Extended Station Blackout Analyses of an APR1400 with MARS-KS

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Abstract

The Fukushima Dai-ichi nuclear power plant accident shows that natural disasters such as earthquakes and the subsequent tsunamis can cause station blackout for several days. The electricity required for essential systems during a station blackout is provided from the emergency backup batteries installed at the nuclear power plant. In South Korea, in the event of an extended station blackout, the life of these emergency backup batteries has recently been extended from 8 hours to 24 hours at Shin-Kori 5, 6 and APR1400 for design certification. For a battery life of 24 hours, available safety means system, equipment and procedures are studied and analyzed in their ability to cope with an extended station blackout. A sensitivity study of reactor coolant pump seal leakage is performed to verify how different seal leakages could affect the system. For simulating of extended station blackout scenarios, the best estimate MARS-KS was used. In this paper, an APR1400 RELAP5 input deck was developed for station blackout scenario to analyze operation strategy by manually depressurizing the reactor coolant system through the steam generator's secondary side. Additionally, a sensitivity study was performed on reactor coolant pump seal leakage.

1. Introduction

Station blackout (SBO) is the complete loss of AC electric power to Class 1E and non-Class 1E switchgear buses. The SBO scenario involves the loss of offsite power (LOOP) concurrent with a turbine trip and failure of the onsite emergency diesel generators (EDGs). SBO does not include the loss of available AC power to buses fed by station batteries through inverters or the loss of power from alternate AC (AAC) sources. In the event of an SBO, a non-Class 1E AAC gas turbine generator (GTG) with sufficient capacity, capability, and reliability provides power for the set of required shutdown loads to bring the plant to safe shutdown [1, 2]. The accident at the Fukushima Dai-ichi nuclear power plants demonstrate the total loss of all AC power could be result from complete failures of both offsite and onsite AC power sources. If the ACC sources were not available in the event of SBO, only active equipment powered from station batteries, passive systems pressurizer relief valves, and safety valves were assumed to be available. An extreme natural disaster can prevent the proper restoration of electric power for several days, so-called extended SBO [3]. Following the complete loss of total alternate AC power, the reactor coolant pump (RCP) seals would lose their cooling support system, as the seal flow is lost. Component cooling water to the RCP would also be unavailable. Leakage of reactor coolant system (RCS) fluid through RCP seals would occur without makeup sources readily available, which may eventually lead to exposing the reactor core.

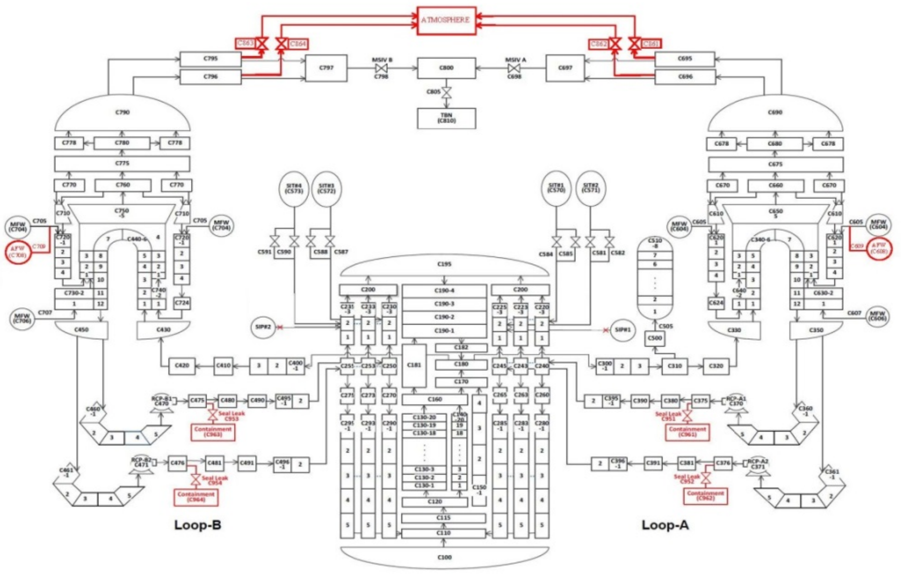


Figure 1. MARS nodalization diagram for extended SBO scenario

TABLE 1. Extended SBO scenario analyzed for RCS depressurization using ADV

Time (sec)	Event
0	SBO accident initiates
	TDAFWPs provide the water to SGs
*	MSSVs are opened to prevent over-pressure until ADVs are opened.
180	RCP seals fail.
1800	ADVs are manually opened for depressurization.
*	Safety injection tanks (SITs) injection is initiated.
28800	TDAFWS is unavailable due to out of station battery (8 hours).
	Severe accident analysis guideline initiates.

* It depends on the boundary condition

TABLE 2. Set of scenario analyzed for sensitivity study of RCP seal

	Seal leak rate per RCP (liters/s (gpm))	TD AFWP	ADV	MSSV
S21	1.325 (21)	On	10% open ~ 70% open	Yes
S120	7.57 (120)	On	10% open ~ 70% open	Yes

A sensitivity study of RCP is performed to verify how different seal leakages could affect the system. For simulating extended SBO scenarios, MARS-KS 1.4 version was used. This study will investigate the effect of RCP seal leakage, and operation strategy of manually depressurizing the secondary side using the atmospheric dump valves (ADVs).

2. Methodology Description

2.1 SBO Model Implementation

To analyze SBO scenarios, the nodalization of RELAP5 input deck for extended SBO was modified from an input deck for large break loss of coolant accident (LBLOCA) as is shown in Figure 1. To model RCP seal leakage, four valves are added in the discharge piping of RCP. The flow area of these valves was adjusted to set RCP seal leakage rate as stated in Table 1. It is assumed that the seal leakage flow rate is 1.325 liters/s, most probable flow rate per RCP [3] and the maximum seal leakage rate per RCP is described as 7.57 liters/s at 155.0 kg/cm^2 in the RCP technical manual of Shin-Kori 3 and 4 [4]. ADV and main steam safety valve (MSSV) flow area are sized as 138.6 kg/s at 70.31 kg/cm^2, 251.9 kg/s at 82.54 kg/cm^2 respectively [2]. Motor driven auxiliary feedwater pumps (AFWPs) and safety injection pumps (SIPs) are unavailable due to loss of electric power. The auxiliary feedwater (AFW) flow rate is determined based on turbine driven auxiliary feedwater pump (TDAFWP) design flow rate which is 41.0 liters/s [2]. The turbine driven auxiliary feedwater (TDAFW) flow control valve is powered by a DC battery and TDAFW flow rate is controlled to meet the steam generator (SG) level wide range. It is assumed that operators take 30 minutes to open the ADVs after the initiating extended SBO.

2.2 Extended SBO Scenario Analysis

The APR1400 has a three-phase approach for mitigating beyond design basis external events (BDBEEs). Phase 1 is the initial response phase using installed equipment, phase 2 is the transition phase using portable equipment and consumables, and phase 3 is the indefinite sustainment of these functions using offsite resources. Given the aforementioned parameters, the APR1400 will consider the following event sequence to address diverse and flexible coping strategy (FLEX) for full-power operation. Phase 1 is determined to go from 0 to 8 hours [2].

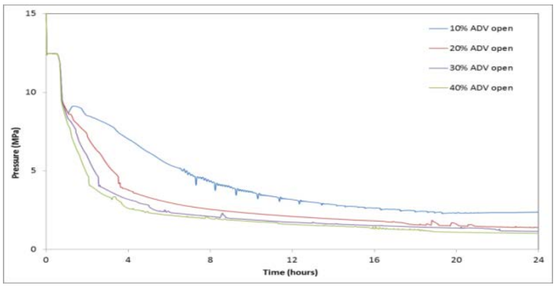
After the extended SBO is initiated, operators follow the operation strategies using installed equipment during phase 1. Two TDAFW pumps automatically start on auxiliary feedwater actuation signal (AFAS) to provide core cooling through the SGs for the station battery life [2]. TDAFW pumps take suction from auxiliary feedwater storage tanks (AFWSTs). Steam generated in the SGs is released through the MSSVs. Class 1E batteries supply direct current (DC) power to essential instrument and control (I&C) equipment, and for the operation of the TDAFW pumps. The RCS is maintained at hot standby condition by natural circulation without any operator action during this phase.

The RCP seals can maintain their function for a maximum of 30 minutes if seal leak-off valves are manually closed within 1 minute following the simultaneous loss of seal injection and cooling water. Based on the emergency operation procedure (EOP), closing the leak-off valves within 1 minute is highly unlikely. It is assumed that RCP seals fail 3 minutes after the extended SBO is initiated [4].

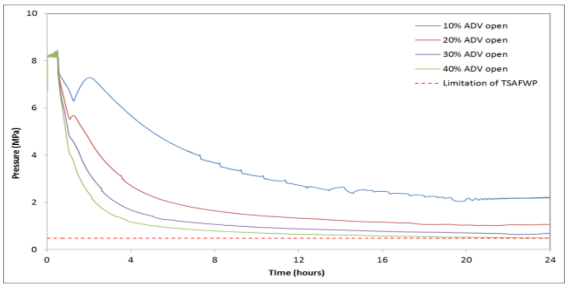
Based on the SBO mitigation operation, the water from SIT is not available since pressure of RCS is maintained higher than the head of SIT. For external injection, a portable generator provides electricity to open the pilot operated safety and relief valves (POSRVs) due to the high pressure difference. Once POSRVs are opened, the inventory of RCS will rapidly decrease. Once the POSRVs are opened, it is hard for the operator to take action to mitigate core uncovering.

2.3 Numerical Model of Extended SBO

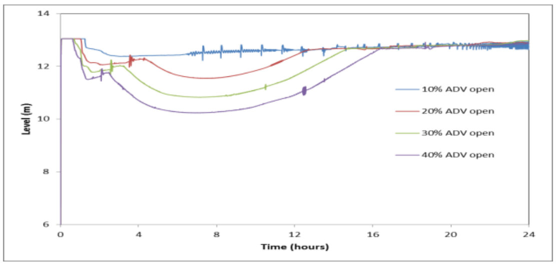
During phase 1, the operator should consider that taking actions to cool down the RCS and SG using available sources. Once the pressure of the primary side has decreased to less than the pressure of SITs, water from.



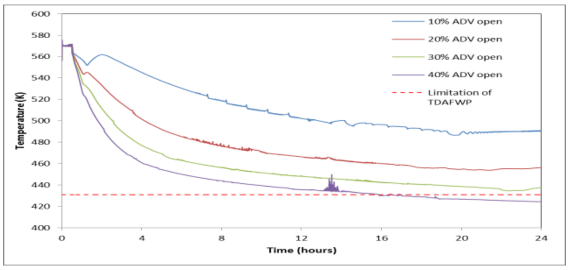
(a) RCS pressure



(b) SG pressure

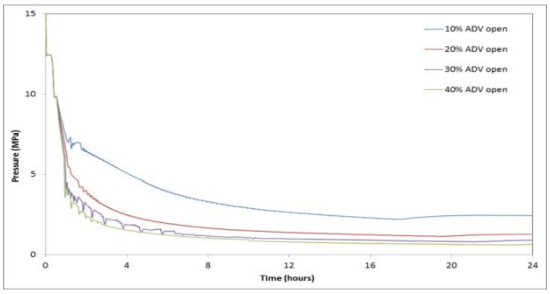


(c) SG level

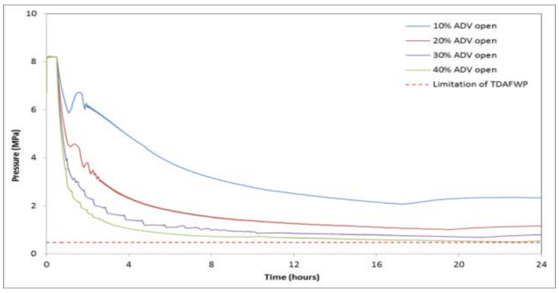


(d) SG temperature

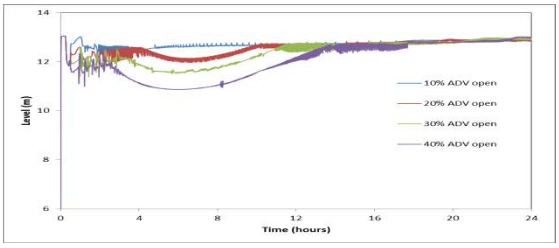
Figure 2. SG secondary depressurization of S21



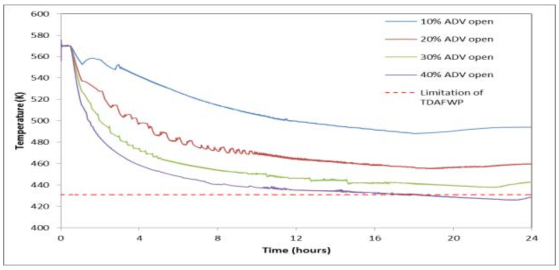
(a) RCS pressure



(b) SG pressure



(c) SG level



(d) temperature

Figure 3. SG secondary depressurization of S120

SITs can be injected to RCS. The SITs contain borated water pressurized by nitrogen cover; which constitutes the passive injection system since no operator action or electrical signal is required for operation. Each SIT contains borated water to a maximum of 2.5 weight boric acid that is 4,400 ppm and minimum of 2,300 ppm [2]. In this calculation, minimum of boric acid (2,300 ppm) is applied. In the event of extended SBO, water from the SITs could be the only source that is available to passively operate until external injection or restoration of electricity is available.

In the primary side, the water from SIT is injected to RCS and water from RCS is leaked through RCP seal. In the secondary side, water from the TDAFW is provided to the SGs for life of the batteries and the steam from the SGs is discharged to ADVs.

Therefore, by opening the ADVs, providing water using TDAFW and releasing the steam from SG through ADVs operation is available in secondary side. The cooldown rate depends on ADV opening size and AFW flow rate. As high feedwater provided to SGs and high releasing flow rate through the ADVs result in increased cooldown rate of RCS and SGs. Based on EOP, SG level should be maintained between 25 ~ 88 % (wide range). The operation condition of TDAFWPs requires supplying steam pressure and temperature which is from 4.92 kg/cm^2, 157.7 ℃ to 85.77 kg/cm^2, 298.8℃.

In primary side, the borated water from SIT is injected to RCS that providing core cooling to minimize fuel damage following a core uncover. Based on RCP technical manual, the maximum seal leakage of RCP can be 7.57 liters/s. The sensitivity study of RCP seal leakage performed from the most probable seal leakage flow rate to the maximum RCP seal leakage (3.155 liter/s, and 7.57 liters/s) is shown in Table 2. Different seal leakage rate per RCP is assumed in sensitivity study with TDAFWPs assumed to be available for batteries life. The leakage area is modeled by assuming that the density of water was 754.15 kg/m^3 and normal operation pressure and temperature were 15.5 MPa, 561K.

3. Results and Discussion

3. Effectiveness of Station Battery Extension

Recently design changes have station battery life extended from 8 hours to 24 hours and have been applied to NRC DC and Shin-Kori 5 and 6 nuclear power plant project. To evaluate the extension of battery life, three operation limitations are considered. First, TDAFW pump can be operated with the steam condition from 4.92 kg/cm^2, 157.7 ℃ to 85.77 kg/cm^2, 298.8℃. Second, the operator keeps the SG level between 25 and 88 % that is wide range of SG level. Third, the RCS cooldown rate limitation is less than 311 K/hour (100 ℉/hour). All scenarios meet the RCS cooldown rate limitation.

Figures 2 and 3 show the impact of depressurization on the RCS pressure for 24 hours in case of S21 and S120 respectively. The RCS pressure shown in 2 (a), and 3 (a) closely follows the secondary side depressurization. In figure 2 (b), the SG pressure of 40% ADVs open case is lower than the limitation of minimum operating pressure of TDAFW pump. In figure 2 (c), SG level of 10%, 20% ADVs open case is maintained higher than maximum wide range of SG level. 30% and 40% ADVs open case are acceptable since the operator maintain the SG level between 25 and 88 %. In figure 2 (d), the SG temperature of 40% ADVs open case is decreased lower than the limitation of minimum operating temperature of TDAFW pump. Therefore, operating range to depressurize the secondary side is determined to 30% ADV open scenario and 40% ADVs open scenario is acceptable until 13.6 hour that meeting the requirement of the maximum SG level in case of S21.

Based on the figure 3, to meet the limitation of TDAFW pump, 10%, 20%, 30% ADVs open scenario are not acceptable since the SG level is maintained higher than the maximum SG level. It is determined that operating range to meet the limitations is 40% ADVs open scenario until 9.84 hours in case of S120.

4. Conclusions

Based on the analyse, among opening ADVs, high operating pressure, RCP seal leakage, opening the ADVs has the greatest impact on the extended SBO scenario.

Different RCP seal leakage are relatively minor impact on the extended SBO analysis.

Based on the sensitivity study of RCP seal leakage, the operation procedure is developed with the expected magnitude of RCP seal leakage during the event of extended SBO.

The results show that injecting water using turbine driven auxiliary feedwater system with RCS depressurization through the SG secondary side is beneficial to delay core uncovery, heat up and effective means for external injection.

The results suggest that developing an optimum strategy to maintain core cooling during extended SBO scenarios should consider the operating condition of TDAFW pump, SG operating level, RCS cooldown rate.

The extension of station battery life strengthens the extended SBO mitigation capability and provide safe margin to bring the plant to safe condition as long as the integrity of the battery is maintained.

References

[1] U.S. NRC, “Station Blackout,” Regulatory Guideline 1.155, 1988

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[3] S. W. Lee., T. H. Hong., M.R Seo,. Extended Station Blackout Coping Capabilities of APR1400, Science and Technology of Nuclear Installations vol 2014, Article ID 980418, 25 May 2014.

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