

A conceptual comparative study of FLEX strategies to cope with Extended Station Blackout (SBO)

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Abstract: The Fukushima Daiichi Nuclear Power Plant accident induced a new challenge to the nuclear society. To enhance the plant safety against the extended station blackout (SBO), Diverse and Flexible Coping Strategies has been considered. The main objective of this paper is to present a comparative study for a small mobile gas turbine generator (GTG) and a large mobile GTG to cope with extended SBO condition. In this study, a small mobile GTG is connected to the class 1E dc bus to recover dc power and battery charger before depletion of the station battery. In the same manner, a large mobile GTG is connected to the class 1E ac bus to recover ac power. PRA model of both cases are developed with simplification. Based on the comparative study results using conceptual simple modelling, the CDF of SBO is more effectively reduced by using the small mobile GTG. It shows the selection of the strategies under severe conditions is different from the selection under normal condition because of different environment.

Keywords: PRA, Extended SBO, mobile gas turbine generator (GTG), FLEX strategies, CDF.

1. INTRODUCTION

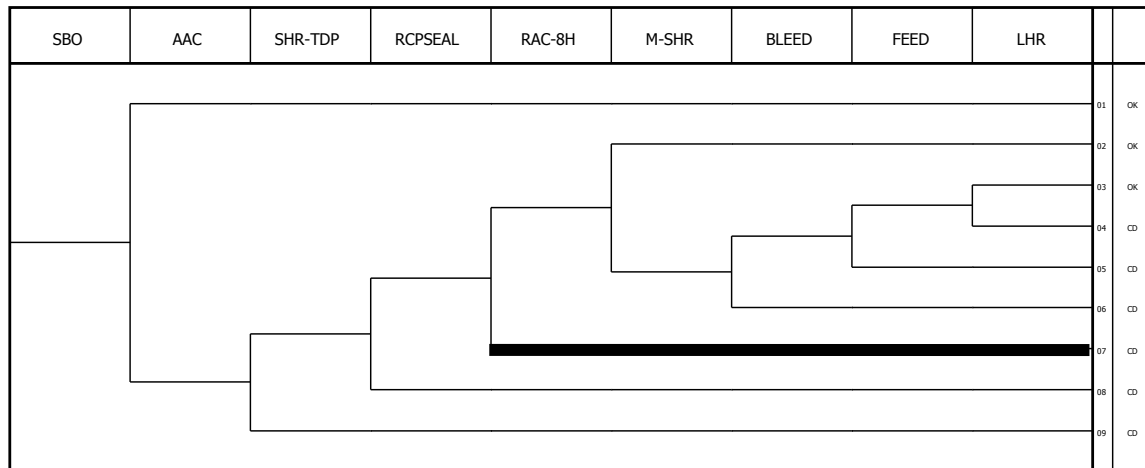
One of the primary lessons learned from the accident at Fukushima Dai-ichi [1] was the significance of the challenge presented by a loss of safety-related systems following the occurrence of a beyond-design-basis external event [2]. The nuclear safety is assured in all situations with the provision of the basic safety functions: control of reactivity, removal of decay heat to the ultimate heat sink, and confinement of radioactive materials [3]. According to the safety requirements, current nuclear power plant design can prevent core damage under SBO condition. However, core damage can occur under beyond-design-basis event, especially extremely severe external events like east Japan great earthquake.

The APR1400 [4] is a pressurized water reactor type with two reactor coolant loops which was designed by Korea Hydro and Nuclear Power (KHNP). The reactor has 1400 MWe core output rating. The APR1400 started to operate in Korea in 2016. The main design philosophy of the APR1400 is the enhancement of safety by using proven technologies and significant experiences gained in design, construction, maintenance, and operation of NPPs, especially OPR1000 units, in South Korea. The APR1400 design is adapted to meet applicable US regulatory requirements such as proven technology, constructability, maintainability, and regulatory stabilization.

In case of APR1400, SBO is the complete loss of ac 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). During an SBO, non-class 1E alternate alternating current diesel generator (AAC DG) and batteries will provide power for the set of required shutdown loads to bring the plant to safe shutdown. Figure 1 shows the typical SBO sequences. An AAC DG power is provided for the operation of the motor-driven auxiliary feed water pump (MDAFWP) during an SBO. Regardless of AAC DG operation, the auxiliary feedwater can be provided by the turbine driven auxiliary feed water pump (TDAFWP) with battery dc power. With procedural load management, the batteries can supply the needed control and instrumentation power for approximately eight (8) hours, and, therefore, lacking any other problems, initial plant cooldown can proceed for about eight hours without restoration of ac power. With loss of all station ac power, RCP seal cooling water will be lost, the seals will begin to degrade and gross seal leakage on the order of several hundred gpm may occur. Over the 8 hours, the loss of the TDAFWP may occur due to the battery depletion. If TDAFW pumps fail to start and deliver feedwater to the steam generators, secondary steam removal through the secondary safety valves or atmospheric dump valves will

continue until the steam generator boil dry. Primary pressure will rapidly rise and the POSRVs will open. Core uncovers and, thus, core damage will occur unless power is restored and auxiliary feed water flow is established. This situation, sequence-07 (bold line) in Figure 1, is called extended SBO that can occur if beyond-design-basis external event (BDBEE) exceeds the assumptions. In order to address these challenges, diverse and flexible mitigation strategies (FLEX) [1] could be used to enhance their ability to cope with BDBEE conditions.

Figure 1: SBO Event Tree for APR1400 [4]



The objective of this paper is to compare two FLEX strategies using mobile generators for mitigation of the extended SBO; small mobile GTG for recovery of dc power and instrumentation & control and large mobile GTG for ac power recovery.

2. DEVELOPMENT OF ACCIDENT SCENARIOS OF EXTENDED SBO WITH MOBILE GTG

The accident sequences with respect to the use of mobile GTG can represent its impact on the plant response given accident condition. In this study, given extended SBO, accident scenarios with small mobile GTG and large mobile GTG are developed to compare the effectiveness of mobile GTGs on the basis of core damage frequencies. The following factors are considered in accident scenario development for extended SBO mitigation strategy to use small mobile GTG and large mobile GTG:

- The environmental conditions hinder the deployment, timing, or implementation of the FLEX equipment. These conditions could include the failure of buildings and structures, or generation of debris that could obstruct access to areas. In the mitigating strategy, small mobile GTG significantly reduces the time required to alternate paths, pre-deployment, or removal of debris. Furthermore, small mobile GTG minimizes the amount of equipment required to be deployed, improves human factors, and facilitates timely restoration of dc power and vital control and instrumentation power.
- The functions of ac or dc power restored by mobile GTGs are different. Small mobile GTG can be connected to the connection box of 480 V of mobile generator to recover dc power and instrumentation & control. Also, large mobile GTG can be connected to a 4.16 kV ac class 1E bus.
- To compare mobile GTG strategies, makeup of RCS inventory loss by RCP seal leakage is not considered in this study. There is large uncertainty when RCP seal failure and consequent core damage occur. If recovery of RCS inventory after RCP seal failure is considered in this study, depending on the conservatism in the RCP seal failure modelling in PRA, the results of this study may be changed.

2.1. Development of Accident Sequence for Extended SBO by using Small Mobile GTG

SBO involves the loss of offsite power (LOOP) concurrent with a turbine trip and failure of the onsite emergency ac power system. During an SBO, a non-class 1E AAC DG with sufficient capacity provides power for the set of required shutdown loads (non-design-basis accident) to bring the plant to safe shutdown. But, if AAC DG is not available and dc battery is only available power source, the TDAFW pump provides feedwater to SG for 8 hours and, after 8 hours, the TDAFW pump is not available due to the depletion of battery. Small mobile GTG is connected to the class 1E dc bus to recover dc power for maintaining secondary heat removal. In addition, small mobile GTG can supply dc power to essential instrumentation and control (I&C) equipment for the operation of the TDAFWPs. Under this plant condition, reactor coolant pump (RCP) seals might fail due to loss of seal cooling and the loss of RCS inventory starts.

2.2. Development of Accident Sequence for Extended SBO by using Large Mobile GTG

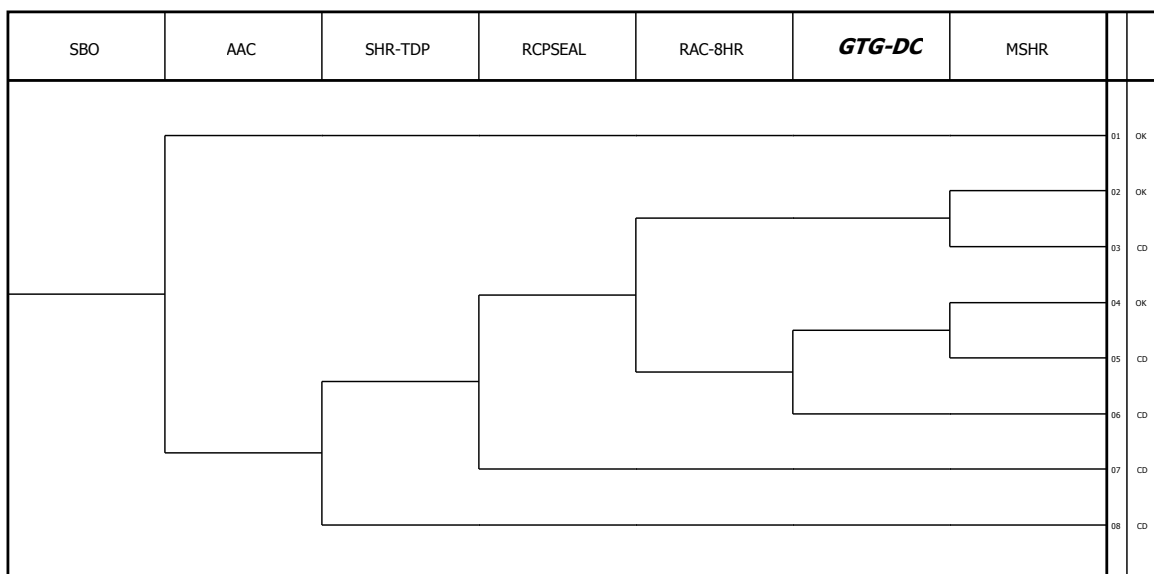
If AAC DG is not available and only dc battery is available power source, before the depletion of battery, class 1E ac power needs to be provided by large mobile GTG for maintaining the plant safety. Large mobile GTG is connected to a 4.16 kV class 1E ac bus. Loss of RCP seal cooling becomes also a challenge to reactor safety by loss of RCS integrity and RCS inventory.

3. MODELING MOBILE GTGs IN PRA

3.1. Modeling Small Mobile GTG

SBO affects plant followed by a failure of all permanent on site ac power sources (EDG and AAC). The FLEX equipment credited for this scenario includes small mobile GTG to recover the dc power and primary side FLEX pump to inject water into RCS inventory. The TDAFW pump is required for the first 8 hours of the scenario to provide sufficient time to deploy the FLEX equipment. Small mobile GTG is deployed and installed to the connection box of 480 V of mobile generator to recover dc power and instrumentation & control. Cable reel of small mobile GTG will be connected to the connection box of 480 V of mobile generator. The onsite diesel generator (EDG) fuel tanks are used as the source of fuel for the mobile GTGs. The capacity of the each EDG fuel tank allows the mobile GTG to operate at rated power for 7 days. The small mobile GTG is deployed at the front of EDG room. Operators can continue the cooldown and depressurization of the steam generators. Figure 2 shows scenarios with small mobile GTG.

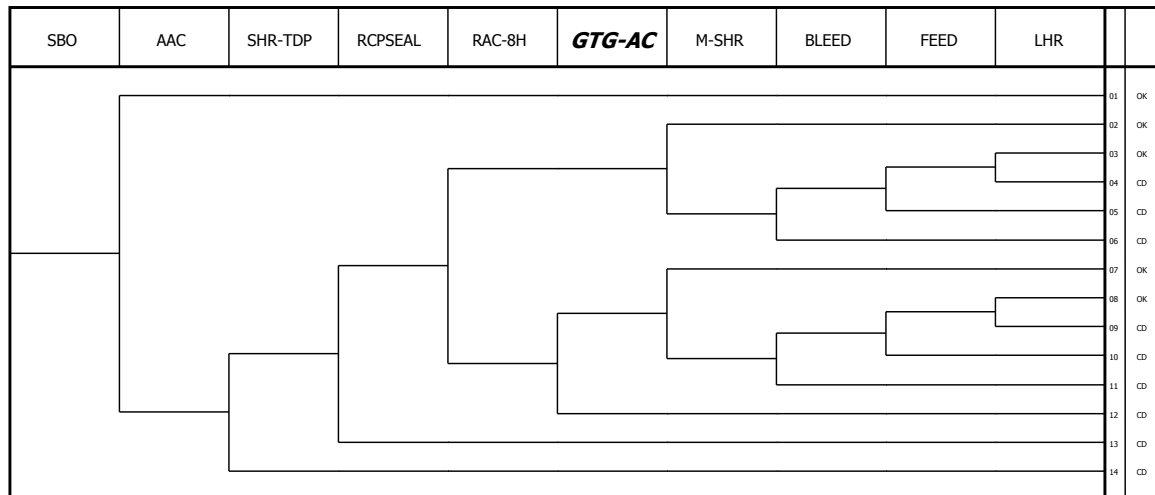
Figure 2: SBO Event Tree with Small Mobile GTG



3.2. Modeling Large Mobile GTG in PRA

The FLEX equipment credited for this scenario includes a large mobile GTG to recover the ac power and primary side FLEX pump to inject water into RCS. The TDAFW pump is assumed to be available for the initial coping phase of SBO, during which it maintains a heat sink to dissipate decay heat from the reactor core. Large mobile GTG is connected to the 4.16 KV class 1E ac bus. Cable reel of large mobile GTG is connected to the 4.16 KV switchgear train A or B. The ac power from large mobile GTG is aligned to 4.16 KV class 1E ac bus. Pre-operational check is required before re-energized the bus. The large mobile GTG is deployed to the front of EDG room. Figure 3 shows scenarios with large mobile GTG.

Figure 3: SBO Event Tree with Large Mobile GTG



3.3. Human Reliability Analysis in PRA

Human reliability analysis is an important aspect in this study to consider the possibility that the crew could make an error in responding to an accident using mobile equipment. In order to calculation of human error probability (HEP), the methods suggested by NEI 16-06 [5] are employed. The cognitive portion is analyzed by cause-based decision tree method (CBDTM), and execution portion is analyzed by technique for human error rate prediction (THERP) method.

Human actions associated with portable equipment include: diagnosis time associated with entering procedures to use portable equipment, potential for debris removal that make the travel path more difficult, transportation and staging of portable equipment, installation of hoses or cables, pre-operational checks after equipment staged installation of portable equipment, and energized bus from portable equipment. In time window analysis, as long as these actions are completed within about 8 hours from the start of the SBO, the steam generators will not overflow or boil dry. It is assumed that after 8 hours the mobile GTG is not effective to mitigate accident.

- $T_{\text{system time window}} = 480$ minutes.
- $T_{\text{delay}} = 60$ minutes. It is the duration of time to diagnose the situation and begin the deployment of the mitigating strategies equipment, measured from the time of initiating event.
- $T_{\text{cog}} = 30$ minutes. It includes the time for operators to receive enough indication, evaluate the written instructions, and take any necessary preparatory actions to begin the deployment actions.
- $T_{\text{exe}} = 150$ minutes. It covers deployment of mobile GTG, staged installation, pre-operational check, start of operation, and re-powering the bus. The time can be increased to account for using spared equipment due to possible failure of equipment.
- Time Margin for Action = $480 - 60 - 30 - 150 = 240$ minutes

Detection, diagnosis, and decision making phase of procedure guides are included in the cognitive portion of the human error probability [6]. To facilitate the identification of Pc is made into failures of the plant information-operator interface and failures of the operator-procedure interface. The Pc process includes identifying clear cues to enter the procedure, clear direction within the procedure on the steps required, and training to be performed. The analysis of execution portion of human error probability (Pexe) includes aspects such as deployment and staging of portable equipment, installation of hoses or cables, pre-operational checks, and re-energized of bus from portable equipment. Errors of omission and errors of commission with performance shaping factors are considered in each part of instruction (action) [7]. Cognition and execution portions of HEP calculation for mobile GTG are shown in Table 1.

Table 1: The Human Error Probability (HEP) of Mobile GTG

	Pc	Pexe	Total HEP
Small Mobile GTG	2.90E-04	1.96E-02	1.99E-02
Large Mobile GTG	2.90E-04	5.06E-03	5.35E-03

3.4. Data Analysis of Mobile GTG

There is no failure data available for portable equipment, while there are adequate sources of generic failure rates for permanently-installed equipment at nuclear power plants. However, there is data on similar type of portable equipment in NUREG/CR-6928 [8] and other sources [9, 10]. In this study, failure probability of diesel generator and combustion turbine generator are used as failure probability of small mobile GTG and large mobile GTG, respectively. The applied data related to mobile GTG are shown in Table 2.

Table 2: Failure Data of Mobile GTGs

Basic Event	Description	Probability	Data Source
GTTGL-L-GTG	Large GTG fails to run for 1 hour	5.79E-03	NUREG/CR-6928
GTTGM-L-GTG	Large GTG unavailable due to maintenance	5.00E-02	NUREG/CR-6928
GTTGR-L-GTG	Large GTG fail to run	8.49E-03	NUREG/CR-6928
GTTGS-L-GTG	Large GTG fails to start	5.12E-02	NUREG/CR-6928
GT-LGTG-REEL	Failure of large GTG cable reel	1.20E-06	NUREG/CR-3263
GT-GTG-DEPLOY	Failure of small GTG deploy and stage	1.12E-04	NEI 16-06
GTTGL-S-GTG	Small GTG fails to run for 1 hour	3.72E-03	NUREG/CR-6928
GTTGS-S-GTG	Small GTG fails to start	2.88E-03	NUREG/CR-6928
GTTGM-S-GTG	Small GTG unavailable due to maintenance	1.34E-03	NUREG/CR-6928
GTTGR-S-GTG	small GTG fail to run	1.52E-03	NUREG/CR-6928
GT-SGTG-REEL	Failure of small GTG cable reel	4.00E-08	NUREG/CR-3263

4. RESULTS AND DISCUSSION

The quantification results of both cases are presented in Table 3. All quantified results are calculated for simplified PRA models and do not represent any specific results for APR1400 design.

Table 3: The Quantification Results of Comparative Study

	CDF	Sum of CDFs Related Sequences	Sequence Numbers related to FLEX Strategies in Figures
Baseline	1.22E-06	2.60E-07	7 (in Fig. 1)
Small Mobile GTG	0.97E-06	3.49E-09	5,6 (in Fig. 2)
Large Mobile GTG	1.00E-06	3.87E-08	9,10,11,12 (in Fig. 3)

The baseline CDF of SBO event tree in Figure 1 is $1.22E-06/\text{year}$. Only sequence 7 in Figure 1 can be affected by mobile GTG strategies in this study, which can be expanded to be sequences 5 and 6 for small mobile GTG and sequences 9, 10, 11, and 12 for large mobile GTG. Sum of CDFs from these sequences are shown in Table 3. Even though small mobile GTG can recover only secondary heat removal by AFTDP, its reduction of CDF is greater than that of large mobile GTG case. In other words, large mobile GTG can recover more safety features, such as feed and bleed operation, than small mobile GTG. However because the reliability (including human failure) of large mobile GTG is worse than small mobile GTG, its impact on plant safety is less than that of small mobile GTG.

5. CONCLUSION

In comparative study of FLEX strategies, extended SBO scenarios with small mobile GTG and extended SBO with large mobile GTG are modelled and compared. Based on this study, the sum of CDFs by sequences in extended SBO condition with large GTG is higher than that with small mobile GTG. Because the reliability of large mobile GTG is worse than that of small mobile GTG, the small mobile GTG is relatively more effective. The HEPs for operation of small mobile GTG and large mobile GTG are important factor to decide the effectiveness of the strategies. To select the strategy under very severe conditions, like east Japan earthquake, the factors needs to be considered for the selection are different from less severe conditions. Deployment, installation, pre-check, etc. which can be conducted easily and reliably under normal condition may become difficult or impossible under severe conditions. In this study, human reliability analysis is followed by NEI 16-06 proposed methodology. In addition, there is no real experience data of mobile GTG. Uncertainties in this study may impact the result of this study. However, it is hardly to obtain real experiences of the employing the mobile equipment.

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