Offsite Power Recovery Time Analysis for Dynamic Probabilistic Safety Assessment

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1. Introduction

The risk of a nuclear power plant is evaluated and managed with probabilistic safety assessment (PSA) and deterministic safety assessment [1]. Every possible initiating event (IEs) is analyzed, and the mitigation systems are considered [1]. In those processes, several conservative assumptions are applied to quantifying the risk. Especially station blackout (SBO), one arbitrary initiating event, should take into account an offsite power recovery event, which operators take. Legacy PSA analyzed that SBO needs offsite power recovery as a critical mitigation event [2]. In that, the offsite power recovery is considered by “early recovery event” and “late recovery event.” The former means that offsite power should be recovered before core damage if every heat removal system and diesel generator (DG) fails. The latter is that when every possible DGs is failed, offsite power recovery alleviates the IE within the turbine-driven auxiliary feed water (TD-AFW) available. It means that secondary side heat removal gains time to restore and that time available for TD-AFW is critical for the success criteria of the recovery. However, although the event is, operator action and time available of TD-AFW could be changed, “early one” and “late one” is just defined as fixed and conservative time values. It can carry out a too-conservative risk assessment and even affect to operator mentally for the action.

Therefore, we have studied dynamic scenarios which show the impacts of time variable changes in IE mitigation sequences. For example, the time required for the preceding event could be a significant variable for the posterior event. In SBO, the time available of TD-AFW determines the mission time of “late.” Moreover, we focused on the operator actions more likely to be critical in time considerations rather than engineering safety features (ESF) which start in automation manner.

2. Scenario Analysis

The target IE is SBO. As Fig. 1 shows, we rearranged the SBO event tree (ET) for dynamic analysis rather than the legacy. When loss of offsite power occurs, DGs try to start. If one of the DGs succeeds, the plant is cooled down with alternating current (AC). If DGs fail, TD-AFW starts with direct current (DC) and battery. For running TD-AFW, DC is required, at which point the lifetime of the battery is significant for the time available of TD-AFW. Until the battery's lifetime, if offsite power is not recovered, the plant could undergo core damage. Even if the DGs start to run, they have a fuel limitation. Until fuel is consumed in the plant, offsite power should also be recovered. In that scenario, we consider TD-AFW since DC is available.

3. Case Study

3.1. Sequence details

For the case study in this paper, we focused on the 7th sequence. It is that all DGs fail, and TD-AFW is taken into account. Therefore, the primary time variable is the time available for TD-AFW and offsite power recovery time. The time available for TD-AFW, as already mentioned, is determined by the battery's lifetime. The lifetime is changeable as well. When SBO occurs, the operator shuts a non-essential load of DC power. If the blockage is performed within 30 mins, the lifetime is extended to 8 hours from 4 hours. Thus, as shown in Fig. 2, the time to shut the non-essential load of DC determines the mission time of offsite power recovery.

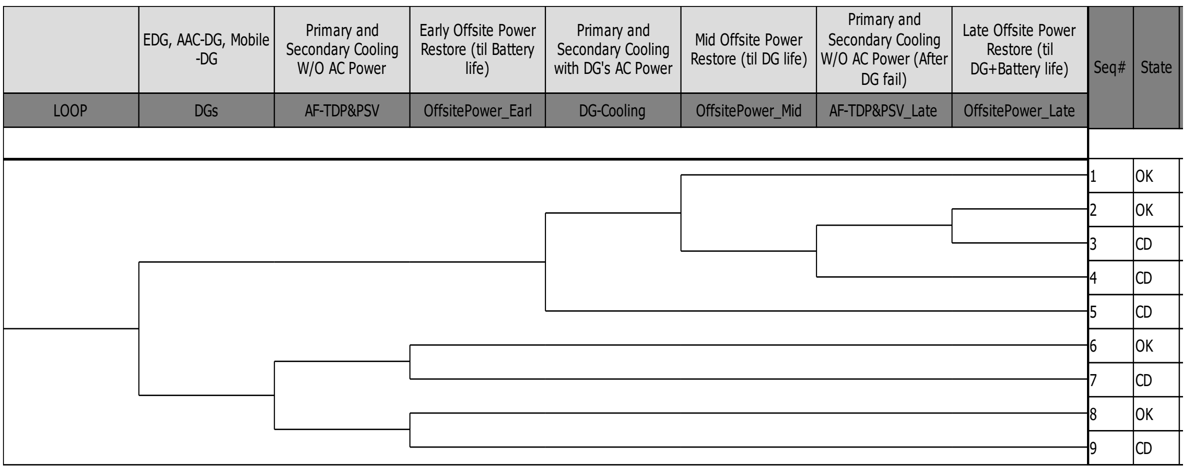

Fig. 1. SBO ET - rearranged for dynamic PSA

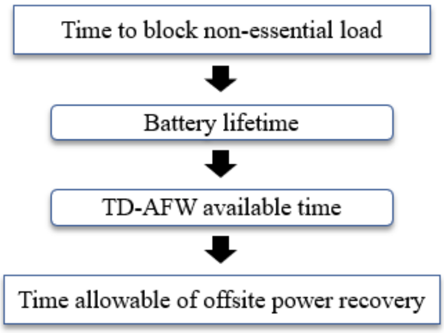

Fig. 2. Relationship between time variables

Moreover, the time to block non-essential load and recovery time are operator events. Thus, we consider the time variables as significant variables and analyze how to change the mission time of offsite recovery according to the time to shut non-essential load.

3.2. Method

Table 1: Example of time available of TD-AFW

Non-essential load blockage time (min)	15	30	45	60
TD-AFW time (h)	10	8	6	4

We calculated the plant status with MAAP 5 software [2,3]. The reference model of the system code is OPR 1000. The calculation is executed by determining the core damage time after the AFW cooling. We defined the mission time of offsite power recovery as the time before core damage as well. In Table 1, the time available for TD-AFW can be found. A total of 10 scenarios are calculated, each with a different non-essential load block time.

3.3. Key assumptions

- Time converting from the blockage time of non-essential load to the battery lifetime is conducted by extrapolations and interpolations.
- SBO occurs 0 second and TD-AFW starts automatically.
- Since we focused on the time variables related powers, the operator action which operator controls steam generator air-dump valve for steam removal is not considered.
- Since the AC power is not available in this study, for cooling RCS, only TD-AFW and pressurizer safety valves are considered. The pressurizer safety valve works for drying out RCS.
- Core damage is defined as over 1478 K of peak cladding temperature (PCT).

3.4. Result

We calculated the system code representing SBO and different times available of TD-AFW until core damage with data in Table 2.

Table 2: Time variables for calculations

Non-essential load blockage time (min)	82.5	75	67.5	60	52.5	45	37.5	30	22.5	15
TD-AFW time (h)	1	2	3	4	5	6	7	8	9	10

3.4.1. Offsite power recovery times

The result shows that core damage occurred after TD-AFW stopped and RCS dried out through the pressurizer safety valves. The mission time of offsite power recovery is conducted as 6.1 h ~ 20. 6 h according to the shutting time of non-essential DC load as shown in Fig. 3 and

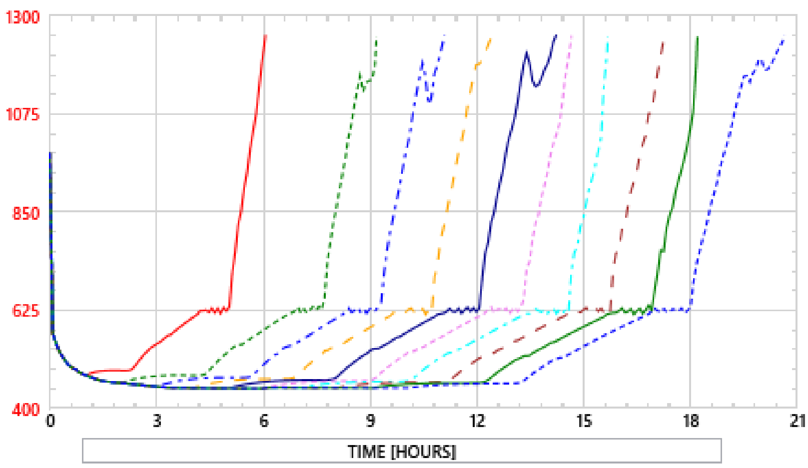

Fig. 3. Peak cladding temperature according to TD-AFW cooling time 1 h ~ 10 h [K]

Table 3. Generally, in legacy PSA, the "late" event similar to sequence 9, which we focus on, is considered seven h. It means that the battery's lifetime is 4 h, and RCS is dried out within 3 hours after TD-AFW stops. Thus, the success criteria of the recovery time became 7 h. Moreover, in this calculation, 4 h of TD-AFW time shows 12.4 h of core damage time, and 8 h shows 17.2 h.

As shown in Fig. 4, before core damage, offsite power mitigates IE successfully whenever that is recovered. The calculation represents 3 hours of cooling with TD-AFW, and, at 11 h, offsite power is recovered. After that, the plant shows successful cooling.

Table 3: Offsite power recovery allowable time

TD-AFW time (h)	1	2	3	4	5	6	7	8	9	10
Time allowable for recovery (h)	6.1	9.2	11.1	12.4	14.2	14.7	15.7	17.2	18.2	20.6

3.4.2. Discussion

Each scenario shows significant differences in allowable time for offsite power recovery until core damage. Even if the scenarios are considered in the same sequence in ET, the mission time of offsite recovery is varied greatly. In legacy PSA, as already mentioned in Introduction, they consider just two kinds of time conditions. Thus, we can confirm that the "early" and "late" are pretty conservative and cannot represent the time-dependently changed scenarios. In the other sequences, we can expect different results in aspects of allowable time for offsite power recovery. Since the manner for extension of the mission time is RCS cooling, considering more ESF in the scenario could be challenging to predict the time allowable.

Moreover, it is dependent on the operators' actions whether SBO can be mitigated or not since the offsite recovery is a critical event in the IE. In aspects of operator event, it is different from mechanical failure or success of components and systems. Operator action time should be considered and can also be varied. In addition, the preceding operator event affects to success criteria of the escorted event. Thus, simple failure within one time criteria is not appropriate for the quantifying risk of the scenarios. Thus, we should consider time-dependently changed scenarios when dynamic PSA scenarios are set before simulations.

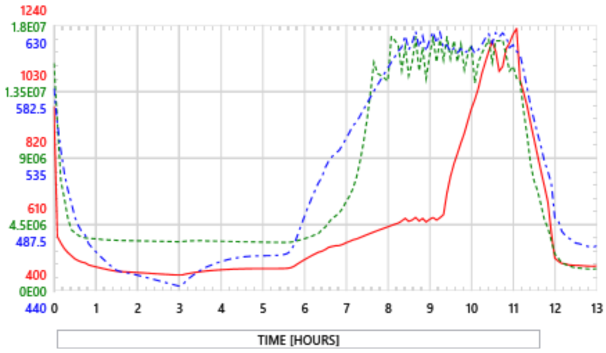

Fig. 4. Plant status of offsite power recovery (red: PCT [K], blue: core water temperature [K], green: PZR pressure [Pa])

4. Conclusion

Through this study, we confirm that the mission time of offsite recovery is varied under the battery lifetime and TD-AFW cooling time. In the process, SBO is selected as IE, and the accident mitigation sequence is rearranged to represent dynamic characteristics by dividing the main time variables at small intervals. Among the time variable, shutting a non-essential load of DC affects to mission time of offsite recovery; meanwhile, both are operator events. The result shows safety criteria of a particular event can be determined by the previous event. Thus, as a dynamic aspect, the mission time of operator action should be considered in this manner. Similarly, in dynamic PSA, numerous scenarios are considered, and safety criteria like mission time need to be appointed in each scenario by reflecting previous event impacts before simulations.

Moreover, quantifications for dynamic PSA should consider the properties of scenarios and accident mitigations. Therefore, further, we will proceed with the studies considering those characteristics. Furthermore, we can suggest the proper allowable time for offsite power recovery, and it can make operators execute while feeling more stable.

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