculations. It can be seen that MARS-KS code runs slightly faster in calculating the ATLAS SBLOCA tests than the RELAP5/MOD3.3 code

Table 10 Run Statistics

Code	Code Environment	Transient Time (s)	CPU Time (s)	CPU/Transient Time	Number of Time Steps
MARS-KS Version 1.2	Intel i5 MS	399.9	727.68	1.82	120448
RELAP5/MOD3.3 Patch 4		400.01	55.15	0.14	34123

8 CONCLUSIONS

In the framework of the ATLAS DSP exercise program, ATLAS 100% DVI line and 6" cold leg SBLOCA tests were analyzed using the best estimate MRS-KS and RELAP5/MOD3.3 codes and compared the results with the ATLAS experimental data. Especially, loop seal clearing phenomena and its impacts on the collapsed core water level as well as on the PCT were investigated in this study.

MAR-KS Version 1.2 and RELAP5/MOD3.3 Patch 4 codes were used to predict the ATLAS DVI line and cold leg SBLOCA experiments and compared the results with the experiments. Both MARS-KS and RELAP5/MOD3.3 codes well predict major thermal hydraulic parameters and chronology during the transients with a reasonable agreement. However, both MARS-KS and RELAP5/MOD3.3 codes have deficiencies in predicting loop seal clearing phenomena and thus the collapsed core water level, and the PCT compared to the ATLAS experiments performed for this study.

The randomness in predicting loop seal clearing sequence during the SBLOCA using the state-of–the-art best estimate system codes is also observed during this study. Therefore, the implication of this random loop seal clearing sequence during SBLOCA and its impact on the safety should be further evaluated for the safety of the commercial nuclear power plants.

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K. Tien, NRC Project Manager

11. ABSTRACT (200 words or less)

In the framework of the ATLAS Domestic Standard Problem (DSP), the loop seal clearing phenomena of the ATLAS Direct Vessel Injection (DVI) line and cold leg Small Break Loss of Coolant Accident (SBLOCA) tests were investigated. MARS-KS and RELAP5/MOD3.3 codes were used to predict the transient thermal hydraulic behavior of the DVI line and cold leg SBLOCA and compared with the ATLAS test data. MARS-KS and RELAP5/MOD3.3 calculations show that both codes predict the sequence of events and major thermal hydraulic behaviors of the tests with reasonable agreement. However, both codes calculate some discrepancies in predicting core collapsed water level, loop seal clearing and thus show large differences in the maximum PCT. Further R&D is required specifically to investigate the loop seal clearing phenomena and its effects on the safety during a postulated SBLOCA

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