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A pre-test analysis of ATLAS SBO with RCP seal leakage using MARS code

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Abstract: The accident in Fukushima Daiichi nuclear power plants shows the important of developing coping strategies for extended station blackout (SBO) scenarios of the nuclear power plants (NPPs). Many NPPs in United State of America are applying FLEX approach as main coping strategies for extended station blackout (SBO) scenarios. In FLEX strategies, outside water injection to reactor cooling system (RCS) and steam generators (SGs) is considered as an effective method to remove residual heat and maintain the inventory of the systems during the accident. This study presents a pre-test calculation using MARS code for the Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) SBO experiment with RCP seal leakage scenario. In the calculation, the turbine-driven auxiliary feed water pumps (TDAFPs) are firstly used after SBO initiation. Then, the outside cooling water injection method is used for long term cooling. In order to minimize operator actions and satisfy requirements of APR1400 emergency operation procedure (EOP), the SGs Atmospheric Dump Valve (ADV) opening ratio, auxiliary feed water (AFW) and outside cooling water injection flow rates were investigated to have suitable values. The analysis results would be useful for performing the experiment to verify the APR 1400 extended SBO optimum mitigation strategy using outside cooling water injection.

Keywords: *Extended SBO, ATLAS, APR1400, RCS, SGs, RCP seal leakage, TDAFP, AFW, outside water injection.*

I. INTRODUCTION

After Fukushima nuclear disaster, the order No. EA-12-049 was issued by the U.S. Nuclear Regulatory Commission (NRC) to require NPPs developing mitigation strategies in order to cope with beyond-design-basis external events. Then, FLEX Implementation Guide (NEI 12-06) was developed by US Nuclear Energy Institute (NEI) to outline methods for performing diverse and flexible mitigation strategies to cope with the scenarios such as extended loss of AC power (ELAP) and loss of normal access to the ultimate heat sink (LUHS) [1]. The main objectives of FLEX are to provide an approach to deploy mobile equipment intended to mitigate a beyond-design-basis external event. In FLEX, outside cooling water injection into RCS and steam generators (SGs) is considered as an effective method to remove residual heat and maintain the inventory of the systems.

During extended SBO, a loss of offsite power and alternate current (AC) power could cause a seal degradation of reactor cooling pumps (RCP), which eventually causes a loss of coolant from RCS through RCP seal leakage.

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With this scenario, it is worthwhile to examine the outside cooling water injection for extended SBO coping strategy by both calculation and experimental demonstration.

In this paper, a pre-test calculation using MARS code for ATLAS extended SBO experiment with RCP seal leakage is presented. In the calculation conditions, the onsite and offsite power (including AAC Diesel Generators) are not available after SBO initiated, causing reactor trip, main feedwater pumps (MFPs) stop running, main steam isolation valves (MSIVs) and turbine valves close. Therefore, core and RCS heat removal relies only on SGs safety relief valves (SRVs) and TDAFPs. After TDAFPs stop working, outside cooling water injection is deployed for long term cooling. In the pre-test calculation, the SGs ADV opening ratio, AFW and outside cooling water injection flow rate were investigated to have suitable values in order to minimize operator actions and satisfy requirements of APR1400 EOP.

II. ATLAS FACILITY AND SCALING PARAMETERS

The ATLAS is a thermal-hydraulic integral effect test facility, which was designed to simulate thermal-hydraulic phenomena of OPR1000 and APR1400 operational/abnormal transients [2]. The three-level scaling methodology developed by Ishii et al. [3] was applied to design the facility.

The ATLAS primary side has the same two-loop features, 1/2 on height, 1/288 on volume, and full pressure simulation in comparison with APR1400. Due to 1/2-height model, the time for the event progression of ATLAS is a squared root 2 times faster than APR1400. The ATLAS secondary side is simplified with a circulating loop-type. The steam from SGs is condensed in a condenser tank and pumped back into the SGs [4]. The ATLAS major scaling parameters compared with APR 1400 are listed in Table I.

Table I. ATLAS major scaling parameters [4]

Parameters	Scaling ratio	ATLAS design
Length	l_{0R}	1/2
Diameter	d_{OR}	1/12
Area	d_{0R}^2	1/144
Volume	$l_{OR}\, d_{OR}^2$	1/288
Core temperature	T_{0R}	1
Velocity	$l_{0R}^{1/2}$	1/1.414
Time	$l_{0R}^{1/2}$	1/1.414
Power/volume	$l_{0R}^{-1/2}$	1.414
Core power	$l_{0R}^{1/2}d_{0R}^2$	1/203.6
Flow rate	$l_{0R}^{1/2}d_{0R}^2$	1/203.6
Pressure drop	l_{0R}	1/2

III. MARS KS CODE

For the pre-test calculation, the Multi-dimensional Analysis of Reactor Safety code (MARS) is used. The code was developed by Korea Atomic Energy Research Institute (KAERI). The code's backbones are the RELAP5/MOD3.2 and COBRA-TF codes of USNRC [5]. The first version of MARS was 1.3 released in 1998. In this study, the MARS-KS code version 1.3 released in 2007 was used. The ATLAS input nodalization diagram used in the pre-test calculation is shown in Fig.1.

IV. CALCULATION RESULTS

A. Steady state calculation

The ATLAS input deck developed by KAERI is used for the steady state calculation, in which all important components and thermal hydraulic parameters of the ATLAS are described. Since the ATLAS facility is a scaled-down test facility of APR1400, the initial and boundary conditions for ATLAS calculation is based on the scaled-down values of the corresponding conditions of the APR1400. The steady state conditions of ATLAS can be archived by running the input file for a couple of minutes. The ATLAS calculated steady state conditions in comparison with the APR1400 are shown in Table II.

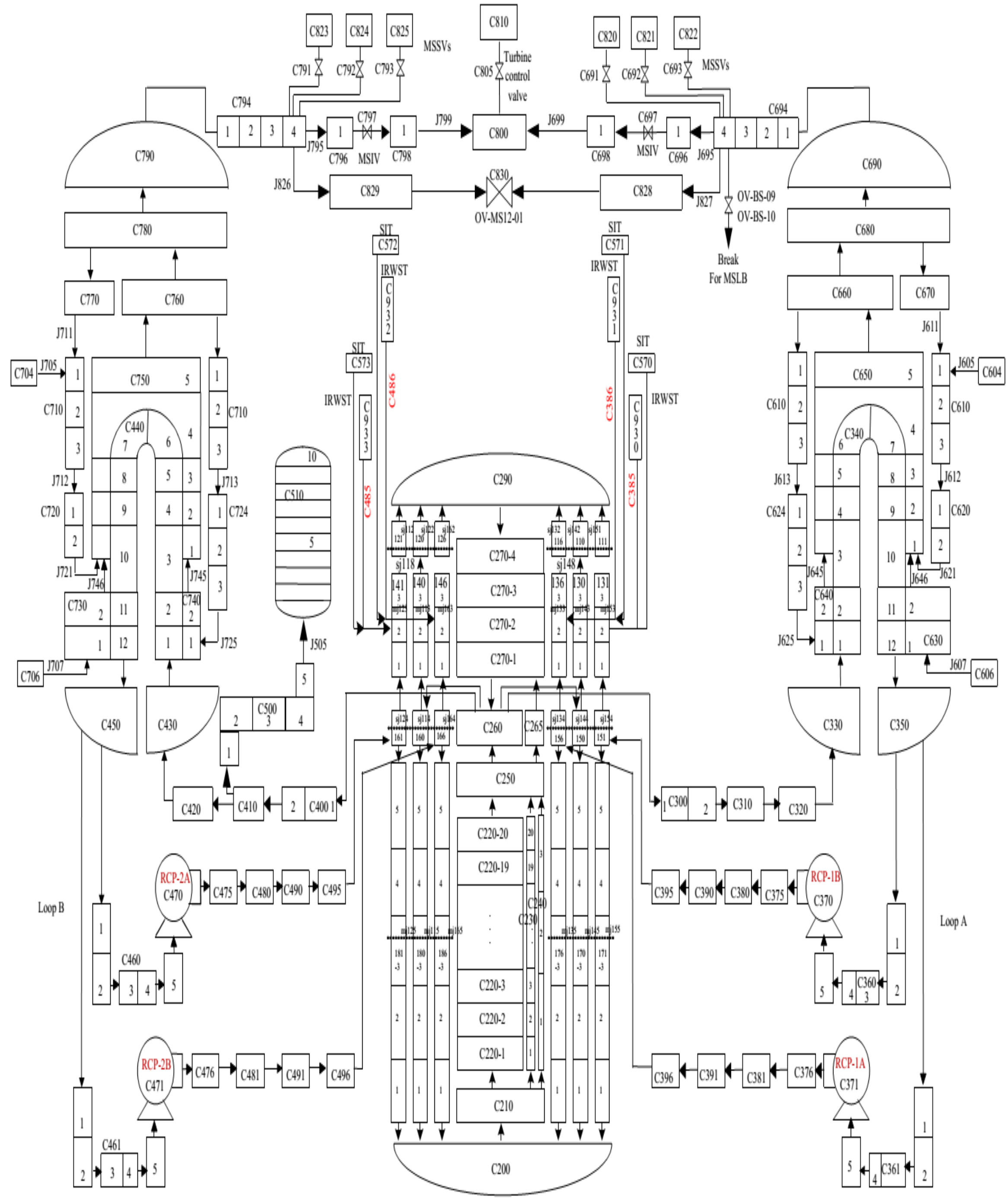

Fig. 1. MARS nodalization diagram of ATLAS.

Table II. Steady state conditions of APR1400 and ATLAS

Major parameter	APR1400	ATLAS Design	Atlas Steady State Cal.
Primary system			
Power (MWt)	3983	1.56	1.56
Pressurizer pressure (MPa)	15.50	15.50	15.55
Core inlet temp. (K)	564.45	563.85	563.80
Core outlet temp. (K)	597.35	597.35	597.30
Secondary system			
SG pressure (MPa)	6.90	7.83	7.82
Steam temp. (K)	558.05	566.65	565.80
Feedwater temp. (K)	505.35	505.35	505.37
Feedwater flow rate (kg/sec)	1152.4	0.44	0.44

B. Transient calculation

The transient calculation conditions of this study are obtained by scaling down the corresponding conditions which have been calculated by J.R. Hwang and S.J. Oh for APR1400 [6]. During SBO, TDAFPs are very important to maintain inventory of SGs. The ATLAS secondary side has no TDAFW trains. However, the TDAFW behavior can be simulated by using ATLAS's feedwater system. The main assumption regarding installed equipment is that TDAFPs should be working until 5 hours 40 minutes after the SBO initiation (8 hours in APR1400). During that period, the repetitive ADVs and TDAFW flow control is not desirable since operators need to focus on various difficult tasks. Therefore, SGs ADV opening ratio and AFW flows were investigated to have a suitable value in order to minimize operator actions and satisfy requirements of current APR1400 emergency operation procedure (EOP) [7].

After 5 hours 40 minutes, the station battery is assumed to be exhausted and TDAFPs stop working. Then, the maintaining primary and secondary inventory should be relied on outside injection sources. The extended SBO main events from transient calculation are shown in the Table III.

In the ATLAS transient input file, the RCPs seal leakage positions were modelled by the valves located on the discharge pipelines of 4 RCPs. The valve flow area was investigated in order to get seal leakage flow rate of 0.036 kg/sec/pump at 15.5 MPa, which is corresponding to 7.3 kg/sec (116.2gpm) in the RCP technical manual [8]. The Henry-Fauske choke flow model and default discharge coefficients in MARS are applied to calculate the seal leakage flow. In addition, a conservative 1973 ANS decay heat curve with a 1.2 multiplication factor is used in the transient calculation.

Table III. Extended SBO main events

Time (hh:mm:ss)	Main Event
00:00:00	SBO accident starts, reactor trip, RCPs coast-down, TD AFPs supply feedwater to SGs (0.45kg/sec)
00:02:08	RCP seal leakage starts (0.036kg/sec/pump at 15.5 MPa)
00:19:07	Reducing AFW flow rate of SGs to 0.07kg/sec (to avoid SG solid state)
01:03:40	Start cool-down and depressurization process by opening ADV(25% equivalent area of MSSV)
01:12:50	SITs start injection (set point 4.02 MPa)
05:40:00	TD AFPs stop, full opening of ADV Start outside water injection to RCS and SGs.
12:00:00	End of calculation

The transient calculation starts with SBO event, the RCP seal leakage is initiated at 128 seconds after SBO initiation (3 minutes in APR1400). The RCP seal leakage flow rate is shown in Fig.2.

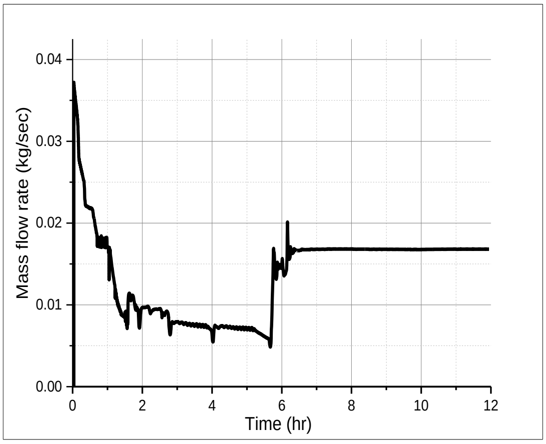

Fig. 2. RCP seal leakage flow rate (1RCP)

Primary pressure starts decreasing after reactor trip and RCP seal leakage initiation. Meanwhile, SGs inventory is maintained by TDAFPs. The SGs MSSVs are cycling open/close to release pressure from SGs before cool-down process is performed. Primary and secondary pressure behaviors are shown in Fig. 3.

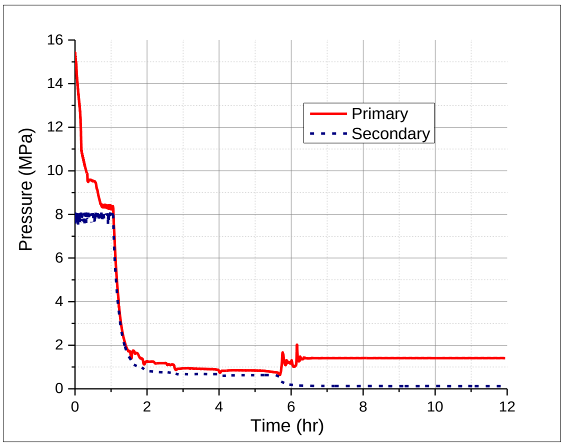

Fig. 3. Primary and secondary pressure

The core water level is gradually decreased due to RCP seal leakage. However, the water level is still kept above top of fuels before SITs injection. The core residual heat is mainly removed via secondary side by natural circulation and depressurization process. The calculation results for core collapsed level and cladding temperature are shown in Fig.4.

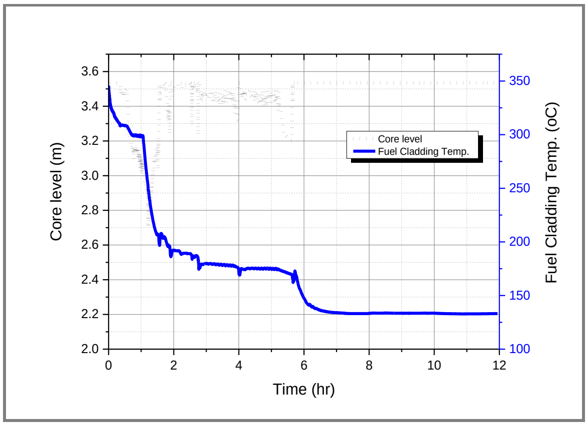

Fig. 4. Core collapsed level and fuel cladding temperature

For the SG inventory, operators should control the TDAFP flows at about 20 minutes to avoid solid state of SGs, and the cool down procedure was started after 1 hour 4 minutes of SBO. The cool down rate using secondary side depends on the SGs water level, main steam pressure, temperature and RCS cool down rate. In this case, one ADV opening area of each train was investigated to be 25% equivalent area of main steam safety valve (MSSV) for cool down and the TDAFP flow rate is set to 0.072 kg/sec to each SG. With this flow rate, SG inventory is maintained above 27% wide range level without any additional flow control by operators. This SG inventory condition during depressurization process is satisfied the current APR 1400 EOP for SG inventory of wide range operation from 25% to 88% [7]. Fig.5 shows the behavior of SG levels during the transient calculation.

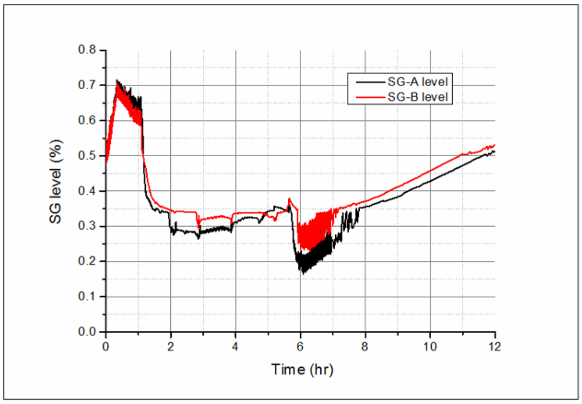

Fig. 5. SGs water level

During the first phase of SBO, the SIT injection flow rates are very important. The behavior of RCS will vary depending on RCP seal leakage, SIT injection time and flow rates. In the APR1400, each of the four SITs equipped a fluidic device which is used for passively controlling the injection flow rate from SIT to RCS. The fluidic device changes injection flow condition from high flow to low flow condition during injection time of the SITs. In the ATLAS SITs, the fluidic device was not equipped as those in APR 1400. The high flow injection condition from ATLAS SITs was simulated by using orifices with an optimized flow area to throttle the SIT discharge line. The low flow injection condition was achieved by changing the opening area of the valves in the SIT injection line [4].

So far, there is no specific conditions in the current APR 1400 EOP [7] for SIT isolation could be satisfied in case of extended SBO with RCP seal leakage, or extended SBO with combined accidents such as LOCA, SG U tube ruptures etc. The current APR 1400 SBO EOP is mainly focusing on restoring power sources and using the installed equipment of the plant to maintain and perform the key safety functions. Since the lately SIT isolation could cause injection of the noncondensable gas (i.e. Nitrogen) to RCS, and the early SIT isolation could affect the RCS inventory recovery process subsequently. Therefore, in the pre-test calculation, the SIT isolation level is assumed to be before the SIT levels drop down to the emptied level of about 2.6m [4], corresponding with fluidic device bottom levels.

In the calculation, some oscillations of the SIT discharge flow during the injection time as shown in the Fig.6. Probably, the interfacial heat transfer in the downcomer area is oscillated when the SIT discharge flow injected to the downcomer. Then, downcomer pressure will be oscillated, causing some oscillations of SIT discharge flow, subsequently. The other reason for the SIT discharge flow oscillation could cause by the numerical problems in simulation. In addition, a very small negative flow was appeared from SIT discharge flow calculation, probably caused by condensation phenomena in SIT discharge pipe. These issues need to be investigated and improved in further study.

The SITs isolation is performed at 3 hours 51 minutes before the SIT levels drop down to the emptied levels. Fig.7 shows the SITs accumulated injection mass. When the SITs are isolated, the total amount of water injected to RCS of each SIT was about 180 kg.

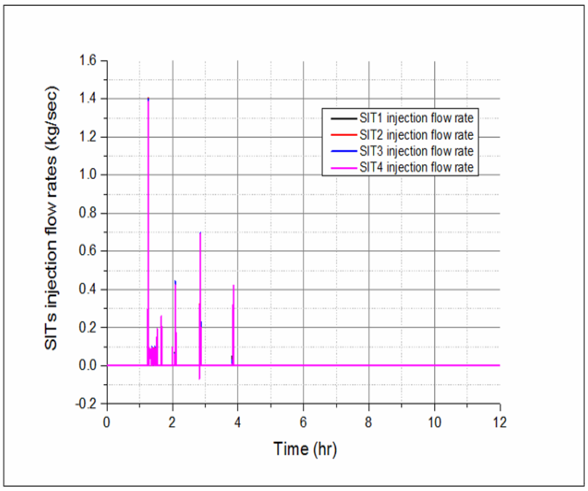

Fig. 6. SITs injection flow rates

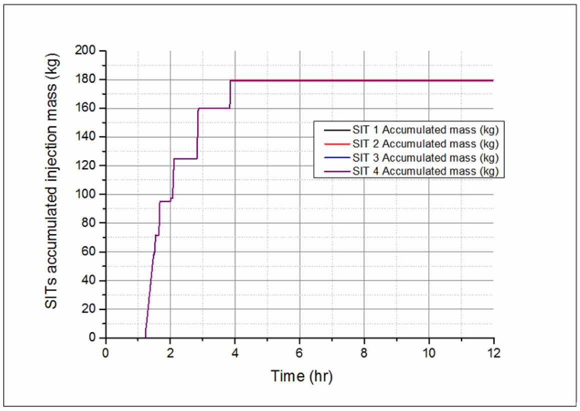

Fig. 7. SITs accumulated injection mass

At 5 hours 40 minutes, the pre-test calculated results for SG pressure and temperature were 0.63 MPa and 162°C, respectively. The steam line pressure is shown in Fig. 8. These conditions are satisfied the TDAFP operation conditions (>0.48 MPa and 157°C) [7].

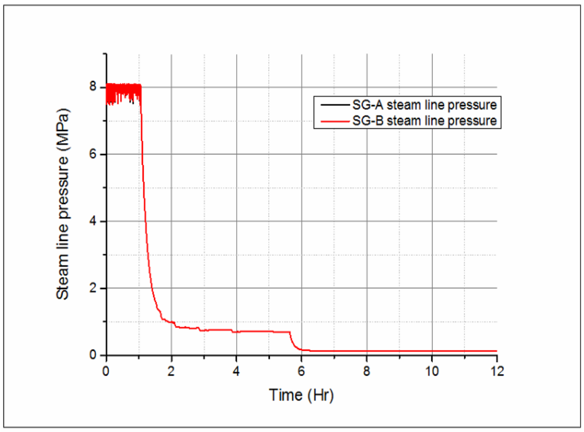

Fig. 8. Steam line pressure

After 5 hours 40 minutes, outside water injection starts for long term cooling. Fig.9 and Fig.10 show the outside injection flow curves from the external pumps to the RCS and SGs depend on the system pressures. The external pumps in the pre-test calculation were selected to be A-l fire trucks, which are widely used in fire stations in Korea with discharge pressure more than 14 kg/cm2 [9]. With the outside injection flow rates as shown above, the inventory of RCS and SGs are maintained until 12 hours without any injection flow adjustment performed by operators.

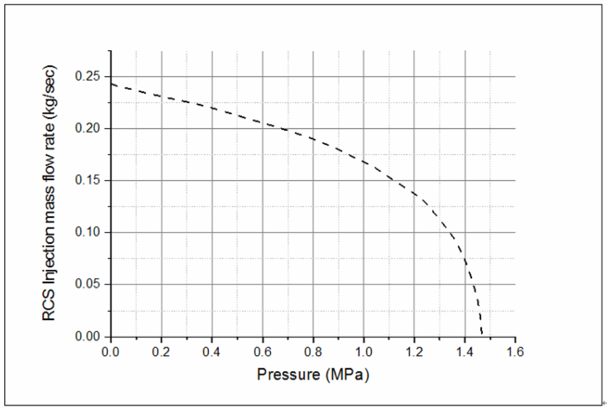

Fig. 9. Outside injection flow rate to RCS

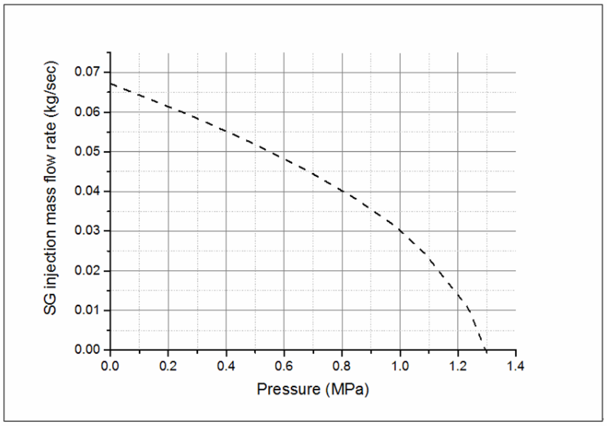

Fig. 10. Outside injection flow rate to SG

III. CONCLUSIONS

The pre-test calculation for ATLAS extended SBO with RCP seal leakage and outside cooling water injection scenario is performed. From the calculation results, outside cooling water injection into RCS and SGs is verified as an effective method during extended SBO when RCS and SGs depressurization is sufficiently performed. The SGs ADV opening ratio, AFW and outside cooling water injection flow rates were investigated in order to minimize operator actions and satisfy requirements of current APR1400 EOP. The pre-test calculation is expected to be useful for conducting the experiment in future to produce the optimal emergency operation and mitigation strategy for APR 1400 to cope with the extended SBO accident scenarios.

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