EXTENDED STATION BLACKOUT ANALYSES OF AN APR1400 WITH MARS-KS

by

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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 electric energy required for essential systems during a station blackout is provided from 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 extended station blackout scenarios, the best estimate MARS-KS computer code 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 on reactor coolant pump seal leakage was carried out.

Key words: extended station blackout, station battery, reactor coolant pump seal leakage, MARS-KS

INTRODUCTION

Station blackout (SBO) is the complete loss of alternative current (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 (EDG). 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 demonstrates that the total loss of all AC power could be a result of the complete failure of both offsite and onsite AC power sources. If ACC sources were not available in the event of a SBO, only active equipment powered from station batteries, passive systems pressurizer relief valves and safety valves are assumed to be available. An extreme natural disaster can prevent the proper restoration of electric power for several days, so-called extended SBO [3, 4].

Following the complete loss of total AAC 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.

The results [5] indicate mitigation measures against extended SBO sequences with 8 hours of station battery life and evaluate the external injection into the RCS and steam generator (SG) before RCS and SG dryout. The overall extended SBO coping capability of the APR1400 is examined to assess the effectiveness of external water injection.

The study [6] investigates the optimal mitigation procedure using external emergency injection into the RCS and SG in the event of a SBO with a conservatively assumed RCP seal leakage. The analysis is done up to 12 hours after the initiation of SBO. The effectiveness of external emergency injection is evaluated as a key feature of the procedure.

The study [7, 8] dealing with Krsko two-loop pressurized water reactor station blackout scenarios performed station blackout analyses up to 7 days or the heat up of the core up to 1500 K using RELAP5/MOD3.3.

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These scenarios were analyzed with depressurization to specified SG pressure with different RCP seal leakages.

Results [9, 10] show that the importance of the SBO initiating event in assessing the implications of strengthening the SBO mitigation capability for the safety of the nuclear power plant is based on probabilistic safety assessment (PSA). The analysis was carried out with different operable times of the turbine-driven auxiliary feedwater system.

In this paper, a sensitivity study of RCP is performed to verify how different seal leakages could affect the system. For simulating extended SBO scenarios, the MARS-KS 1.4 version was used. The backbones of the MARS-KS 1.4 are RELAP5/MOD3 [11] and COBRA-TF [12] codes which constitute the bases of 1-D and 3-D modules of the MARS code, respectively. New features in RELAP5/MOD3.2.2 have been implemented in MARS-KS 1.4. In the present work, only the 1-D module is used.

This study investigates the effectiveness of station battery extension with different RCP seal leakages, the effect of different safety injection tank (SIT) operating pressures, RCP seal leakage, and operation strategy of manually depressurizing the secondary side using atmospheric dump valves (ADV).

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

Time [s]	Event
0	SBO accident initiates
	TDAFWP provide the water to SG
*	MSSV are opened to prevent over-pressure until ADV are opened
180	RCP seals fail
1800	ADV are manually opened for depressurization
*	Safety injection tanks (SIT) injection
28800	TDAFWS is unavailable due to put of station battery (8 hours)
	Severe accident analysis guideline initiates

* It depends on the boundary condition

METHODOLOGY DESCRIPTION

SBO model implementation

To analyze SBO scenarios, the nodalization of the RELAP5 input deck for an extended SBO was modified from an input deck for a large break loss of coolant accident (LBLOCA) used in APR1400 analyses, as shown in fig. 1. For more information on the MARS-KS code, the reader can refer to [13]. To model RCP seal leakage, four valves were added to the discharge piping of RCP. The flow area of these valves was adjusted to set the RCP seal leakage rate as stated in tab. 1. It is assumed that the seal leakage flow rate is 1.325 l/s, the most probable flow rate per RCP [14] and the maximum seal leakage rate per RCP is described as 7.57 l/s at 15.2 MPa in the RCP technical manual of Shin-Kori 3 and 4 [6].

ADV and main steam safety valve (MSSV) flow area are sized as 138.6 kg/s at 6.895 MPa, 251.9 kg/s at 8.09 MPa, respectively [2].

Motor driven auxiliary feedwater pumps (AFWP) and safety injection pumps (SIP) are unavail-

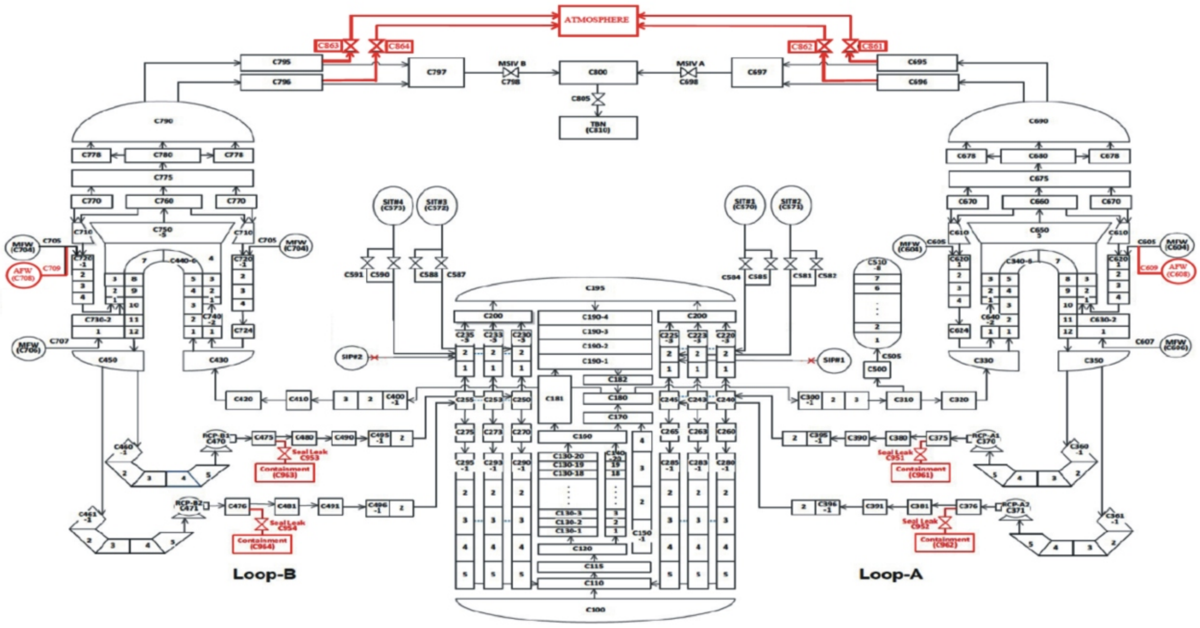

Figure 1. MARS nodalization diagram for extended SBO scenario of NPP with APR1400

able due to loss of electric power. The auxiliary feedwater (AFW) flow rate is determined based on the turbine driven auxiliary feedwater pump (TDAFWP) design flow rate which is 41.0l/s [3]. 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) water level wide range. It is assumed that it takes operators 30 minutes to open the ADV after the initiating extended SBO.

Extended SBO scenario analysis

The APR1400 has a three-phase approach for mitigating external events (BDBEE) beyond the design basis. Phase 1 is the initial response phase using installed equipment, phase 2 is the transition phase using portable equipment and consumables, phase 3 the indefinite sustainment of these functions using offsite resources. The initial phase requires the use of installed equipment and resources to maintain or restore core cooling, the containment function, and spent fuel pool (SFP) cooling capabilities.

The transition phase requires providing sufficient, portable, onsite equipment and consumables to maintain or restore these functions. The initiating event is assumed to be a loss of offsite power (LOOP) with a concurrent loss of all AC power and loss of ultimate heat sink (LUHS) during full-power operation. Given the afore mentioned parameters, the APR1400 will consider the following event sequence to address a diverse and flexible coping strategy (FLEX) for full-power operation. Phase 1 is determined to go from 0 to 8 hours [3].

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

RCP seals can maintain their function for a maximum of 30 minutes if seal leak-off valves are manually closed within one 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 [6].

Current extended SBO coping procedure

After the extended SBO is initiated, RCS pressure will begin to decrease due to control rod insertion followed by maintaining the pressure by no heat being released through the SG.

SG pressure will increase because of the turbine trip, until it reaches the setpoint of the MSSV. MSSV are opened to prevent the main streamlines from overpressurizing. RCS pressure will rapidly decrease as a result of heat transfer to the SG. TDAFW flow rate will continuously decrease as the decay heat decreases.

However, if the operator's action to recover the existing electric power is not successful until battery exhaustion time, the TDAFW system is terminated. Consequently, the reactor core starts to boil off after SG inventory dries out and, eventually, the RCS inventory is depleted. If the restoration of electric power is not successful, mitigation measures are not available.

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

Numerical model of extended SBO

During phase 1, the operator should consider 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 SIT, water from the SIT can be injected into the RCS. The SIT contain borated water pressurized by a nitrogen cover which amounts to a passive injection system since no operator action or electrical signal is required for the operation.

Each SIT contains borated water to a maximum of 2.5 weight percent boric acid of 4,400 ppm and a minimum of 2,300 ppm [2]. In this calculation, the minimum of boric acid (2,300 ppm) is applied. The SIT are pressurized to a nominal pressure of 4.21 MPa for normal operation. The design pressure of SIT is 4.82 MPa, their design temperature 93.3 °C.

In the event of an extended SBO, water from the SIT could be the only source available to passively operate until external injection or restoration of electricity is available. At the primary side, the water from the SIT is injected into the RCS, while the water from the RCS is leaked through the RCP seal. At the secondary side, water from the TDAFW is provided to the SG to sustain battery life and the steam from the SG discharged to ADV.

Therefore, by opening the ADV, providing water using TDAFW and releasing the steam from SG through the operation of ADV, is available at the secondary side. The cool-down rate depends on the ADV opening size and AFW flow rate as high feedwater provided to SG and the high release flow rate through the ADV result in an increased cool-down rate of RCS and SG. Based on EOP, the SG water level should be maintained between 25 % ~ 88 % (wide range). The operating condition of TDAFWP requires supplying steam pressure and temperature ranging from 0.482 MPa, 157.7 °C to 8.41 MPa, 298.8 °C.

At the primary side, the borated water from SIT is injected into the RCS, providing the cooling of the core to minimize fuel damage following its uncovering. Based on the RCP technical manual, the maximum seal leakage of a RCP can be 7.57 l/s.

The sensitivity study of RCP seal leakage performed for the most probable seal leakage flow rate to the maximum RCP seal leakage (3.155 liter/s, 4.732 liters/s, 6.31 liters/s, and 7.57 liters/s) is shown in tab. 2. A different seal leakage rate per RCP is assumed in the sensitivity study with TDAFWP assumed to be available for battery life (8 hours). The leakage area is modelled by assuming that the density of water was 754.15 kg/m^3 and normal operation pressure and temperature were 15.5 MPa, 561 K, respectively.

During phase 2, RCS depressurization is prerequisite, since the external injection pump shutoff head is relatively low [2]. Essentially, to depressurize the RCS, the preparation of an external power generator is required since the POSRV cannot be opened manually due to the inaccessibility of the inside of the containment. If a portable power generator is in place, the operator opens two out of four POSRV 30 minutes after the severe accident analysis guideline (SAMG) entry condition because the power generator can provide only one of two electric trains. Then SAMG mitigation-3 (injection into RCS) initiates [15].

RESULTS AND DISCUSSION

Base extended SBO case analysis

Thirty-four calculations are performed for five scenarios at seven different SG depressurizations, as shown in tab. 2.

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

Scenario	Seal leak rate per RCP [l/s (gpm*)]	TD AFWP	ADV	MSSV
S21	1.325 (21)	On	10 % open ~70 % open	Yes
S50	3.155 (50)	On	10 % open ~70 % open	Yes
S75	4.732 (75)	On	10 % open ~60 % open	Yes
S100	6.31 (100)	On	10 % open ~70 % open	Yes
S120	7.57 (120)	On	10 % open ~70 % open	Yes

*gpm: gallon per minute

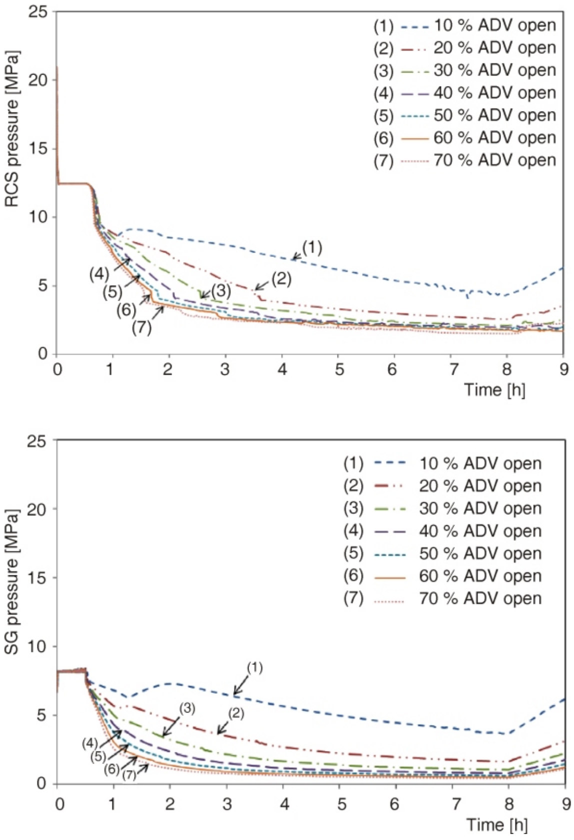

Figure 2. RCS and SG pressure as function of depressurization –S21

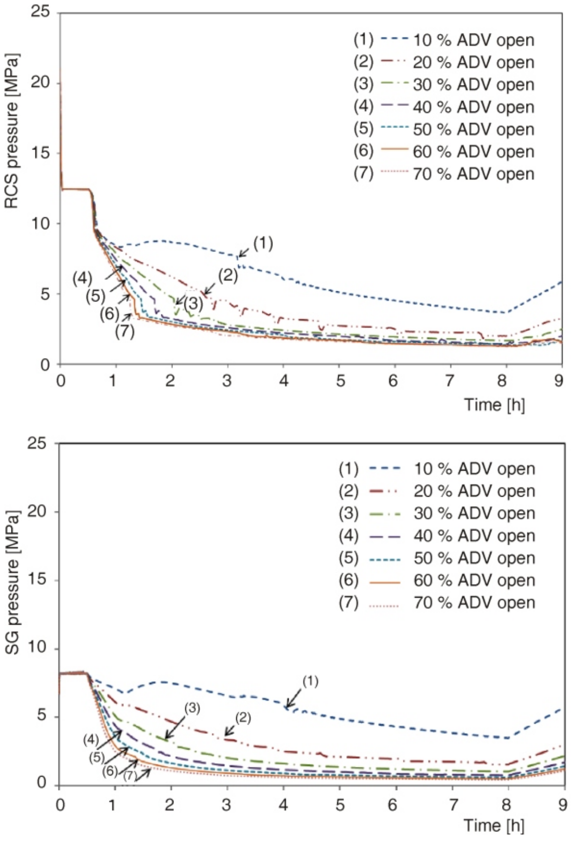

Figure 3. RCS and SG pressure as function of depressurization – S50

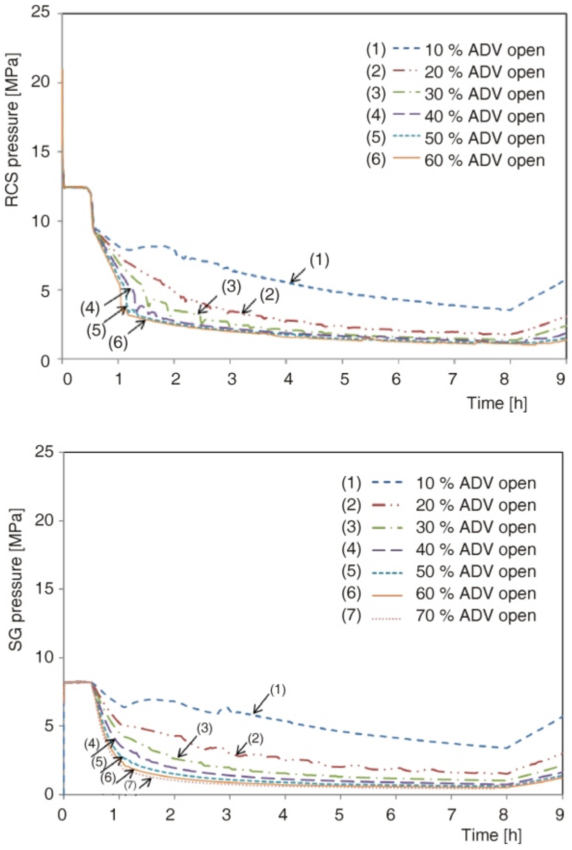

Figure 4. RCS and SG pressure as function of depressurization – S75

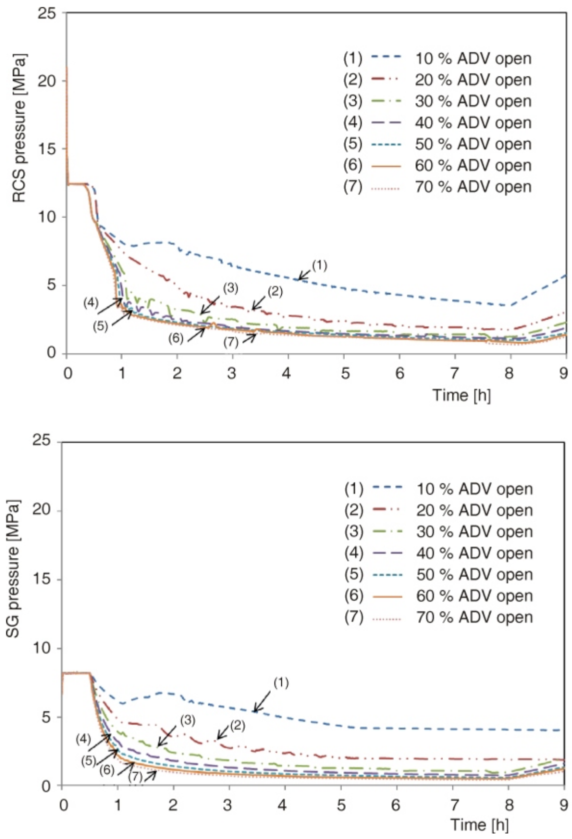

Figure 5. RCS and SG pressure as function of depressurization – S100

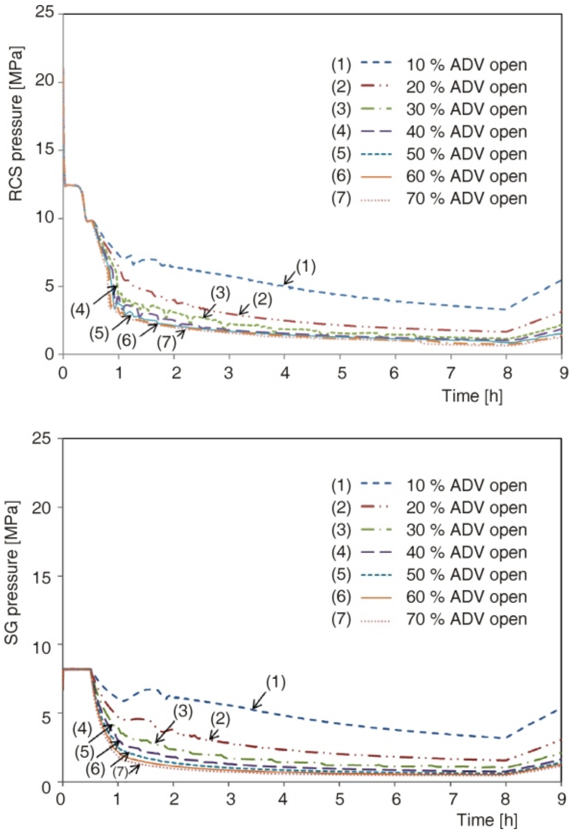

Figure 6. RCS and SG pressure as function of depressurization – S120

Figures 1 through 6 represent the impact of depressurization in an extended SBO as a function of the ADV opening size in case of different RCP seal leakages and the impact of the RCP seal break size in an extended SBO. RCS local pressure drops in figs. 2, 4, 6, 8, and 10 mean that the water from the SIT is being injected into the RCS at the time. When RCS pressure is lower than 40.3136 10^5 Pa, the borated water from the SIT is injected into the RCS. As soon as the water from the SIT is injected, SIT pressure drops due to the volume expansion of the covered nitrogen gas whereupon the SIT injection is stopped until the RCS pressure is lower than the pressure of SIT.

The analysis of different SIT operating pressures only performed scenario S21 described in tab. 2, since the probable RCP seal leakage is applied and in viewpoint of RCS pressure, scenario S21 is the most conservative case [5]. The leak flow rate from the RCP seal is small in comparison to the water from the SIT that cannot be injected into the RCS. ADV opening size has a considerable influence on RCS pressure.

Therefore, the conclusion is that the effect of borated water from the SIT is less effective than depressurizing the RCS through the secondary side, since the SIT injection with high pressure keeps RCS pressure higher than 4.41 MPa, 4.3 MPa, 4.29 MPa, and 4.51 MPa in case of S21 for 8 hours. However, RCS pressure was not decreased to lower than the shut off pressure of the external injection pump of 1.5 MPa

[5]. By opening the ADV 80 %, only in one instance can the RCS pressure be decreased to 1.44 MPa for 8 hours. The implementation of mitigation procedures should not to be based on a single case.

Effectiveness of station battery extension

Recent design changes have station battery life extended from 8 to 24 hours and have been applied to the NRC DC and Shin-Kori 5 and 6 nuclear power plant project. Detailed recommendations for strengthening the SBO mitigation capability for design basis and beyond it are referred to in [16].

To evaluate the extension of battery life, three operation limitations are considered. First, the TDAFW pump can be operated with the steam condition from 0.482 MPa, 157.7 to 8.41 MPa, 298.8. Second, the operator keeps the SG water level between 25 % and 88 %, i.e. within the wide range of the SG water level. Third, the RCS cooldown rate limitation is less than 311 K per hour (100 per hour). All scenarios meet the RCS cooldown rate limitation.

Figures 7, 9, 11, and 13 show the impact of depressurization on RCS pressure for 24 hours in case of S21, S50, S75, and S120, respectively. RCS pressure shown in figs. 7, 9, 11, and 13 closely follows the secondary side depressurization.

In fig. 7, in the case of 40 % ADV open, SG pressure is lower than the limitation of the minimum operating pressure of the TDAFW pump. In fig. 8, SG water level of 10 %, 20 % ADV open is maintained higher than the maximum wide range of the SG water level. Percentages of 30 % and 40 % ADV open are acceptable since the operator maintains the SG water level between 25 % and 88 %. In figure 8, the SG temperature of 40 % ADV open decreases below the limitation of the minimum operating temperature of the TDAFW pump.

Therefore, the operating range for depressurizing the secondary side is determined as the 30 % ADV open scenario in case of S21, while the 40 % ADV open scenario is acceptable up to 13.6 hours, satisfying the requirement of the maximum SG water level in fig. 8.

In figs. 9 and 10, it is determined that the operating range to meet the limitations is the scenario of 30 % ADV open up to 10.45 hours and 40 % ADV open up to 13.33 hours in the case of S50. In figure 10, SG water level is increased to the maximum SG water level at 10.45 hour in a 30 % ADV open scenario and at 13.33 hours in a 40 % ADV open scenario, respectively. In the 30 % ADV open scenario, the operator needs to control the TDAFW valve to decrease the flow rate or open ADV to decrease the SG water level before the 10.45 limit.

Based on figs. 11 and 12 for meeting the limitations of the TDAFW pump, the 10 % ADV open scenario is not acceptable. It is determined that the ac-

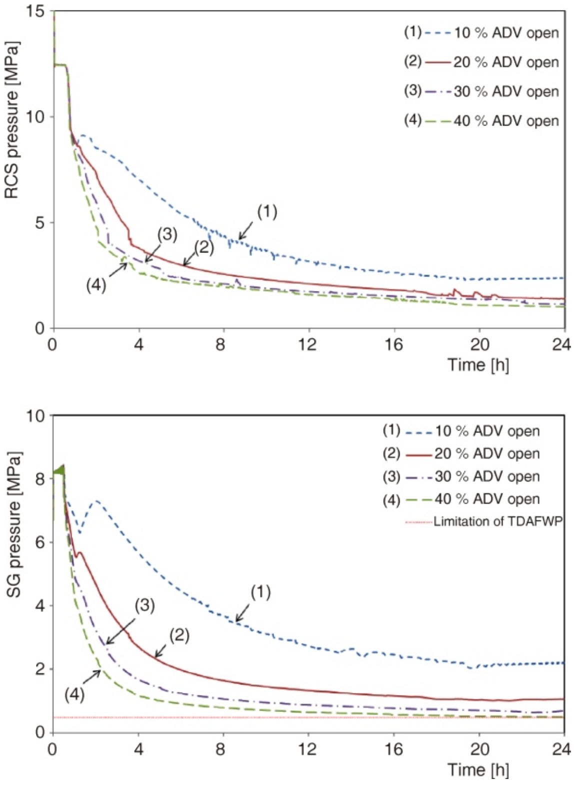

Figure 7. RCS and SG pressure as function of depressurization during 24 hours – S21

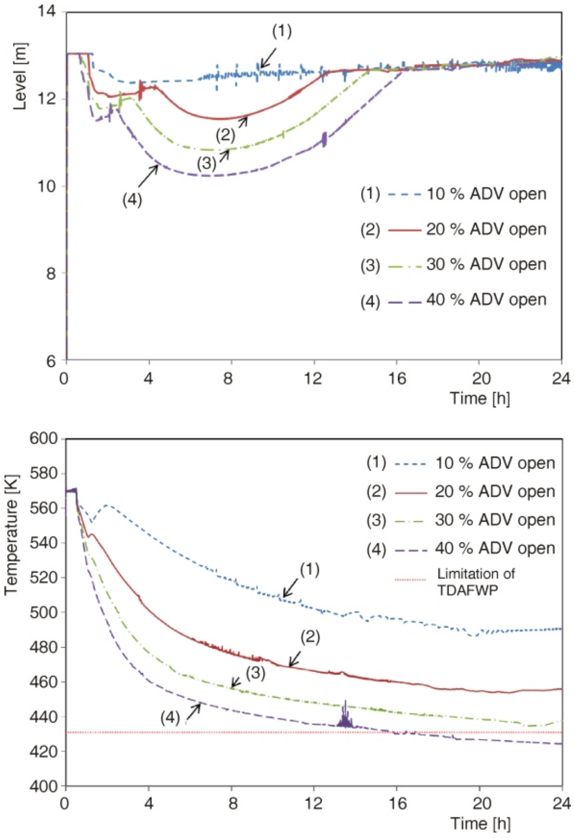

Figure 8. SG water level and temperature as function of depressurization during 24 hours – S21

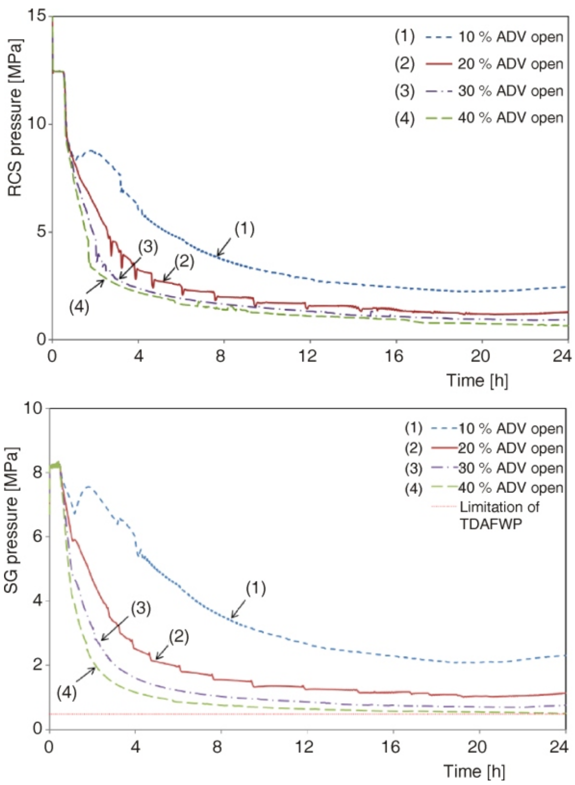

Figure 9. RCS and SG pressure as function of depressurization during 24 hours – S50

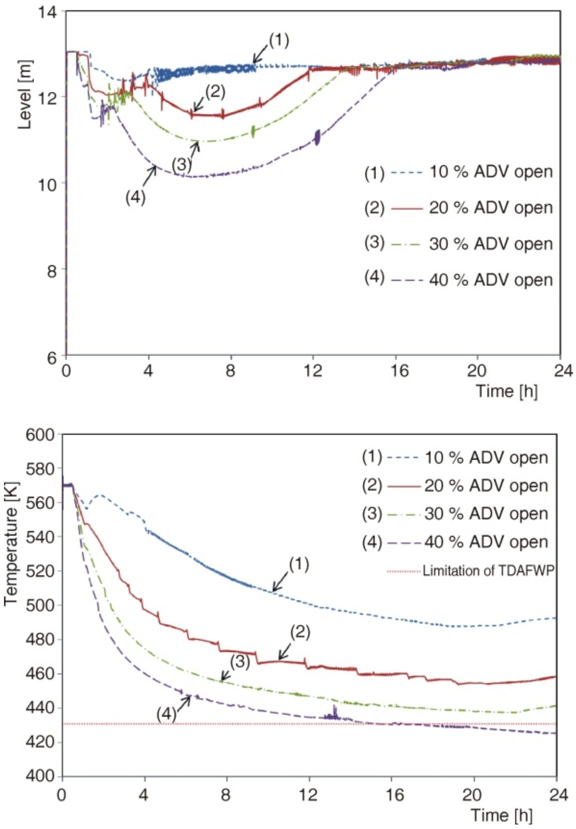

Figure 10. SG water level and temperature as function of depressurization during 24 hours – S50

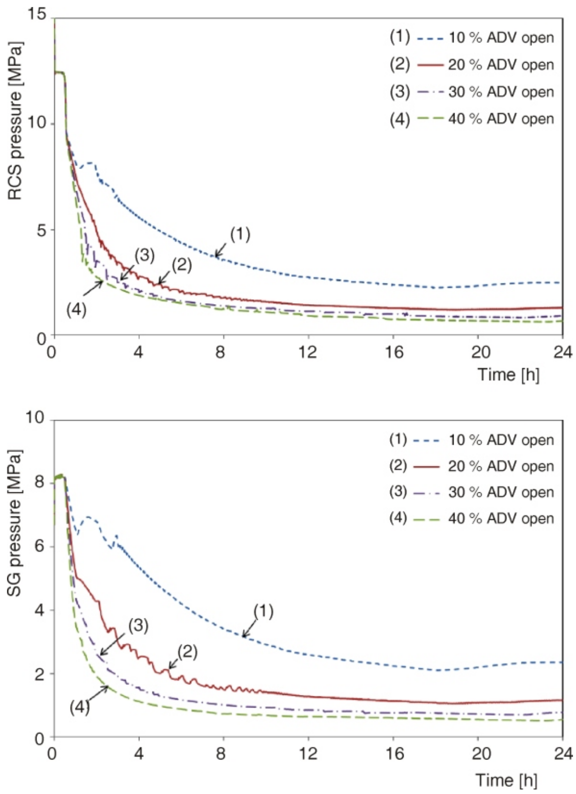

Figure 11. RCS and SG pressure as function of depressurization during 24 hours – S75

ceptable operating range is the 30 % ADV open scenario up to 10.18 hours and that of 40 % ADV open up to 10.99 hours in the case of S75.

Figures 13 and 14: to meet the limitations of the TDAFW pump, the 10 %, 20 %, 30 % ADV open scenarios are not acceptable since the water level is maintained higher than the maximum SG level. It is determined that the operating range to meet the limitations is the scenario of 40 % ADV open up to 9.84 hours in the case of S120.

CONCLUSIONS

Based on the results of our analyses, between the opening of ADV and RCP seal leakage, the impact of ADV on an extended SBO scenario is definitely the more significant one.

In the extended SBO, since the leak flow rate from the RCP seal is small, the borated water from SIT cannot be injected into the RCS based on the sensitivity study of RCP seal leakage, the operation pr developed procedure with the expected magnitude of RCP seal leakage during the event of an extended SBO.

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

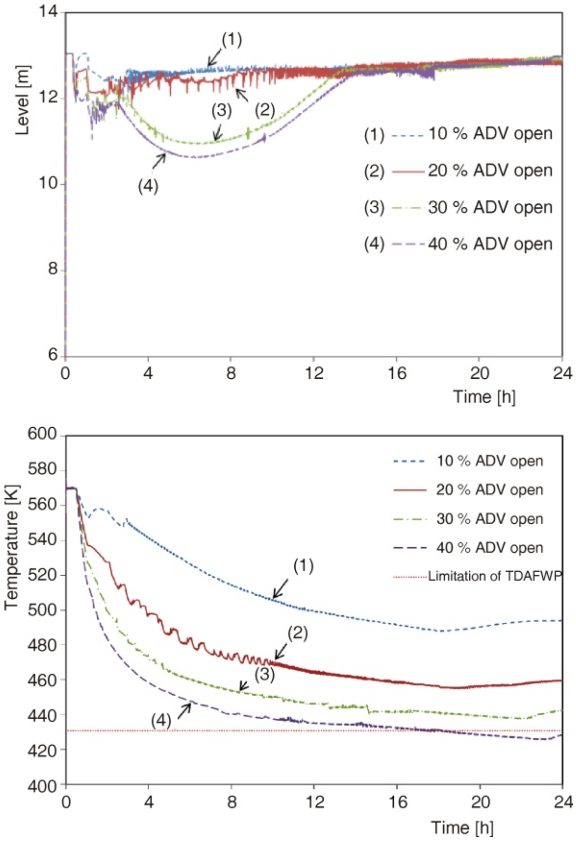

Figure 12. SG water level and temperature as function of depressurization during 24 hours – S75

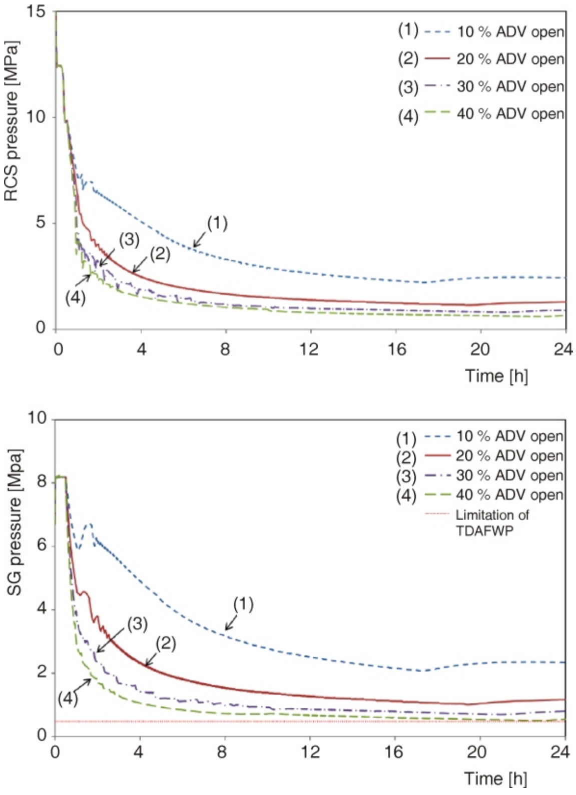

Figure 13. RCS and SG pressure as function of depressurization during 24 hours – S120

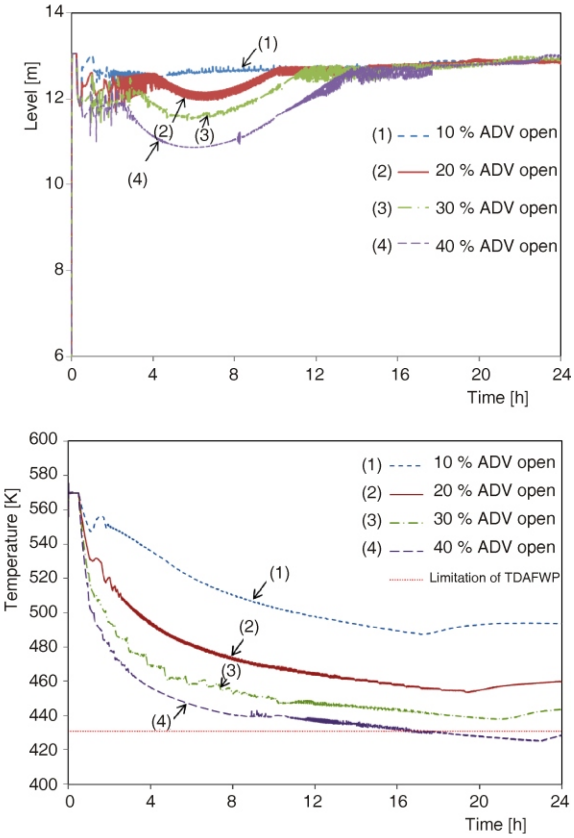

Figure 14. SG water level and temperature as function of depressurization during 24 hours – S120

These results suggest that developing an optimum strategy to maintain core cooling during an extended SBO scenario should scrutinize the operating condition of the TDAFW pump, SG operating water level and the RCS cooldown rate.

The extension of station battery life strengthens the mitigation capability of an extend SBO and provides a safe margin for restoring the safe operation of the plant, as long as the integrity of the battery is maintained.

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AUTHORS' CONTRIBUTIONS

W. Kim and H. Jang applied RELAP code simulations of Extended SBO scenarios to evaluate RCS depressurization through the SG secondary side. S. Oh initiated the research and guided the authors to the to the completion of the study, providing the review comment. S. Lee selflessly shared his insight and background knowledge of RELAP5. All authors analyzed and discussed the results.

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Вунгбае КИМ, Хјунгвук ЈАНГ, Сеунгјонг ОХ, Сангјонг ЛЕЕ

АНАЛИЗА ДУГОТРАЈНОГ НЕСТАНКА ЕЛЕКТРИЧНЕ ЕНЕРГИЈЕ У АПР1400 ПОМОЋУ MARS-KS КОДА

Акцидент у нуклеарној електрани Фукушима Даичи показује да природне непогоде као што су земљотрес и пратећи цунами могу изазвати вишедневни губитак електричне енергије. Електрична енергија потребна виталним системима током нестанка струје обезбеђује се помоћним генераторима постављеним у нуклеарној електрани. У Јужној Кореји, у случају нестанка електричне енергије, радни капацитет ових генератора продужен је са 8 часова на 24 часа у Шинкори 5 и 6 и АПР1400, ради сертификације дизајна. За случај дуготрајног нестанка електричне енергије, испитани су безбедносни системи, опрема и поступци и извршена је анализа могућности двадесетчетворочасовног радног капацитета генератора. Студија осетљивости цурења вентила пупме за хлађење реактора спроведена је како би се утврдио утицај различитих врста цурења вентила на систем. За потребе симулације дуготрајних губитака електричне енергије употребљен је програмски пакет MARS-KS. У овом раду развијен је улазни пакет података APR1400 RELAP5 за губитак електричне енергије у електрани како би се анализирала оперативна стратегија ручног снижавања притиска реакторског система за хлађење кроз секундарну грану парогенератора. Поред овога, обављена је и процена осетљивости цурења вентила пупме за хлађење реактора.

Кључне речи: дуготрајни губитак електричне енергије, батерија електране, цурење вентила пупме за хлађење реактора, MARS-KS