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

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1. Introduction

One of the primary lessons learned from the accident at Fukushima Dai-ichi was the significance of the challenge presented by a loss of safety-related systems following the occurrence of a beyond-design-basis external event [1]. 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]. A station blackout (SBO) is defined in IAEA Safety Guide SSG 34 as a plant condition with complete loss of all alternating current (ac) power from offsite sources, from the main generator and from standby ac power sources important to safety to the essential and nonessential switchgear buses [4]. In case of APR1400, SBO is the complete loss of alternating 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 (EDGs). During an SBO, non-class 1E alternate alternating current (AAC) DG and batteries will provide power for the set of required shutdown loads to bring the plant to safe shutdown. An AAC DG power is provided for the operation of the motor-driven auxiliary feedwater pump (MDAFWP) during an SBO. If AAC DG is not available, the turbine driven auxiliary feed water pump (TDAFWP) will be provided with battery dc power. Electrical systems have sufficient capability and capacity to provide core cooling and containment integrity in an SBO. But over the 8hours, the loss of the TDAFWP may occur due to the battery depletion or deletion of the water source. 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 uncover and, thus, core damage will occur within 1 hour unless power is restored and auxiliary feed water flow is established. This situation is called extended SBO that can occur if beyond-design-basis external event (BDBEE) exceeds the assumptions used in the design and licensing of a plant. In order to address these challenges, diverse and flexible mitigation strategies (FLEX) [1] could be used to enhance their ability to cope with conditions. The extended SBO scenario is shown in fig. 1.

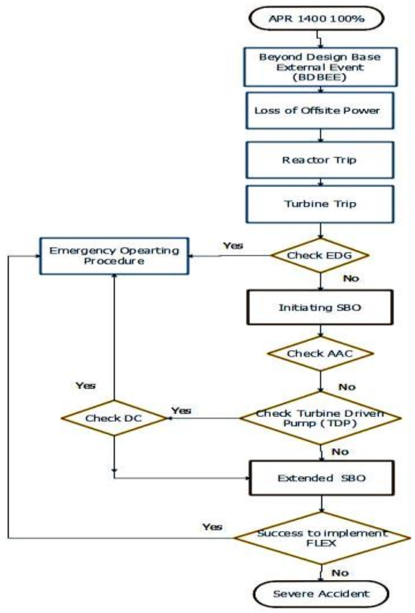

Fig. 1 Flow chart of Extended SBO Scenario

The objective of this paper is to consider the mitigation of the station blackout scenario by compare with the FLEX strategies. In this paper, small Mobile Gas turbine Generator (GTG) is used for recovery of dc power and instrumentation & control to assess the implications of the strengthening of the SBO mitigation capability on the safety of the NPP. Also, large mobile GTG is used for ac power recovery to assess the SBO scenario.

2. Overall framework of Comparative study of FLEX Strategies

This section provides an overall framework of a comparative study of FLEX strategies of extended SBO scenario. The design and operation of the plant are analyzed in order to identify the sequences of events that can lead to core damage and the core damage frequency is estimated through probabilistic risk assessment (PRA). In this study, SBO event with small mobile GTG and large mobile GTG can be developed of accident sequences and mitigating models. In order to comparison the results of the two models, can verify the effectiveness of FLEX strategies that means efficiency of mobile gas turbine generators. The process for extended SBO of APR 1400 analysis using PRA methods are: an Initiating event analysis, make an event tree and success criteria, make fault tree, quantification analysis, sensitivity analysis minimum cutset analysis, and core damage frequency (CDF). SAREX software (i.e. computer program) can be used to develop of accident sequences and mitigation models. Success criteria is determined by thermal hydraulic analysis or related document. In the HRA, human actions that are required for different accident sequences modeled in the PRA are identified. Human recovery actions are considered in the cases where it could be demonstrated that the action is plausible and feasible. All of the human operator actions in fault tree model are post-initiators where THERP (Technique for Human Error Rate Prediction) is used to analysis post-initiators. The fault trees and event trees are solved in an integrated manner to quantify core damage frequency (CDF). Quantification is performed by SAREX.

It is clear, there have been many enhancements made around the world that have significantly improved the ability of nuclear plants to safely protect against even very highly improbable events. In order to achieve the indefinite coping capability, FLEX provides phased approaches that utilize on- site permanent equipment, pre or permanently staged equipment, and portable equipment [1]. In this study, small mobile GTG may be treated as a pre staged portable equipment and large mobile GTG can be considered as offsite portable equipment. The following factors can be considered 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 this point of view, the failure probability of deploy and install of large mobile GTG is higher than the small GTG.
- Permanently pre-staging the small mobile GTG significantly reduces the time required to deploy and to start the GTG. However, large mobile GTG required to be transported and setup in the first hours following a BDBEE event.
- In order to assure reliability and availability of the FLEX equipment required to meet these capabilities, the program may require that the site has N+ 1 sets of FLEX equipment, where N is the number of units on site. Small mobile GTG can satisfy the requirement due to cost effective. The mobile GTG can ensure availability and reliability. Whereas, large mobile GTG may not satisfy to fulfill the requirement.
- The strategy minimizes risk that can be located more small mobile GTG within a robust structure that is adequately protected from all applicable external events.
- The availability of time margin to complete necessary actions is an important consideration in during the mitigating strategies equipment. Time to deploy and time to install of small mobile GTG can be considered.
- The use of small mobile GTG allows re-energizing the critical plant electrical loads more quickly and efficiently than the use of large size GTG that would have to be transferred from the FLEX storage building.

Furthermore, small mobile GTG minimizes the amount of equipment required to be deployed, improves human factors, and facilitates timely restoration of lighting and vital control and instrumentation power. The strategy of using small mobile GTG, as described above, is capable of mitigating a simultaneous loss of all ac power and loss of normal access to the ultimate heat sink. This strategy has adequate capacity to address challenges to core cooling.

3. Copying strategy of Extended SBO scenario

The goal of accident sequence modeling with respect to the use of portable equipment is to determine which scenarios could benefit from the use of the equipment. Accident sequences are graphically modeled in event trees in a PRA model.

3.1 Copying strategy of Extended SBO by using small size Mobile GTG

A representative event tree for extended SBO scenario is shown in fig. 2. 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, capability, and reliability provides power for the set of required shutdown loads (non-design-basis accident) to bring the plant to safe shutdown. The AAC DG is started and manually connected to the set of required shutdown equipment within 10 minutes in accordance with regulatory. But, under the extended SBO, Assumed that AAC DG is not available and DC (Direct Current) battery is only available. After depletion of battery, small mobile GTG is connected to the class 1E dc bus to recover dc power, inverter, and battery charger. The Class 1E batteries supply dc power to essential instrumentation and control (I&C) equipment, and for the operation of the TDAFWPs. This is necessary for monitoring and control of both the SGs as well as pressurizer (i.e. level, pressure & temperature), and consequently send the AFAS signal to provide the necessary amount the feedwater to the SGs for decay heat removal during a SBO. Additionally, the dc power procedures assumes that the TDAFW pump provides feedwater for 8 hours while the FLEX equipment is deployed. Since the TDAFW pump is not available. If one of this portable equipment is not available, core damage can be occurred.

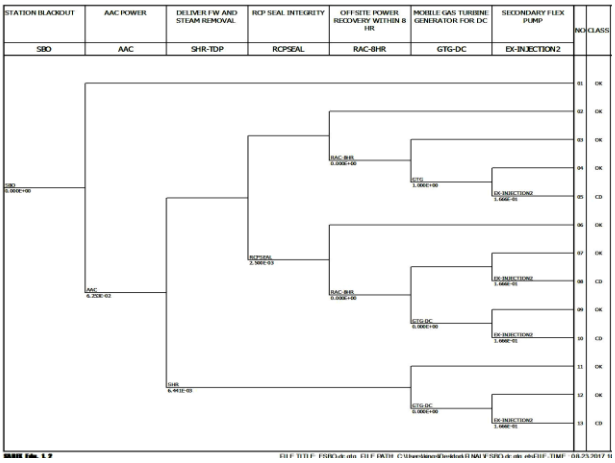

Fig. 2 Event Tree for Extended SBO using Small GTG

3.2 Copying strategy of Extended SBO by using large size Mobile GTG

A representative event tree for extended SBO scenario is shown in fig. 3. SBO event is initiated by Loss of Off-site Power (LOOP) with concurrent failure of both emergency Diesel Generators (EDGs). The alternate alternating current (AAC) DG can be used to cope with SBO scenarios. If AAC DG is failed for extended SBO, reactor coolant pump (RCP) seals might fail due to loss of seal cooling that could result in core damage. On the other hand, the TDAFW pump should be available to remove decay heat, and keep natural circulation cooling. If offsite power is recovered within 8hours, it can provide power for MDAFWP, feed & bleed operation and containment heat removal. After depletion of battery, the operation of TDAFWP is inoperable, large mobile GTG is connected to the class 1E ac bus to recover ac power. Moreover, secondary injection from outside of secondary FLEX pump is connected to SG to remove decay heat. The success criterion of secondary FLEX pump is to inject sufficient water to SG and opening ADV valve, otherwise, core will be uncovered.

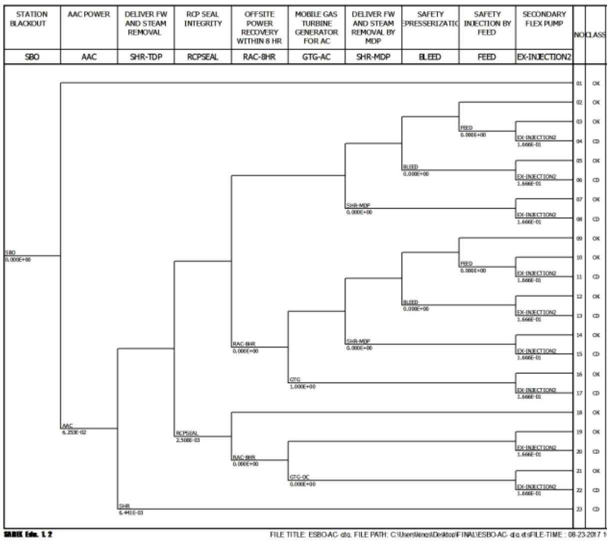

Fig. 3 Event Tree for Extended SBO using large GTG

4. Modeling Mitigating strategies of FLEX Equipment in the PRA

The PRA models for nuclear power plants are designed to model the as-built, as-operated plant. The PRA model allows the analyst to identify potential vulnerabilities and risk insights based on how the plant is built and how the operators respond to initiating events. When procedures dictate the use of portable mitigation equipment to cope with initiating events, it is appropriate to include this equipment in the PRA.

4.1 Modeling Mitigating strategy of Small Mobile GTG in the PRA

Station blackout (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 a mobile gas turbine generator to recover the DC power and a secondary FLEX pump to inject water into steam generator. The following assumptions are applied to the example;

- The plant procedures are written to use the FSGs (FLEX Support Guidelines) for any LOOP(Loss of Offsite Power) followed by the subsequent failure of all permanently-installed alternate ac power sources (Station Blackout).
- The plant has two TDAFW pumps. The TDAFW pump is required for the first 8 hours of the scenario to provide sufficient time to deploy the FLEX equipment.
- Operators will begin to cool down and depressurize the steam generators beginning at the declaration of an ELAP.
- Steam generator atmospheric dump valves may be controlled manually if DC power is not available.
- Small Mobile Gas Turbine GTG) can be connected to the connection box of 480 V of mobile generator to recover dc power and instrumentation & control.
- Operators will connect cable reel from mobile GTG to the connection box of 480 V of mobile generator

  The mobile gas turbine generator requires transportation from a storage building to the in front of EDG room.
- Secondary FLEX pump can be connected to the auxiliary feedwater (AFW) supply line by hoses pipe.
- The secondary FLEX pump and mobile GTG are required to be refueled prior to 24 hours from EDG fuel tank in Auxiliary building.

4.1 Modeling Mitigating strategy of large Mobile GTG in the PRA

The FLEX equipment credited for this scenario includes a large mobile gas turbine generator (GTG) to recover the AC power and a secondary FLEX pump to inject water into steam generator. The following assumptions are applied to the example;

- The plant procedures are written to use the FSGs (FLEX Support Guidelines) for any LOOP (Loss of Offsite Power) followed by the subsequent failure of all permanently-installed alternate ac power sources (Station Blackout).
- The TDAFW pump for the initial coping phase of an ELAP, during which it maintains a heat sink to dissipate decay heat from the reactor core.
- Large Mobile Gas Turbine GTG) can be connected to the 4.16 KV class 1E safety bus to recover ac power.
- Operators will connect cable reel from mobile GTG to the connection of 4.16 KV switchgear.
- The mobile gas turbine generator requires transportation from a storage building to the in front of EDG room.
- Secondary FLEX pump can be connected to the auxiliary feedwater (AFW) supply line by hoses pipe.
- The secondary FLEX pump and mobile GTG are required to be refueled prior to 24 hours from EDG fuel tank in Auxiliary building.

5. Conclusion

One of the challenges faced by the nuclear power industry, after the Fukushima Daiichi NPP accident, is how to mitigate sequences caused by BDBEE, specifically the extended SBO. The APR1400 has evolved from current PWR technology that incorporates features intended to make the plant safer and easier to operate as compared to currently operating plants. In comparative study of FLEX strategies, SBO model with small mobile GTG and SBO model with large mobile GTG have been modelled and compared. The result of station blackout core damage frequency has been compared. Based on the comparative study results, the Core damage frequency (CDF) of SBO with small mobile GTG is reduced. The PRA results and risk insight shows low probability and it means safety for operation. The system comprising of a small mobile gas turbine generator can be more effective. A key to maintaining proper instrumentation and control is supply of reliable, continuous power which small mobile GTG can be connected to the class 1E 120 Vac instrumentation and control power system. The opportunity to improve response times, simplify required manual actions, and utilize robust equipment in robust locations can be justified this small size of mobile GTG to as a mitigating strategy of extended SBO. For further study, sensitivity analysis can be performed that would be provided a deeper insight into the risk analysis, add to credibility of the results.

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