

Time-Dependent SBO Risk Modeling and FLEX Integration for Emerging Nuclear Power Programs

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1 Introduction

Station blackout (SBO), which is as a result of Loss of Offsite Power (LOOP) with unavailable onsite AC, remains a key contributor to nuclear risk. Emerging grids have time-varying restoration and logistical limits on portable mitigation, making early-hour dynamics critical. This paper develops a time-dependent model tailored to such contexts to quantify core-damage risk and the realistic risk reduction achievable with Flexible and Diverse Coping mechanisms (FLEX). This study models run-failures of onsite sources, increasing-hazard grid recovery, and FLEX as a delayed probabilistic restoration path, yielding representative results relevant to first-of-a-kind (FOAK) plants for deployment timing and reliability.

2 Methods and Results

This study applies a time-dependent model over a 72 hour mission window to evaluate SBO risk and coping effectiveness in an emerging nuclear program, analyzing and summarizing representative results relevant to FOAK plants in a developing country. To evaluate risk reduction, this study models a single baseline configuration that is evaluated with and without FLEX, enabling a direct comparison of the baseline and FLEX-enhanced performance.

This case models the AC-dependent SBO coping, considering the EDG and AAC with constant failure-to-run rates (λ_E , λ_A) [1] and offsite power restoration using the Weibull distribution. It also includes the TDP, modeled as a non-AC coping system. It is assumed to actuate automatically at LOOP initiation ($\tau = 0$), triggered automatically by the Auxiliary Feed water Actuation Signal (AFAS), providing feedwater independent of AC sources. By providing immediate non-AC cooling capacity, the TDP diversifies coping strategies and reduces reliance on AC restoration. The event tree (Fig. 1) traces LOOP $\rightarrow$ EDG $\rightarrow$ AAC $\rightarrow$ TDP $\rightarrow$ offsite recovery, with core damage when all AC paths fail or grid restoration lags beyond coping capacity.

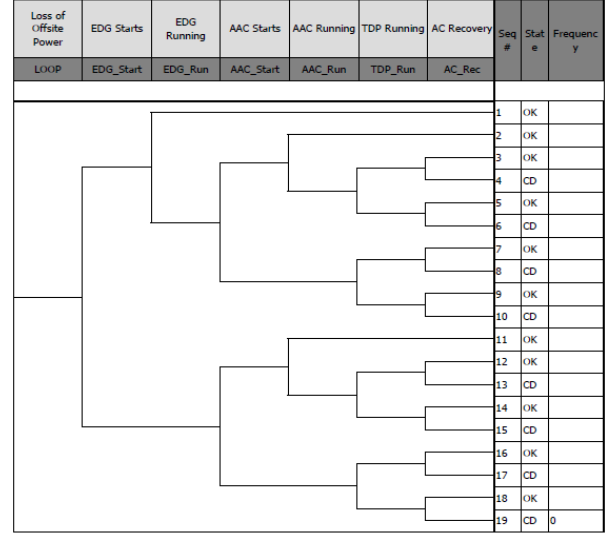


Fig 1: Sequential logic of LOOP initiation

2.1 Mathematical Formulation

The EDG is modeled with a constant failure-to-run rate, where λ_E is the run failure rate (in hr^{-1}) [2], the probability density function (PDF) for EDG failure at any time τ over the mission time is given by:

$$f_E(\tau) = \lambda_E e^{-\lambda_E \tau} \quad (1)$$

In the event of EDG failure, the AAC source assumes the role of maintaining power, where λ_A is its failure-to-run rate (in hr^{-1}), and t_E is the time at which the EDG fails and the AAC begins operation. Its failure PDF at time τ , given activation at t_E , is defined as [3]:

$$f_A((\tau|t_E)) = \lambda_A e^{-\lambda_A(\tau-t_E)} \quad (2)$$

Offsite power recovery follows a Weibull survival function to represent non-recovery behavior over time. This distribution shows the increasing likelihood of restoration as time progresses [4], a characteristic feature of developing grid systems. The survival function, indicating the probability that offsite power has not been restored by time τ , is given by:

$$S_{off}(\tau) = \exp\left(-\left(\frac{\tau}{\eta}\right)^\beta\right) \quad (3)$$

This function is particularly suited for modeling offsite power behavior in developing countries, where uncertainties in restoration timelines are significant.

The TDP is considered as a non-electric coping function, and its running failure probability, where λ_{TDP} is the failure rate and τ is the elapsed time, is given by:

$$P_{TDP_fail}(\tau) = 1 - \exp[-\lambda_{TDP} \cdot \tau] \quad (4)$$

FLEX success is modeled with a survival function that defines the likelihood that it has not restored AC power by any time τ , where τ represents the elapsed time since the initiating LOOP event. The function is defined as:

$$S_{FLEX} = \begin{cases} 1, & \tau < \tau_F \\ \exp(-\lambda_F(\tau - \tau_F)), & \tau \geq \tau_F \end{cases} \quad (5)$$

Where τ_F denotes the time at which FLEX deployment begins, and λ_F represents the constant hazard rate of FLEX in restoring AC power once operational. The function assumes that FLEX has no mitigating effect before deployment and that its failure to restore power follows an exponential decay function post-deployment.

The Joint Probability of total AC loss at time τ is obtained by substituting equations (1), (2) and (3);

$$P_{noAC}(\tau) = \int_0^\tau f_E(t_E) \cdot f_A(t|t_E) \cdot S_{off}(\tau) dt_E \quad (6)$$

Therefore, the probability of SBO occurring anytime up to τ for EDG, AAC, and Offsite Power is given by;

$$P_{SBO}(\tau) = \int_0^\tau P_{noAC}(\tau) dt \quad (7)$$

Including the TDP, this probability is given by multiplying equations (4) and (7);

$$P_{SBO}(\tau) = P_{TDP_fail}(\tau) \cdot \int_0^\tau P_{noAC}(\tau) dt \quad (8)$$

FLEX is then integrated into the model to evaluate its impact on reducing the SBO risk, and the joint probability, is given by;

$$P_{SBO}^{FLEX}(\tau) = P_{SBO}(\tau) \cdot \exp[-\lambda_F(\tau - \tau_F)] \quad (9)$$

2.2 FLEX Deployment

FLEX is modeled as a phased, logistics-constrained deployment that incorporates installed systems with pre-staged portable assets, such as an on-site gas turbine generator (GTG), and when required, off-site support from nearby hydro or thermal plants to sustain coping within the 72-hour window [5]. Beyond this, coping capacity is assumed exhausted and core damage progression is inevitable. FLEX reliability is treated as time-sensitive,

incorporating the effects of human response, equipment availability, and terrain-related deployment delays. This study summarizes it as follows;

Table 1: FLEX Deployment phases

Phase	Time window	Description
1	0–8 h	Installed systems
2	8–24 h	On-site deployment of pre-staged portable equipment
3	24–72 h	Off-site tie-ins
>72 h	—	Coping window exceeded; core damage

This study considers this model for an emerging program context facing challenges such as grid and logistics constraints. From fig. 2 below, FLEX contribution is low in the early hours but its effect steadily grows by 24–48 hours as deployment becomes effective. By 72 hours, a cumulative risk reduction 43.2% is observed.

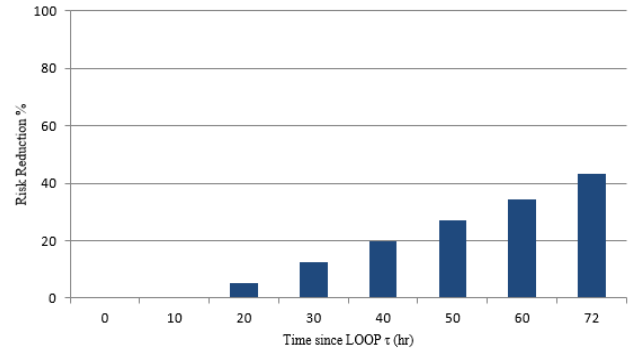


Fig 2: Risk Reduction due to FLEX

3 Conclusions

This study shows that for emerging nuclear programs facing challenges such as grid unreliability, constrained emergency logistics, and maturing regulation, analyzing SBO risk over time with phased FLEX deployment turns probabilistic results into clear targets for procedure timing, equipment staging, and staffing. It focuses resources in the highest risk hours, while maintaining a ready non AC path for decay heat removal alongside AC dependent systems.

Academically, this study presents a concise, phase mapped model that treats FLEX as a time indexed success function across AC and non AC systems. In the absence of empirical data, this approach remains practical for risk-informed decision making and policy planning, producing outputs like clear deployment windows and measurable readiness checks for operators and regulators, and can be refined when site-specific data becomes available. Although FLEX is considered to be adopted after commercial operation begins, the framework is

timing neutral and supports planning from commissioning through operation. Start failures, multiple component interactions, common cause failures, and human reliability, while not considered in this study, are recommended as priorities for future work.

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