FLEX Strategy to Cope with Extended SBO for APR1400

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***Abstract*—The accident in Fukushima Daiichi nuclear power plants demonstrates the vulnerability of the currently operating nuclear power plants (NPPs) during extended station blackout (SBO) events. According to the probabilistic safety analysis results for NPPs, SBO is the most probable and significant factor contributes to core damage. During the extended SBO scenario, heat removal capacity and inventory of reactor core, reactor cooling system (RCS) and spent fuel pool need to be maintained. The purpose of this paper is to develop a coping strategy against extended SBO scenario for APR1400 by applying diverse and flexible coping strategy (FLEX). Particularly, this study focus on using outside core cooling water injection method and improvement of the useable time of installed batteries during the extended SBO. Analysis results showed that the inventory of RCS and steam generator (SG) are maintained until 16 hours after SBO without any injection flow adjustment performed by operator with outside injection flow rates of 34.5kg/sec at 0.77 MPa for RCS and 8.2 kg/sec at 0.63MPa for each SG, respectively.**

Keywords—FLEX; SBO; APR-1400;TDAFP;

I. INTRODUCTION

The Fukushima accident has shaken the safety of nuclear industry and it also proves that the extreme natural phenomena could challenge the existing prevention, mitigation and emergency preparedness defense in depth layers. During the events at Fukushima, the challenges faced by the operators were beyond any faced previously at a commercial nuclear reactor and one of the lessons learned from this accident is the significance of the challenge presented by a loss of safety related systems following the occurrence of a beyond design basis external event (BDBEE). So for the safety of the public, additional requirement should be imposed to mitigate beyond design basis external events. These additional requirements impose guidance and strategies to be available if the loss of power, motive force and normal access to the ultimate heat sink to prevent fuel damage in the reactor and spent fuel pool affected all units at a site simultaneously.

Though the existing plants can survive many scenarios like offsite power or flood, after Fukushima the regulators are changing their safety strategies for dealing with the long-term loss of normal safety systems. Instead of figuring out which events might happen, the strategies focused on significantly improving the plants' flexibility and diversity in responding to extreme natural phenomena, such as severe flooding and earthquakes. The plants' strategies must protect or restore key safety functions indefinitely in the case of an accident. The strategies focus on keeping the reactor core cool, preserving the containments barrier that prevents or controls radiation releases, and cooling the spent fuel pool. The strategies also must protect the plant indefinitely, so plants may need to bring in additional equipment or resources.

After Fukushima nuclear disaster, the U.S. Nuclear Regulatory Commission (NRC) issued order EA-12-049 requiring nuclear power plants to develop mitigation strategies for beyond-design-basis external events (i.e. FLEX). The Nuclear Energy Institute (NEI) has developed a generic framework for response to this order that is documented in the FLEX Implementation Guide (NEI 12-06). The framework outlines an approach for adding diverse and flexible mitigation capabilities to increase defense-in-depth for beyond-design basis scenarios to address an extended loss of AC power (ELAP) and loss of normal access to the ultimate heat sink (LUHS) at all units of NPPs. The objective of FLEX is to provide a programmatic and controlled approach to transition to mobile equipment intended to mitigate a beyond-design-basis external event. Portable equipment that supplements installed systems will enable key safety functions to be maintained despite a postulated extended loss of normal AC power and loss of normal access to the ultimate heat sink. Protection, access and connections for the portable equipment must also be provided [1].

FLEX strategies involve three phase approach for mitigating beyond-design-basis external events. The initial phase uses installed equipment and resources. The transition phase requires providing sufficient, portable, onsite equipment and consumables until they can be accomplished with resources brought from off site. The final phase obtains sufficient off-site resources to sustain those functions indefinitely.

As a FLEX strategy, onsite tank water or nearby stream water injection procedure for APR1400 is developed in case of extended SBO scenario. Onsite water sources are Condensate Storage Tank, Demineralized Water Storage Tank and Fresh Water Storage Tank. Backup power system will provide essential power to the emergency sensors and devices. This work, especially focus on how to inject, operate and maintain instrumentation from outside during such BDBEE. The FLEX will enhance the defence-in-depth for beyond-design-basis accident to cope with extended SBO and loss of normal access to the LUHS for APR1400.

II. MODEL AND SAFETY ANALYSIS

To cope with the extended SBO scenario, the analysis of the thermal hydraulic behavior of the plant is required. Especially, the seal leakage of reactor coolant pump (RCP) plays very important role during such event. Therefore, this work focused on the case with RCP seal leakage to analyze the APR 1400 thermal hydraulics behavior. MARS computer code is used to analysis the accident scenario. The MARS code is best estimate thermal-hydraulic computer code, which is used for the safety analysis.

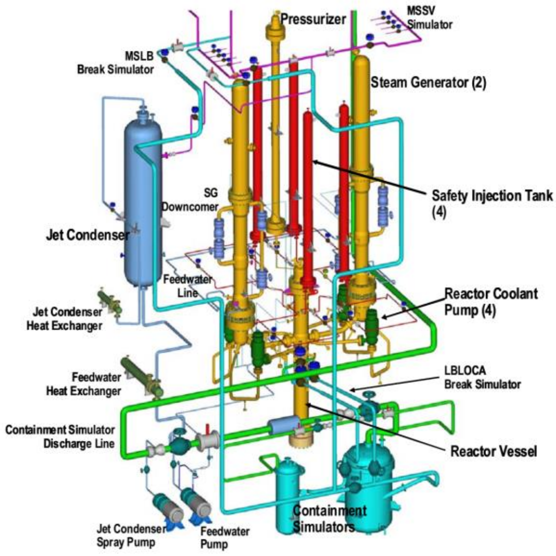

Fig. 1. 3D View of ATLAS [4]

The Advanced Thermal-hydraulic Test Loop for Accident Simulation (ATLAS) input file is used instead of APR 1400 input file for the analysis since the ATLAS facility is designed according to APR1400 design. The ATLAS (Fig. 1) has the same two-loop features as the APR1400 and is designed according to the well-known scaling method suggested by Ishii and Kataoka [2] to simulate the various test scenarios as realistically as possible. It is a half-height and 1/288-volume scaled test facility with respect to the APR1400. According to the scaling law, the reduced height scaling has time-reducing results in the model. So the time for the scaled model of ATLAS is square root 2 times faster than APR1400. Some main scaling parameters of ATLAS compare with APR1400 are shown in Table 1.

Table 1: Major scaling ratios of ATLAS to APR1400 [3]

Parameters	Scaling ratio	ATLAS design
Length (height)	l0R	1/2
Area	d2oR	1/144
Core temperature rise	ΔToR	1
Velocity	l1/2oR	1/1.414
Time	l1/2oR	1/1.414
Power/volume	l-1/2oR	1.414
Heat flux	l-1/2oR	1.414
Core power	l1/2oR d2oR	1/203.6
Flow rate	l1/2oR d2oR	1/203.6
Pressure drop	l0R	1/2

III. SELECTION OF EQUIPMENT FOR FLEX COPING STRATEGY

A. Water Sources and Outside Water Injection Strategies for APR1400

During the extended SBO scenario, heat removal capacity and inventory of reactor core, reactor cooling system and spent fuel pool need to be maintained. The containment cooling also need to be considered due to containment function is threatened by SB- LOCA (from RCP seal failure) or hydrogen generation. For APR 1400, outside connectors can be installed to inject cooling water to the systems using fire trucks or portable pumps. Using these connectors, outside cooling water can be provided to reactor, steam generators, containment spray system, and spent fuel pool [5].

According to the Severe Accident Management Guideline (SAMG) technical bases report of APR1400, required cooling water mass for external injection until 72 hours after SBO is around 2,500 ton. First priority of water source is Condensate Storage Tank, because the connection points are close to this tank. The other options are Demineralized Water Storage Tank and Fresh Water Storage Tank. Total capacities of these tank water is more than 6,000 m^3. In the worst case, that if all the water sources of the tank, inside the plant are depleted, water of nearest stream can be used.

B. Mobile Pump Selection

Original basic strategy of emergency external injection to primary, secondary, and SFP was using fire engine whose discharge pressure was 15 kg/cm^2. Regarding the availability and efficiency Korea hydro and nuclear power (KHNP) changed the strategy from fire engine to portable diesel engine having discharge pressure of 20 kg/cm^2 considering pressure loss and margin.

C. Essential Instrumentation and Batteries

Necessity of measures for Loss of DC Power situation is one of the lessons learned from the Fukushima accident precipitated by an earthquake and tsunami, the direct caused that both AC and DC power were unavailable.

Essential power for operating some important equipment such as pilot operated safety relief valve (POSRV), turbine-driven auxiliary feed water pump (TDAFWP) control power, other important valves, and instrumentation is supplied by Uninterrupted Power Supply (UPS) system which is consists of battery, inverter, and battery charger in case of SBO. But operation time of this UPS system is limited only for 8 hours, because there is no power source to recharge the battery in case of SBO. The most important condition is depressurization of primary and secondary system to allow enough flow to RCS by portable pumps against system pressure. After external injection start, some essential parameter of plant should be monitored because injection flow should be controlled depending on pressurizer (PZR) level, PZR pressure, SG wide range level, and RCS hot leg temperature which are the minimum required parameters during external injection. Therefore, at least these four essential instrumentations should be remained in operable more than

72hours. However, there are no means to supply power to these instrumentations after UPS system depletion. Backup battery system only for these essential instrumentations can be used which can serve after UPS system depletion in case of extended SBO accident.

IV. EXTENDED SBO SCENARIO

Figure 2 shows simplified event tree of the problem. Restoring offsite power is not considered here because if one of the offsite power sources is restored, don't need to take action any more to mitigate extended SBO. Operation of TDAFWP is essential because this pump is only mean of RCS heat removal during this accident. And also during TDAFWP operation, condition for external injection should be prepared with adequate operation action such as depressurization and decrease temperature of primary and secondary side. The most probable case during SBO event is the RCP seal leakage i.e. the loss of primary inventory through the RCP seal.

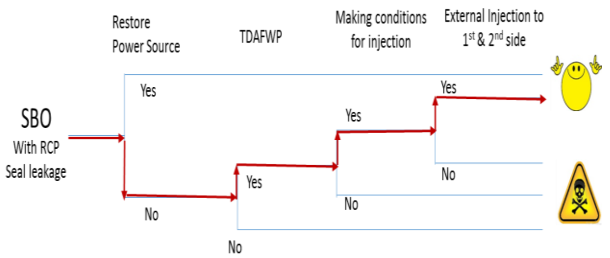

Fig. 2. Simplified event tree of FLEX mitigation strategies

The basic assumptions are external events caused all onsite and offsite power are unavailable and the SBO initiated reactor trip, main steam supply isolation valve (MSSIV) closes, and consequently turbine trips. The TDAFWP is the only way to cool down the reactor up to the exhaustion of battery life, and the battery power is assumed to be available up to 8 hours.

Table 2: Event sequence after SBO

Main Event	Time (hh:mm)
Initiating event Station Blackout – Loss of all onsite and offsite AC power	00:00
Reactor Trip MSIVs Close – MSSV opens/closes by SG pressure increases and decreases	00:00
TDAFP starts supplying water to SG at design flow rate	00:01
RCP seal leakage (116 gpm/pump)	00:03
Operator regulate (decrease) TDAFP flow rate to 16 kg/sec	00:30
Cooldown procedure starts ADVs are opened (25% area of MSSV) for cool down	01:30
Accumulators begin injecting (Primary side pressure: 4.02 MPa)	01:43
TDAFP stops supplying water to SG Outside water injection to RCS and SG. ADVs are opened (100%) for depressurizing secondary side	08:00
End of calculation	16:00

In this case, RCP seal were failed due to loss of seal injection and seal cooling water. Consequently, the primary inventory and pressure decreases, just like as small break loss of coolant accident (SBLOCA). The worst case for this event might be core uncovery but on the other side, it can help to activate safety injection tanks (SITs) or outside injection due to pressure decrease through the leaks. The summary of event progression, operator actions and thermal hydraulics phenomena are shown in Table 2.

V. DISCUSSIONS AND RESULTS

The TDAFP starts automatically when the reactor trip happened due to SBO, and the primary side starts to cool down by means of natural circulation. The cooling is possible using TDAFP up to the availability battery power.

In this case, the seal leakage is assumed to starts after 3 minutes of SBO. The seal leakages are assumed to be 120 gpm at 2204 psi according to the RCP technical document [6]. The RCP seal leakage rate also decreases along with the primary pressure decrease, and it will continue as long as the RCS pressure is higher than the environment pressure. When the RCS pressure reached at its set point, the safety injection tank (SIT) starts automatically to recover the RCS inventory. The seal leakage flow behavior is shown in Fig. 3.

The operator should control the TDAFWP flow at 30 minutes to avoid solid state of SG, and the cool down procedure was started after 90 minutes of SBO. The cool down rate using secondary side depends on the SG water level, main steam pressure, temperature and RCS cool down rate. In this case, one atmospheric dump valve (ADV) opening area of each train was selected to 25% of MSSV for cool down and the TDAFWP flow rate is set to 16 kg/sec to each SG. In this flow rate, SG inventory should not be depleted without additional flow control by operators.

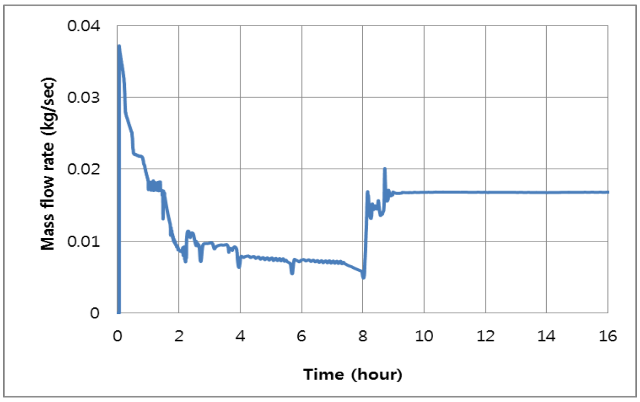

Fig. 3. RCPs seal leakage

It is assumed that the TDAFWP stops at 8 hours due to depressurization by opening ADV 100% and outside injection initiation. TDAFWP will stop working since at that time the operational conditions for TDAFP are not satisfied (not by batteries exhausted because we have recharger for batteries). The fire truck and supply water is ready after 8 hours, and then outside injection is deployed for cooling the system. Meanwhile, one ADV in each train is fully opened in this time to depressurize SGs. Primary and secondary pressure behaviors are shown in Fig's. 4 and 5.

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

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removed via secondary side by natural circulation and depressurization process. The calculation results for core collapsed level and cladding temperature are shown in Fig's 6 and 7.

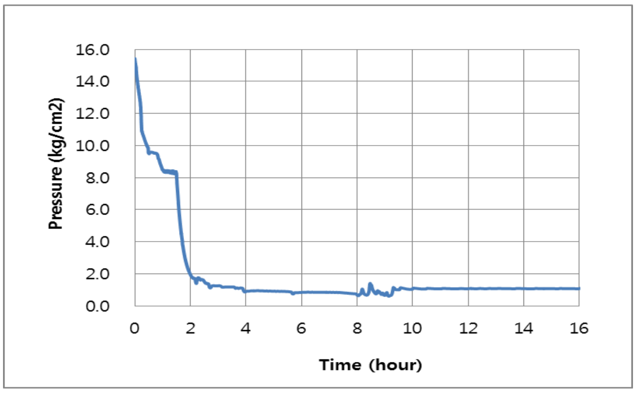

Fig.4. Primary side pressure with time

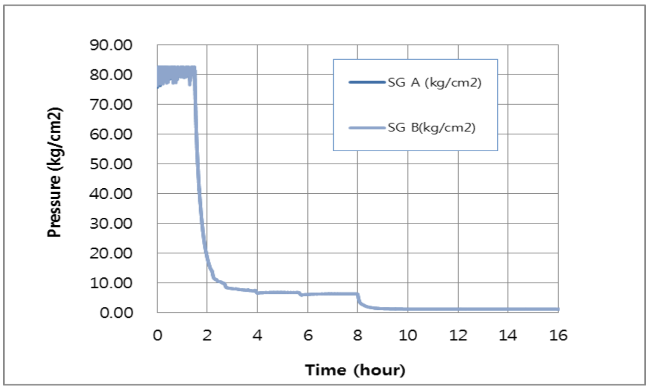

Fig. 5. Secondary side pressure with time

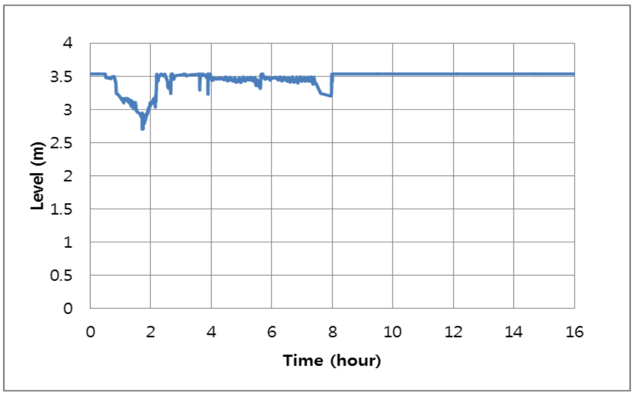

Fig. 6. Core water level

Before 8 hours, the calculated results for SG pressure and temperature were 0.63 MPa and 162°C, respectively. The RCS cool down rate was about 19°C/hr. These conditions are satisfied the requirements of current APR1400 emergency operation procedure (EOP).

After 8 hours, outside water injection starts for long term cooling with injection flow rate of 0.17kg/sec at 0.77 MPa for primary side and 0.04kg/sec at 0.63MPa for secondary side, respectively. These injection flow rates in case of APR1400

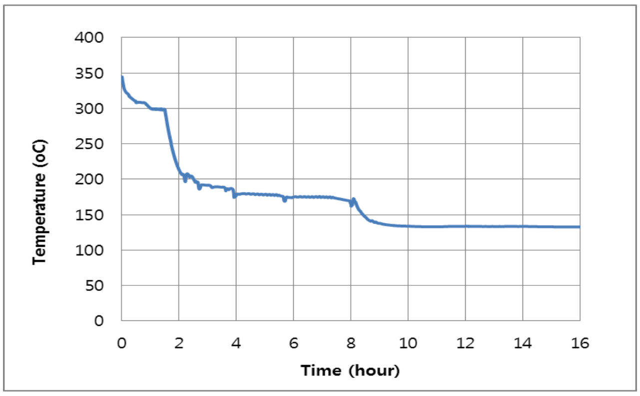

Fig. 7. Fuel cladding temperature with time

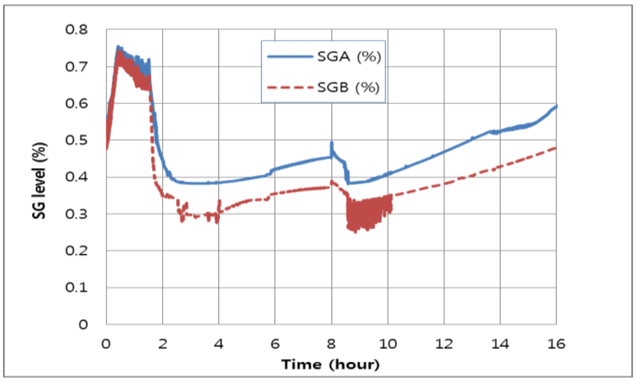

Fig. 8. SG water level

are corresponding with 34.5kg/sec at 0.77 MPa for RCS and 8.2 kg/sec at 0.63MPa for each SG, respectively. With these outside injection flow rates, the inventory of RCS and SG are maintained until 16 hours without any injection flow adjustment performed by operator. Fig. 8 shows the behavior of SG levels during the calculation time.

VI. CONCLUSION

- The inventory of RCS and SG are maintained until 16 hours without any injection flow adjustment performed by operator with outside injection flow rates of 34.5kg/sec at 0.77 MPa for RCS and 8.2 kg/sec at 0.63MPa for each SG, respectively.
- The mobile pump capacity is enough to mitigate the accident. In addition, pump's flow rate can be controlled during the mitigation times.
- The instrument will be functionable during the mitigation strategy with installed batteries and recharger.
- Water sources for outside injection are redundancy source, can be easily access.
- Outside injection will be accomplish by portable diesel driven pump and calculation shows that outside water source is sufficient for long term SBO. However, operators need to control the RCS and SGs level during outside injection time to avoid solid state of the systems.
- The extended SBO coping capability results in maintaining inventory and heat removal for primary and secondary side during in the presence of the

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reactor coolant pumps leakage. The bottom-line result from the analysis is that this mitigation strategy is suitable and applicable for coping with extended SBO scenarios.

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