Main steam line break accident simulation of APR1400 using the model of ATLAS facility

A S Ekariansyah, Deswandri, Geni R. Sunaryo
Center for reactor nuclear safety and technology (BATAN), Puspiptek area, Setu, Tangerang Selatan
andi_se@batan.go.id

Abstract. A main steam line break simulation for APR1400 as an advanced design of PWR has been performed using the RELAP5 code. The simulation was conducted in a model of thermal-hydraulic test facility called as ATLAS, which represents a scaled down facility of the APR1400 design. The main steam line break event is described in an open-access safety report document, in which initial conditions and assumptions for the analysis were utilized in performing the simulation and analysis of the selected parameter. The objective of this work was to conduct a benchmark activities by comparing the simulation results of the CESEC-III code as a conservative approach code with the results of RELAP5 as a best-estimate code. Based on the simulation results, a general similarity in the behavior of selected parameters was observed between the two codes. However the degree of accuracy still needs further research an analysis by comparing with the other best-estimate code. Uncertainties arising from the ATLAS model should be minimized by taking into account much more specific data in developing the APR1400 model.

Keywords: main steam line break accident, ATLAS facility, APR1400, best-estimate, RELAP5

1. Introduction
The Advanced Power Reactor 1400 (APR1400) is a pressurized water reactor (PWR) design, which was developed mainly by Korea Engineering Power Corporation (KEPCO) in 2001. Its design is basically an enhancement and improvement of previous Korea’s major nuclear power plant model of OPR1000 [1]. 4 units of APR1400 are under construction in 2 sites of Korea for planned operation from 2016 to 2018, plus additional 4 more at United Arab Emirates for scheduled operation by 2020 [2]. The APR1400 is a two-loop pressurized water reactor supplying its nuclear steam supply system (NSSS) to a rated thermal output of 4000 MW or 1455 MW electrical output. The safety of APR1400 against various design bases accidents (DBA) has been described in the Design Control Document, which can be assessed via U.S.NRC website as part of design certification application review [3]. Related to the APR1400 accident analysis contained in that document, not many academic research papers have written the results of analyses nor a direct comparison using different tools or codes with event sequences of all DBAs in the document. Most academic papers associated the APR1400 accident analysis with the experimental results performed using a thermal-hydraulic test facility, which is called as ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) facility. Such accident analyses using the ATLAS involved several initiating events, which was conducted by W. Baek et al [4] for LOCA events, by Y. Kim et al [5] for station blackout event, and...
by K. Kang et al [6] for steam generator tube rupture event. Those researches did not relate the experimental results with the APR1400 accident analysis described in the Design Control Document since the ATLAS facility is regarded as a scaled down representation of the APR1400 design [7], except by Ki-Yong Choi et al [8], who compared the APR1400 accident analysis, ATLAS experimental results, and MARS code prediction. Nevertheless, there are many initiating events described in the APR1400 Design Control Document, which are not yet studied by benchmarking the APR1400 accident analysis with the safety analysis codes such as MARS, RELAP5, etc.

The purpose of this paper is to discuss a benchmark activity of one selected accident event using the RELAP5 code from a model of the ATLAS facility. The ATLAS facility has been modelled using RELAP5 code by other researcher [9], but this paper will associate the ATLAS model using the similar code developed from available ATLAS facility data, that has been used for the best estimate and uncertainty method analysis of direct vessel injection (DVI) line break [10]. The initiating event to be analyzed is the main steam line break (MSLB) in the APR1400 as described in the document. The reason of selecting is the availability of several MSLB simulations using different codes such MARS [11] and SPACE [12]. Both researches described the simulation results with the ATLAS experiment but not with the results contained in the document. The MSLB event will be simulated by the RELAP5/SCDAP/Mod3.2 using the previous ATLAS nodalization [10], so that the accuracy of the ATLAS model can be assessed. At the end, this research activity will explore more the main sequences related to the MSLB event and the level of safety of the APR1400 design to cope the accident.

2. Main steam line break (MSLB) in APR1400

Main steam line break (MSLB) event in the APR1400 is classified as postulated accident in the design basis accident definition. The event is defined as steam system piping failures or shortly steam line break (SLB) occurring inside or outside the containment. The NSSS response of the APR400 has been simulated using the CESEC-III [3] as a licensing conservative code with simple thermal-hydraulic nodalization. Two important safety concerns of MSLB accidents considered in the APR1400 Design Control Document is among others the return to power (RTP) due to the positive moderator reactivity feedback after reactor trip from a overcooling of the core [13] and fluid flashing in the reactor upper head and hot legs [14]. MSLB cases leading to the RTP after reactor trip are large (double-guillotine) MSLB occurred inside the containment during full or zero power operation. On the other side, MSLB cases occurred outside the containment are chosen to maximize the potential of fuel degradation before reactor trip, in which one of those during the full-power operation is selected in this analysis. The case to be validated using RELAP5 is an MSLB before the main steam isolation valve (MSIV) on one of two main steam piping lines outside the containment, which is occurred with a loss of offsite power (LOOP) following a reactor trip. Assumptions and initial conditions before the event are that the core is in full power level of 4,062 MWt, pressurizer pressure of 163.45 bar, core inlet temperature of 296 °C, two safety injection pumps are inoperation, and offsite power is lost concurrent with reactor trip. The sequences simulated using the CESEC-III as described in the Design Control Document are showed in Table 1 along with the setpoint value of APR1400 protection and mitigation system.
Table 1. Sequences of MSLB outside containment in the APR1400 [3]

| Event                                              | Setpoints of protection and mitigation systems or condition |
|----------------------------------------------------|-------------------------------------------------------------|
| Steam line break starts                            | -                                                           |
| Overpower trip signal reached                      | 121.0 %                                                     |
| Auxiliary feedwater flow (AFW) started from         | -                                                           |
| overpower trip signal                              | -                                                           |
| Delayed reactor trip after overpower trip signal    | -                                                           |
| Loss of offsite power (LOOP) initiates Turbine trip | after reactor trip                                          |
| and reactor cooling pump (RCP) trip                | -                                                           |
| MSIV close signal from steam generator pressure     | 52.73 bar                                                   |
| setpoint                                           | -                                                           |
| Main feedwater isolation valves (MFIV) close from   | -                                                           |
| steam generator pressure setpoint                   | -                                                           |
| Safety injection actuation signal from pressurizer  | 109.32 bar                                                  |
| pressure setpoint                                   | -                                                           |
| Point shutdown cooling initiated                    | Core inlet temperature 176.7 °C                              |
|                                                    | Pressurizer pressure 31.64 bar                               |

Overpower is caused by the reactor cooling system (RCS) cooldown, which initiates an increase in core reactivity based on the negative moderator and doppler reactivity coefficients. That RCS cooldown is caused by a decrease in temperature and pressure in the reactor cooling system (RCS) from increased heat transfer from the primary system to steam generators secondary side [15]. Those events presented in Table 1 has been judged distorted by other researcher [16], therefore a best-estimate simulation is necessary to evaluate those event sequences using the ATLAS test loop facility as described in this research paper.

The ATLAS itself is a test loop facility representing a scaled-down primary and secondary cooling system of the APR1400 consisting similar loop arrangement of 2 hot legs, 4 cold legs, 2 steam generators, and 4 reactor cooling pump (RCP). It also incorporates safety injection features similar to the APR1400 such as 4 safety injection tanks (SITs) as passive emergency core cooling system (ECCS) and 2 high and low-pressure safety injection pumps for performing direct vessel injections [17]. The ATLAS dimensions are a half in height and length and 1/288 in volume of the APR1400 and capable for a full pressure simulation up to 20 MPa with maximum 10 % of the scaled nominal core power [7]. In this paper, the MSLB event will be conducted using the ATLAS model, which has been developed completely by the RELAP5/SCDAP/ Mod3.4 code and been used for the best estimate and uncertainty method analysis of direct vessel injection (DVI) line break [10]. Additional nodalizations are needed in order to simulate the MSLB event according to the event sequences as determined in the APR1400 design control document.

3. Methodology
The MSLB simulation requires a model of steam lines, MSIV, and valve for turbine isolation, which have to be incorporated in the basic ATLAS model. The steam line piping data of the ATLAS and its related components are not available, therefore a scaled-down calculation has been conducted in order to obtain proper dimensions based on the APR1400 piping data. Based on APR1400 Design Control Document [3], the largest effective steam blowdown area on each steam line is around 30 % of the steam line cross-section area or 0.119 m². It means that the 100 % steam line cross-section area is 0.3967 m². From that value, the main steam line cross-section area of the ATLAS model is calculated from the scaling parameter formula [17] to be 0.00275486 m². In the steam generator upper-head, a flow restrictor is installed to limit the steam discharge at the SLB with an area of 0.00170211 m² [12]. In order to simulate a double-ended guillotine break, the SLB nodalization consists of 3 quick opening valves modelled in steam line B. One valve is an normally open valve connecting the steam
line B during normal operation, which will be closed when the SLB starts. Two other normally close valves will connect the other ends of the steam line to simulate steam flows from both direction discharged in to a volume with atmospheric pressure. On each steam line A and B, a normally open valve is modelled to simulate the MSIV before it is be merged in a joined steam line (steam header) with assumed double steam line area, passed through a turbine trip valve in to a discharged volume with the steam generator operating pressure of 7.7 MPa. The length of particular steam line is determined by assumption. Figure 1 shows the ATLAS nodalization using the RELAP5 for the SLB simulation referring the steam generator upper dome.

Figure 1. ATLAS nodalization in the steam generator for double-ended guillotine MSLB simulation using RELAP5

Before the MSLB simulation, the ATLAS is operated with its nominal heater power of 1,638 kW. The sequences after the MSLB are that the main feedwater pumps (MFWs) supplying feedwater in to the steam generator secondary side is stopped after the heater power reaches 121 % nominal power, which are replaced by the operation of auxiliary feedwater pumps (AFWs). The AFW volumetric flow rate of APR1400 is 3,596 liter per minute or 59 kg/sec, which is converted by the ATLAS scaling formula to 0.2953 kg/sec. The overpower trip signal will generate reactor trip, in which the heater power is dropped to simulate a decay reactor power. The heater power of the ATLAS will follow the APR1400 core power during the transient as calculated by the CESEC-III code [3]. In the same time, loss of offsite power is assumed, which initiates turbine valve to close and RCP begins to coast down. All safety injections either from passive injection system (4 SITs) and active injection system (2 SIPs) are considered to be operable during the SLB sequences. Parameters to be evaluated are steam generator secondary side pressure in the affected steam line B and affected steam line A, pressurizer pressure, inlet and outlet core coolant temperature, and reactor pressure vessel (RPV) upper head flashing phenomena.

4. Results and discussion
The SLB simulation is performed based on the steady-state condition as described in the methodology. Table 2 shows resulted steady state parameters for the primary and secondary system of ATLAS facility after 1000 sec RELAP5 simulation before the the SLB simulation. There are 4 initial conditions assumed in the APR1400, which are core power, pressurizer pressure, core mass flow rate, core inlet temperature and pressurizer water volume. The APR1400 core power of 4,062 MW is scaled down in the ATLAS facility to a heater power of 1,638 MW. The pressurizer pressure is unchanged of around 163 bar as also the core inlet temperature of 568 K. The pressurizer water volume of APR1400 is 39.9 m3, which is scaled down into 0.1385 m2 for the ATLAS pressurizer. The cold leg mass flow is calculated from the APR1400 core mass flow of 23,619.44 kg/sec, which is scaled down by the ATLAS scaling formula to around 29 kg/sec after divided by 4 cold legs. Those values for the ATLAS
facility should be maintained during the ATLAS simulation using the RELAP5 as shown in the Table 2.

Table 2. Steady-state parameter of the ATLAS calculated by RELAP5 before the MSLB simulation

| Parameter                          | ATLAS    |
|-----------------------------------|----------|
| Primary system                    |          |
| Heater power (MW)                 | 1,638.0  |
| Pressurizer pressure (bar)        | 162.95   |
| Core inlet temperature (K)        | 567.77   |
| Core outlet temperature (K)       | 571.08   |
| Cold leg flow rate (kg/sec)       | 23.44    |
| Secondary system                  |          |
| SG dome pressure (bar)            | 77.96    |
| Main feedwater flow rate (kg/sec) | 0.433    |
| Main steam flow rate (kg/sec)     | 0.431    |
| Primary to secondary heat removal (MW) for 1 SG | 0.82    |

From the Table 2, the steam flow rate in the one steam line is around 0.43 kg/sec, which is consistent with the main feedwater flow rate supplying water into the steam generator (SG). The core inlet temperature of 567.7 K is close to the 568 K of the APR1400 initial condition. The cold leg flow rate is selected to be 23 kg/sec, which is not much deviated from the 29 kg/sec. The heat losses from the primary and secondary system into the environment are not considered in the model meaning that adiabatic boundary conditions are applied to the ATLAS model.

The MSLB is initiated by opening the 2 normally close valves and closing 1 normally open valve in the steam line B as shown in Figure 1. Figure 2 shows the break flow rates from the 2 directions of the affected steam line simulating the double-ended break. Those actuations of the break valves will direct the steam line from the SG-B and SG-A into the discharge volume or steam collector with 1 bar pressure.

The initial break mass flow is calculated to be 13 kg/sec from both directions of steam line. The break flow from the SG-A is interrupted with the actuation of MSIV in the both steam lines, while the break mass flow from SG-B will continue to follow the available steam inventory. There is no comparison of APR1400 break mass flow to evaluate the calculated mass flow in the ATLAS, however a similar SLB experiment conducted in the ATLAS has shown an experimented break mass
flow of around 6 kg/sec [11]. Therefore a modified model in the steam line is performed by given different loss coefficient with the result of simulated break flow of 8 kg/sec as shown in Figure 2.

The discharged steam flow will decrease the pressure measured on top of both SGs as shown in Figure 3. There are differences in the SG pressure between the SG-B and SG-A from the initial steam pressure of 77.96 bar.

On Figure 3, the pressure in the SG-A and B are dropped rapidly due to the continuous discharged steam flow through the breaks. As the steam pressure decreases to the value of 52.73 bar, both MSIVs are closed with 6 second time delay. The MSIV-A blocks the discharged steam from the SG-A, while the closing of MSIV-B has no effect on the discharged steam from SG-B because the MSLB occurs upstream of the closed MSIV-B. That is the reason for the increase of SG-A pressure after closing of MSIVs on Figure 3. The SG-B pressure characteristics from the ATLAS model is almost similar with the APR1400 model, however the SG-A pressure is much different. In the APR1400 calculation, a continuous decrease of the SG-A pressure is obvious, while in the ATLAS calculation the SG-A pressure is almost stagnant without the actuation of AFW pump, even the values are slowly decreased. The SG-A pressure of the ATLAS decreases more clearly when dedicated AFW pump is operated to supply water into the secondary system thus cooling down the steam temperature. The SG-A behavior of the APR1400 calculation can only occur, when the operator performs a steam venting via automatic depressurization system (ADS) or operates turbine bypass to depressurize the pressure or additional heat loss is considered in the APR1400 model. That discrepancy of the unaffected SG pressure has been also validated, when a environmental heat loss is taken in to consideration as performed by other ATLAS model simulated by MARS[11] and SPACE code[12].

The primary cooldown due to increased inventory leakage flow rate in the SG secondary system initiates a pressurizer pressure decrease [18] as shown in Figure 4. The primary depressurization calculated in the ATLAS occurs bigger than CESEC-III calculation of APR1400 even though there is no heat loss from the primary to environment. A comparison with the RELAP5 calculation is included in the figure by showing a similar analysis with the MARS code [11]. Both best-estimate calculation show an uncertainty in the result involving the ATLAS model. The primary pressure achieves its level back, when the safety injection pumps (SIPs) inject water directly to the vessel after primary pressure setpoint of 109.7 bar has been achieved with some time delay.
Figure 4. Pressurizer pressure after MSLB

The primary cooldown as shown by the primary pressure decrease will also cause the decrease of saturation pressure. In that event, vapor void is appeared in the upper head of the vessel, where the static pressure is lower compared to other part of the ATLAS vessel. The value of vapor void fraction is shown in Figure 5 between the APR1400 and ATLAS model calculation. The maximum value of vapor void in the ATLAS model will be higher in correlation with the higher MSLB mass flow. The vapor void fraction will increase until additional water injection from the SIPs increase the water density as the vapor void fraction decreases.

Figure 5. Vapor void fraction in the vessel upper head

The differences in the steam pressures between SG-A and SG-B have effect on the temperature of cold legs taking heat from the secondary system. During the MSLB transient, the coolant temperature in the cold legs downstream of the SG-B is lower than the one of the SG-A. Therefore a non-uniform temperature distribution occurs at the core inlet [19]. Figure 6 presents the characteristics of the core inlet and outlet temperature during the MSLB event.
The behavior of the core inlet temperature in the ATLAS model is closely related with the rate of heat removal from the SG-B due to the discharged steam during the MSLB. The primary system takes more heat from the SG-B in the ATLAS model as indicated by the bigger decrease of pressurizer pressure in Figure 4. Therefore, the resulted core inlet temperature in the ATLAS is lower than the APR1400 model. The decrease also follows the heater power characteristic after reactor trip.

The overall results of ATLAS simulation using RELAP5 code show a general similarity in the behavior of selected parameters with the APR1400 calculated by CESEC-III. However, the magnitude of the parameter fluctuations is different between the calculation results of the two codes. The uncertainties arising from the RELAP5 calculation as a best-estimate code become higher since the comparison is conducted based on the ATLAS model not on experimental results. A validation with other best-estimate code might be necessary by considering much more data of the APR1400 model.

5. Conclusion
Based on the MSLB simulation using the ATLAS model calculated by the RELAP5/SCDAP/Mod3.2, the overall results of the secondary pressure, primary pressure, inlet and outlet core temperature, and vessel vapor void show a general similarity with the results of APR1400 model calculated by CESEC-III. Since the CESEC-III code is a code based on a conservative approach, the magnitude of the parameter fluctuations is different with the calculation results of RELAP5 as a best-estimate code. The degree of the calculation results requires further validation with other best-estimate code by considering much more data of the APR1400 model. Nevertheless, the research has given a valuable experience regarding the benchmarking process of a safety analysis described in a safety analysis report.

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