Atlas' contribution to nuclear safety

The advanced thermal-hydraulic test loop for accident simulation, which started up in 2006, plays a key role for safety validation and improvement of light water reactors. Today, international research at the facility focuses on thermal-hydraulics safety issues highlighted by the Fukushima Daiichi accident. By Ki-Yong Choi, Chul-Hwa Song, and Won-Pil Baek

The "advanced thermal-hydraulic test loop for accident simulation" (Atlas) is a large integral-effect test facility, with the APR1400 (Advanced Power Reactor, 1400MWe) – in active use in Korea and overseas – as a reference plant. It was designed to simulate various transients and accident scenarios at full pressure and temperature conditions, including design-basis and beyond design-basis accidents, without the risk of radiation.

The Atlas programme dated back to 1997, when there was no consensus on whether to build a large thermal-hydraulic integral effect test loop. There was also some debate about whether to choose PWRs or SMRs as a reference plant. Eventually, the APR1400 conventional advanced LWR was selected as a target plant for reasons of technical urgency and better universality over the small modular reactors. Some key design features of the operating LWRs in Korea were reflected in the design.

After going through a lengthy basic design phase, the Atlas programme started in earnest in 2002 with strong support from the Korean government's national nuclear R&D programme.

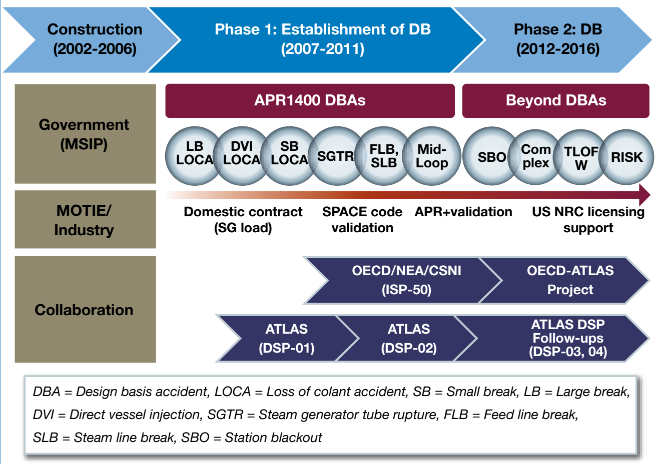
Most nuclear safety researches were switched to the beyond design basis accidents (BDBAs) after the Fukushima accident. Re-assessment of accident prevention features and improved of defence-in-depth are being revisited worldwide. In this respect, it is expected that Atlas would be used to gain better understanding of the actual phenomena and to provide the best guidelines for accident management.

Table 1. Comparison of major available integral-effect test facilities

Design	LSTF (Japan)	PKL (Germany)	Atlas (Korea)
Volume scale	1:48	1:145	1:288
Height scale	1:1	1:1	1:2
Loop configuration	2 (2 HL x 2 CL)	4 (4 HL x 4 CL)	2 (2 HL x 4 CL)
Max pressure (MPa)	17.95	4.5	18.7
Core power (MW)	10 (14%)	2.5 (10%)	2.15 (11%)
Axial profile	9-step chopped cosine	Flat	11-step chopped cosine
Radial profile	3-region	3-region	3-region
RPV diameter (mm)	640	360	408
DC gap (mm)	46 (fully annular)	26 (annular at upper; pipe at lower)	26.2 (fully annular)
No. of heater rods	1008	314	390
Heater rod diameter (mm)	9.5	10.75	9.5
No. of U tube (instrumented)	141 (6 at 9 axial levels)	28	176 (3 at 8 axial levels)
No. of U tube (elevations)	3	7	13
U tube diameter (mm)	19.6	19.6	12

HL = hot leg; CL = cold leg

Figure 1. R&D history of the Atlas programme



Atlas has made a significant contribution to LWR safety validation and upgrading since it started operating in 2006. More than 90 integral effect databases have been established for major design-basis accidents of the APR1400.

The main applications of Atlas are two-fold. First, more or less direct utilisation of the Integral Effect Test (IET) data for the development of advanced plants by plant optimisation, for verification of new safety concepts, and for resolution of safety issues. Performance tests can be conducted to provide realistic thermal-hydraulic insight for plant designers as well as safety analysts. The other application is validating safety analysis codes, using IET data, for accident scenarios. The Atlas IET data play a critical role in awarding new plants a licence from the regulator.

Atlas has been used continuously to aid in developing industrial technology since 2006 and it has been contracted to support development of the domestic nuclear industry. Atlas is recognised by the international community as a critical facility in understanding the thermal-hydraulics of an ALWR.

In form, Atlas adopted the well-known three-level scaling methodology, which consists of integral scaling, boundary flow scaling, and local phenomena scaling. There were a lot of debates about the height scaling, but 1/2 height was chosen because it has several advantages over a full-height facility. The free volume of the reactor coolant system was reduced by a factor of 1/288 and the diameter of the main flow piping was scaled down by a factor of 1/12. Atlas is the world's third-largest such facility. It also has different design features from other similar facilities: a unique loop configuration with one hot leg and two cold legs per steam generator; either direct vessel injection or cold leg injection can be simulated; multi-dimensional two-phase behaviour in the annular down-comer region can be realistically reproduced; it has been heavily instrumented and provides enough

Table 2. Summary of the Atlas domestic standard problem (DSP) programme

Name	Test item	Type	Period
DSP-01	100% DVI line break	Open	June 2008-Feb 2010
DSP-02	6" CL Break SBLOCA	Open	April 2010 - Sep 2011
DSP-03	MSLB at 8% power without LOOP	Open	Oct 2012 - March 2014
DSP-04	MBLOCA with long-term cooling	Double blind	Feb 2015 - Sep 2016

local information to validate system-scale safety analysis codes; 10% decay power (2.1MWe) can be simulated by 390 electrical heater rods, providing different radial power profiles and a chopped cosine axial power profile. The major design characteristics of Atlas are compared with other facilities in Table 1.

Contributions since commissioning

Atlas installation was completed in 2005 and extensive commissioning tests were carried out in 2006. The active first phase began in 2007 (see Figure 1). In the first phase, design basis accidents for APR1400 were the main target of the programme because the APR1400 was in the licensing process at the time.

First, more than 10 integral effect tests on the reflood phase of a large break LOCA were conducted to resolve a safety issue of the APR1400 raised by the regulator. Key test data were utilised by Korean industries to obtain licensing approval and the Korean industry used the Atlas data to develop and improve its own safety analysis methodology for a LBLOCA. The results are well summarised in the literature.

Afterwards, the Atlas programme switched to simulating APR1400 SBLOCAs where direct vessel injection (DVI) line break and cold leg break LOCAs were taken into account. Sensitivity tests for different DVI line break sizes were performed and an integral effect database was established for break sizes of 5%, 25%, 50%, and 100%. As for the cold break SBLOCAs, various sensitivity tests for different break sizes of the cold leg were conducted. In addition, parameter survey tests were also taken into account in a test matrix to investigate the effect of break location. A counterpart test to the 6-inch SBLOCA data of the Large Scale Test Facility (LSTF) in Japan was performed in order to evaluate the scaling of the Atlas facility.

Later in the first test phase steam generator tube rupture accidents were simulated. A single tube rupture and five tube rupture accidents were investigated and the effects of leakage from either the hot side or the cold side were also examined for sensitivity work. In addition, after the major integral effect tests on LOCA series accidents had been completed, typical non-LOCA events were conducted, including a feed line break and a steam line break. A loss of residual heat removal capability during the mid-loop operation phase was included in this phase of the test programme.

Another contribution of the Atlas facility was to carry out integral effect tests to validate the heat removal performance of a new passive design for the APR+ (the Passive Auxiliary Feedwater System). In the first phase of the APR+ programme, several separate effect tests were carried out with a stand-alone facility called PASCAL. In the following phase, a new passive heat removal loop was constructed and connected to Atlas. With the Atlas-PAFS facility, several integral effect tests such as feed line or steam line break and SGTR were conducted to characterise the passive natural circulation flow behaviour.

In the first phase from 2007 to 2011, Atlas worked with Korean nuclear industries to carry out technical development with more efficiency. One example is an engineering contract with Doosan Heavy Industry to help it to perform structural analysis by providing detailed thermal-hydraulic conditions inside the steam generator during fast transients. Intensive integral effect tests to investigate the blowdown load during the steam generator feedwater line break were conducted and the data was transferred to Doosan.

In 2006, a large national project aiming at developing an advanced thermal-hydraulic system analysis code, called SPACE (Safety and Performance Analysis CodE for NPPs) was launched. During its second test phase, which focused on code validation using separate effect tests, integral effect tests, and plant transient tests, Atlas played a key role in producing integral effect test data for the APR1400. Several Atlas database were used in the V&V matrix of the SPACE, including LBLOCA, SBLOCA, SGTR, FLB, and SLB.

Second phase programme

In the second phase, from 2012, the Atlas programme was directed towards the more severe high-risk multiple failure scenarios – beyond design basis. This was welcomed by the industry following the unprecedented nuclear disaster in Fukushima in 2011. First, station blackout accidents were investigated – reflecting public concerns about the safety margin of Korea's plants, along with some variants associated with the most conservative blackout scenarios. In addition, more complex accident cases were investigated, taking into account multiple failures.

Meanwhile, Korea Hydro & Nuclear Power required R&D to support its application to the US Nuclear Regulatory Commission for certification of the APR1400 design and a programme was launched in July 2011. A set of integral effect tests, focusing on the LBLOCA reflood phase, were conducted, reflecting a design change from two to four train electricals. It turned out that the four-train system had better safety performance.

National and international collaborations

Since 2008 Korea Atomic Energy Research Institute has co-ordinated a series of domestic programmes combining most nuclear organisations in Korea – the safety authority, research institutes, industries, and universities. Three programmes have been completed with up to 17 participants. They used open calculation, where Atlas data was open to the participants before calculation and the participants tried to predict the Atlas data. In most cases, the MARS-KS and RELAP5/MOD3.3 code were dominantly used. In one programme the new SPACE code was also used for validation. In the course of this programme, inexperienced code users interacted with experienced users and experience of using various codes were shared. Very useful

Table 3. Test matrix of the OECD-Atlas project

Topic	Number of tests	Remarks
A1-Prolonged SBO		
Asymmetric 2nd cooling	1	asymmetric FW supply and additional failure (ex. Stuck open of MSSV)
Asymmetric passive 2nd cooling	1	asymmetric passive FW supply (ex. PAFS)
A2-SBLOCA during SBO		
SBO+RCP seal failure	1	effect of leakage flow rate
SBO+SGTR	1	TISGTR
A3-TLOFW		
1ry and 2nd bleed + 1ry feed	1	with additional failures such as stuck open POSRV, ATWS and a SGTR
A4-MBLOCA		
PZR surge line break (10-inch)	1	safety injection through cold leg (DVI)
A5-Open items	2	counterpart test for addressing scaling issues
TOTAL	8	

outcomes included: identifying models or correlations which need improvement, confirming the importance of user effects, developing guidelines to predict a target scenario and establishing a network among the participants.

In 2015, the 4th DSP programme was launched. It is still under discussion but it has been agreed that it will be operated double blind: only the test specification will be open and the test will be performed at the end of the blind calculation.

Internationally, the 50% DVI line break database of Atlas was selected as the 50th International Standard Problem (ISP-50) sponsored by the OECD/NEA Committee on the Safety on Nuclear Installation Working Group on Analysis and Management of Accidents in 2009. The ISP-50 was performed in two consecutive phases: “blind” and “open”. A total of 17 calculations were collected from 13 participating organisations. Seven different kinds of system analysis codes were used (including RELAP5/MOD3, TRACE, MARS-KS, KORSAR, APROS, CATHARE, and ATHLET). Quantitative comparisons were performed using the Fast Fourier Transform Based Method (FFTBM) to compare the overall accuracy of the collected calculations. The blind phase revealed user effect, showing it is still one of the major issues around the system thermal-hydraulic code application. Open calculations showed better prediction accuracy than the blind calculations, in terms of average amplitude value from the Fourier transform.

Since ISP-50 recognised the value of Atlas in 2011 it has been used to improve LWR safety in a project dubbed OECD-Atlas. So far 15 countries and 19 organisations have signed up to the project, which started in April 2014 and will continue till March 2017. It will investigate beyond design basis accidents, or those that involve additional failures to identify the major thermal-hydraulic design issues. Furthermore, two counterpart tests against the previous IETs are planned in order to address the scaling issues.

A follow-up OECD-Atlas programme is planned.

Photograph of the ATLAS facility

Improvements and outlook

For the future, improvements are being made to enhance Atlas’s measurement capability by adopting multi-dimensional and high-precision instruments. The simulation capability is being expanded beyond the reactor coolant system. First, detailed local temperature measurement capability was improved: profile temperature sensors were installed at different axial locations in the hot and cold legs, which capture multi-dimensional thermal-hydraulic behaviour of the main loops such as thermal stratification, mixing, and countercurrent flow; fine thermocouple grids have been installed at the steam generator inlet and exit plena, which help investigate thermal mixing and flow reversal behaviour in the U-tubes and lower plena; a large condensation tank with a load cell has been added to the existing break flow measuring system, which will give more reliable measurement of the break flow; and the I&C system has been updated to manage to complex scenarios easily.

It is planned to install a gas chromatography system to measure non-condensable gas fraction in the loops and the reactor pressure vessel. This system will locate the nitrogen gas inside the reactor coolant system when the safety injection tank (accumulator) is depleted and cold nitrogen is introduced into the primary system. Another new instrument is a video probe to visualise internal flow topology, especially in the annular downcomer region.

As well as expanding its simulation range, Atlas will be used with other components. A large-scale containment to be connected to Atlas will make it possible to simulate combined thermal-hydraulic behaviour between the reactor coolant and containment system at the same time. Although we are in the conceptual design stage at present, internal unique geometric characteristics such as various compartments, IRWST, and sump are being taken into account. It is expected that an integrated test loop of Atlas with the containment will help establish an integral effect database to validate the containment analysis code itself, as well as a coupled calculations of thermal-hydraulic and containment codes.

Among the new safety concepts, a hybrid safety injection tank (H-SIT), operable in high and low- pressure conditions, is gaining most attention. It is one of the most promising design change concepts, which can replace the existing SIT at minimum cost and have better cooling capability to cope with the SBO event. Performance tests of the H-SIT are planned, with the first planned for the second half of 2016. Mechanical and measurement systems are being updated.

Domestic and international collaborations will be continued. In particular, the continuation of DSP activity is believed to be the most efficient way to strengthen the safety analysis network, as well as to transfer safety analysis technology to the next generation. There have been several discussions about co-operation with international nuclear communities. A contract is underway with Switzerland’s Paul Scherrer Institute (PSI) to work on thermal-induced SGTR. PSI will conduct separate effect tests from the phase 1 to 3. In phase 4, Atlas will be used to carry out two integral effect tests to simulate a high temperature gas-steam environment. This project is also attracting other project partners. The Atlas team is discussing co-operation with GRS (Germany), IRSN (France), MTA-EK (Hungary) and the United Arab Emirates. ■

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