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Light Water Reactor Sustainability Program

Utilizing FLEX Equipment for Operations and Maintenance Cost Reduction in Nuclear Power Plants

Vaibhav Yadav and John Biersdorf

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Utilizing FLEX Equipment for Operations and Maintenance Cost Reduction in Nuclear Power Plants

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EXECUTIVE SUMMARY

Economic or financial causes have led to closure or announcement of early retirement of several United States (U.S.) nuclear reactors in the last five years. The published report, "Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet—Cost and Revenue Study," by Idaho National Laboratory identified that 63 of the 79 studied nuclear power plants (NPPs) lost money in the year 2016. The revenue-gap analysis performed in the study also concluded that additional revenue is required to return most of these nuclear power units to profitable operations. This can be achieved by reducing operation and maintenance (O&M) costs that account for about 70% of total operating expenditures for an NPP. The Light Water Reactor Sustainability (LWRS) Program conducts research and development, sponsored by the U.S. Department of Energy, that provide a technical foundation for licensing and managing the long-term safe and economical operation of current NPPs, utilizing the unique capabilities of the national laboratory system. Reduction in O&M costs aligns with the LWRS program's mission of providing science-based solutions to the nuclear industry to implement technology and methodologies for safe, efficient, and economical long-term operation.

There are many ways of reducing O&M costs; this work presents an innovative framework of reducing O&M costs by utilizing onsite FLEX equipment at NPPs. FLEX strategies were postulated by the U.S. Nuclear Regulatory Commission (NRC) in the wake of Fukushima Dai-ichi accident to address beyond-design-basis accidents and improve plant flexibility. Onsite FLEX includes equipment such as portable pumps, generators, batteries, compressors, and other supporting equipment or tools, all stored in a dedicated and secure building designed to withstand external hazards. In the past years, several NPPs have invested in procuring and maintaining onsite FLEX assets that stand unutilized most of the time. Recently, active efforts have been made to develop strategies through which NPPs can take credit for this FLEX equipment. This report focuses on identifying areas where FLEX equipment can be utilized during normal plant operation and develop a framework that would aide in reduction of O&M costs without impacting plant safety.

Earlier work in the current project, published in INL/EXT-18-51531, presented the risk- and cost-analysis framework for utilizing FLEX portable equipment during technical-specification required shutdown due to component failure. The licensee event report (LER) database of the NRC shows that commercial NPPs in the U.S. reported 86 technical specification required shutdowns since 2010. When a component failure or unavailability leads to a technical specification required shutdown, an NPP suffers both direct costs, in terms of loss of revenue arising from the loss of generation, and indirect costs in the form of reporting and inspection required by the NRC.

INL/EXT-18-51531 developed the following framework and implemented it on a demonstration model, based on probabilistic risk assessment (PRA), to utilize the portable FLEX equipment when a component failure could potentially lead to a technical specification required shutdown:

1. Identify the components, the failure or unavailability of which would result in a 10 CFR 50.73(a)(2)(i)A-reportability requirement, postulated

by the NRC for a technical specification required shutdown to be reported in NRC's LER database.

2. Identify the FLEX equipment that could be utilized as a standby to the failed component.
3. Develop a PRA model that incorporates the FLEX equipment within the current plant PRA model.
4. Perform PRA calculations to determine change in core-damage frequency and change in risk-informed allowable outage time.
5. Perform cost-benefit analysis to determine the economic feasibility of implementing the FLEX equipment.

The work presented in this report implements the above framework in a plant PRA model obtained from a U.S. commercial nuclear power plant by prestaging onsite FLEX equipment as a redundancy to the existing auxiliary feedwater system, and coordinating with offsite FLEX centers before any event. The new configuration increases allowable outage time by about fifty percent overall for an event in which the diesel generator is out of service. The benefits to NPPs of utilizing the FLEX equipment during normal operations, and performing the PRA developed in this work, include:

1. A risk-informed plant shutdown alternative to the current technical specification required shutdown.
2. Extension of allowable outage time to initiate technical specification required shutdown.
3. Reduced economic impact of component failure, avoiding plant shutdown, and maximizing generation.
4. Saving of direct and indirect costs associated with technical specification required shutdowns.

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ACRONYMS

AFW	auxiliary feed water
AOT	allowed outage time
BWR	boiling water reactor
CCF	common cause failure
CDF	core-damage frequency
CT	completion time
DBE	design basis event
DCS	distributed control system
DI&C	digital instrumentation and controls
DOE	Department of Energy
EDG	emergency diesel generator
EPRI	Electric Power Research Institute
HEP	human-error probability
HPSI	high-pressure safety injection
HRA	human-reliability analysis
I&C	instrumentation and controls
ICCDP	incremental conditional core-damage probability
INL	Idaho National Laboratory
LCO	limited condition of operation
LER	licensee event report
LWRS	Light Water Reactor Sustainability program
MCR	main control room
MDP	motor-driven pump
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NRC	(U.S.) Nuclear Regulatory Commission
O&M	operations and maintenance
PRA	probabilistic risk assessment
PWR	pressurized water reactor
R&D	research and development
RAW	risk achievement worth
SBO	station blackout
SG	steam generator

SPF	spent-fuel pool
TDP	turbine-driven pump
TS	technical specification
U.S.	United States

Risk and Cost Analysis of Utilizing FLEX Equipment for O&M Cost Reduction in Nuclear Power Plants

1. INTRODUCTION

Economic or financial causes have led to closure or announcement of early retirement of several United States (U.S.) nuclear reactors over the last five years. The published report, "Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet—Cost and Revenue Study," by Idaho National Laboratory (INL) identified that 63 of the 79 studied nuclear power plants (NPPs) lost money in the year 2016.[1] The revenue-gap analysis (Figure 1) performed in the study also concluded that additional revenue is required to return most of these nuclear power units to profitable operations.[1] This can be achieved by reducing operation and maintenance (O&M) costs that account for about 70% of total operating expenditures for an NPP (Figure 2). This report presents an innovative framework for reducing direct and indirect maintenance costs by utilizing the onsite FLEX equipment at an NPP.

There are many ways of reducing O&M costs; this work presents an innovative framework for reducing O&M costs by utilizing onsite FLEX equipment at NPPs. FLEX strategies were postulated by the U.S. Nuclear Regulatory Commission (NRC) in the wake of Fukushima Dai-ichi accident to address beyond-design-basis accidents and improve plant flexibility.[2] FLEX strategy comprises both onsite and offsite component storage for the provision of additional materials and equipment. The onsite FLEX includes equipment like portable pumps, generators, batteries, compressors, and other supporting equipment or tools, all stored in a dedicated and secure building designed to withstand external hazards. These equipment are used to provide various safety functions to cool the reactor core, maintain containment integrity, and cool a spent-fuel pool (SFP, see Figure 3). Further details on required safety functions from FLEX equipment for pressurized water reactors (PWRs) and boiling water reactors (BWRs) are available in the Nuclear Energy Institute (NEI) FLEX-implementation guide.[4] In the past years, several NPPs have invested in procuring and maintaining onsite FLEX assets that stand unutilized most of the time. Recently, active efforts have been made to develop strategies through which NPPs can take credit for FLEX equipment. This work focuses on identifying areas where FLEX equipment can be utilized during normal plant operation in a developed framework that would reduce O&M costs without impacting plant safety.

Two areas that have potential to utilize portable FLEX equipment: 1) in the event of a technical-specification (TS)-required shutdown due to component failure, and 2) during scheduled maintenance—e.g., a refueling outage. This report presents the risk- and cost-analysis framework for technical specification required shutdowns due to component failure. The licensee event report (LER) database of the NRC shows that the commercial NPPs in the U.S. reported 86 technical specification required shutdowns since year 2010. When a component failure or unavailability leads to a technical specification required shutdown, an NPP suffers both direct costs, in terms of loss of revenue arising from the loss of generation, and indirect costs in the form of reporting and inspection required by the NRC.

This work develops the following framework to utilize the portable FLEX equipment when a component failure could potentially lead to a technical specification required shutdown:

1. Identify the components, the failure or unavailability of which would result in a 10 CFR 50.73(a)(2)(i)A reportability requirement,[3] postulated by the NRC for technical specification required shutdown to be reported in NRC's LER database.
2. Identify the FLEX equipment that could be utilized as a standby for the failed component.
3. Develop a model, based on probabilistic risk assessment (PRA) that incorporates the FLEX equipment within the current plant PRA model.

4. Perform PRA calculations to determine changes in core-damage frequency (CDF) and risk-informed allowable outage time.
5. Perform a cost-benefit analysis to determine the economic feasibility of implementing the FLEX equipment.

In this work, a demonstration-PRA model is developed of a portable FLEX pump and 480V diesel generators, when an emergency diesel generator has failed to start, that incorporates these equipment within the plant PRA model of a U.S. NPP. The cost analysis presents direct and indirect savings to the NPP from utilizing the portable FLEX equipment as specified. The PRA models developed in this work are distinct from the models that incorporate FLEX equipment for their intended use, like station blackout, but not during normal plant operation. Complying with the non-disclosure agreement between Battelle Energy Alliance and the commercial utility, conscious efforts have been made to ensure that the plant PRA models discussed and illustrated in this report do not reveal the identity of the NPP.

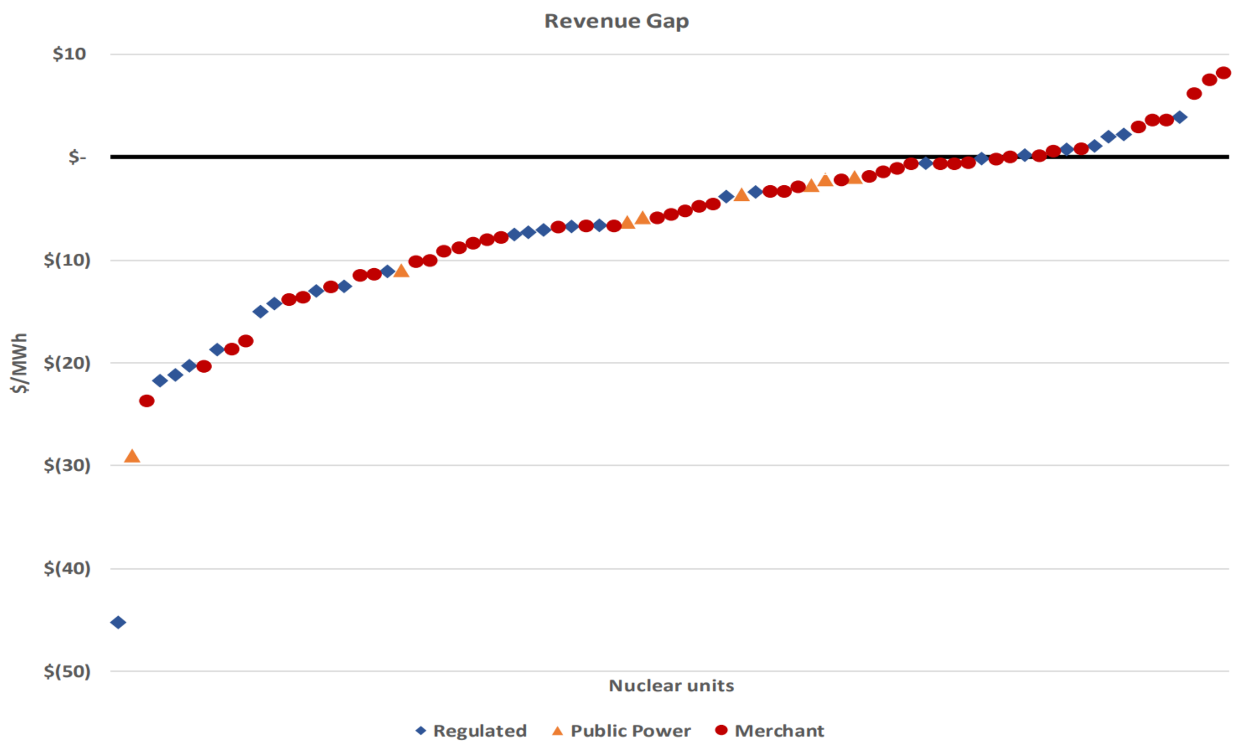

Figure 1. Revenue gap of NPPs in USA.[2]

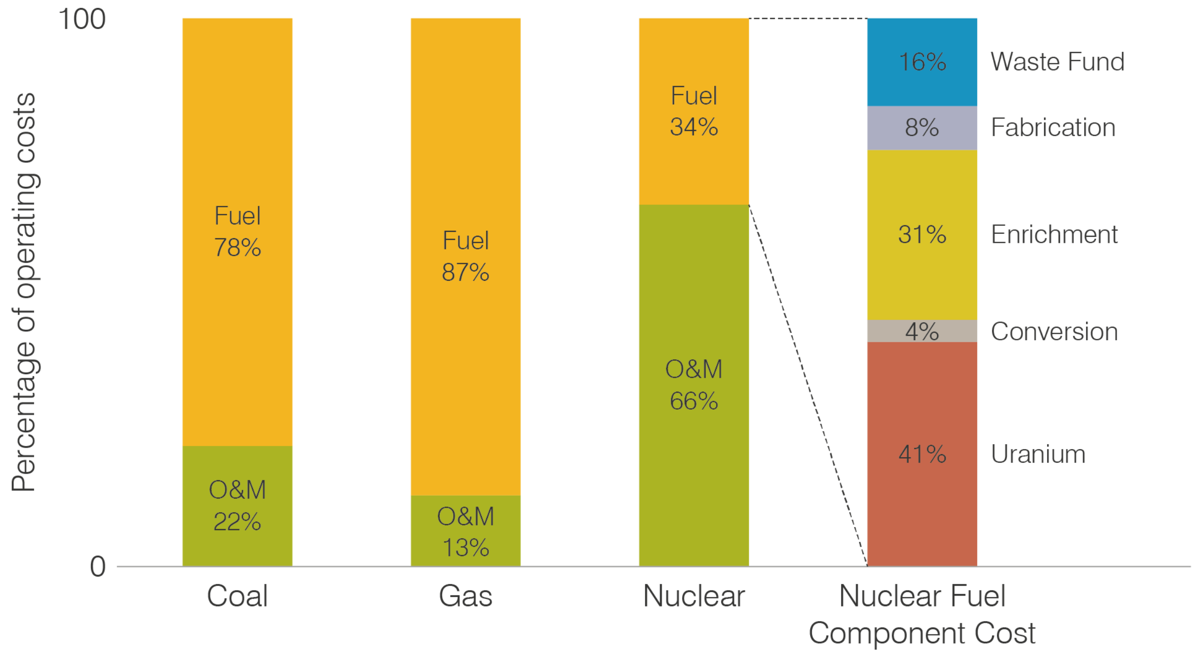

Figure 2. Contribution of O&M costs and fuel costs in coal, gas, and nuclear power plants. Source: NEI.

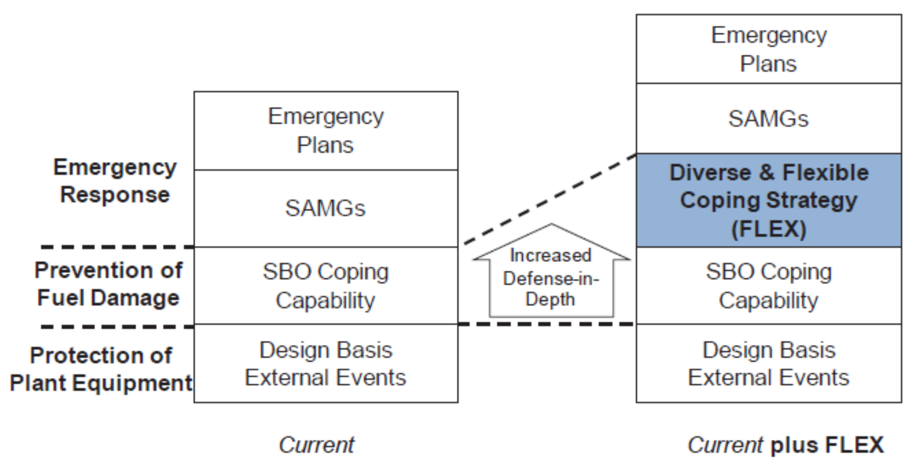

Figure 3. FLEX strategy.[8]

2. METHOD

The general approach of this research is shown in Figure 4. The first stage is to incorporate the existing FLEX strategy into an NPP risk model to expand the plant-risk margin.[5] The second stage leverages portable FLEX equipment, when not in use in station blackout (SBO) mitigation, to enable a flexible O&M program which may reduce O&M costs.[4] This process is hypothesized to recover some portion of the plant-risk margin expanded from the first stage. The plant's end state is expected to have both a lower risk compared to the original plant configuration and a reduced O&M cost.

Several key guidelines[4] must be emphasized prior to implementing this proposed approach. The first is that portable equipment should not be used to replace design-basis equipment. Portable equipment, however, may be implemented in mitigating strategies where they provide a safety function or in efficiency strategies to provide improvements in plant operations. Another important guideline is that there be a well-defined procedure for compensatory actions to return FLEX equipment for use in their original SBO-mitigation strategy when they are deployed for O&M flexibility purposes. This procedure should take into account the required time to deploy, install, and start FLEX equipment and the corresponding human-error probability (HEP) to perform it. This HEP should be reflected in the plant-risk model for an SBO event.

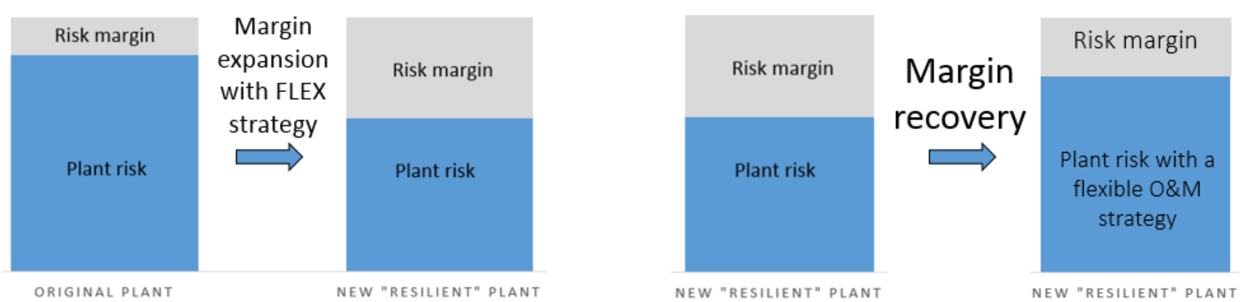

Figure 4. Research approach.

2.1 FLEX in the Plant PRA Model

Although FLEX strategy has been implemented in NPPs in the U.S., it has not been sufficiently credited in the plant risk-assessment model. Reference 5 provides guidance to perform this task, categorized into three tiers. Tier 1 follows a qualitative approach, Tier 2 uses a semi-quantitative approach, with a decision tree, and Tier 3 utilizes a full PRA model to quantify the effect of FLEX strategy on plant risk. The NRC has assessed this guidance,[5] recognizing the importance of incorporating FLEX strategy into the PRA models to reflect as-built, as-operated conditions. However, NRC's assessment also noted several issues that must be addressed to credit FLEX strategy into a PRA model that would comply with existing regulations. These issues, among others, include human-reliability and equipment-reliability quantification.

Guidance[4] describes the insufficiency of current human-reliability analysis (HRA) methods to quantify HEP in human actions that would be required for implementing FLEX strategies. The document further suggests using engineering judgements or equivalent failure probabilities from existing HRA methodologies as surrogates for actions in FLEX strategies. NRC notes, however, that insufficient details are provided on using engineering judgement or surrogates for that purpose. The guide therefore requires further improvements to meet the American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) PRA standard. NRC also underlined how the technical bases for HEP to initiate mitigating strategies should be submitted for a regulatory review. NRC highlights the need for acceptable guidance to identify and assess initiating human failures in maintenance of FLEX equipment that may render the equipment unavailable during an event.

NRC emphasized that realistic failure rates for FLEX equipment should be used in lieu of the failure rates of permanently installed equipment. The failure estimates for permanent equipment should not be used because the limited information available for FLEX equipment indicates a potentially significant difference from permanent plant equipment. In order to obtain realistic values for FLEX equipment, plant-specific generic data should be collected and analyzed using acceptable approaches. Furthermore, NRC recommends the use of currently available common-cause failure (CCF) parameters because these conservatively correspond to the higher CCF failure rates of FLEX equipment.

2.2 FLEX Equipment in Online Maintenance

The portability of FLEX equipment can be leveraged to create accident-mitigation strategies in order to enable online maintenance of installed equipment. NRC regulation[6] governs the risk-acceptance guidelines due to a one-time change in an equipment's TSs. This regulation can be used to estimate how long installed equipment can be taken out of service, i.e., its allowed outage time (AOT), without shifting to the lower plant-operation mode (e.g., shutdown), as illustrated in Figure 5. AOT extension using portable equipment may shift component maintenance from a refueling outage period to online maintenance. This maintenance scheme may reduce the burden of outage maintenance, allow more-effective outage planning, and increase an NPP's capacity factor.

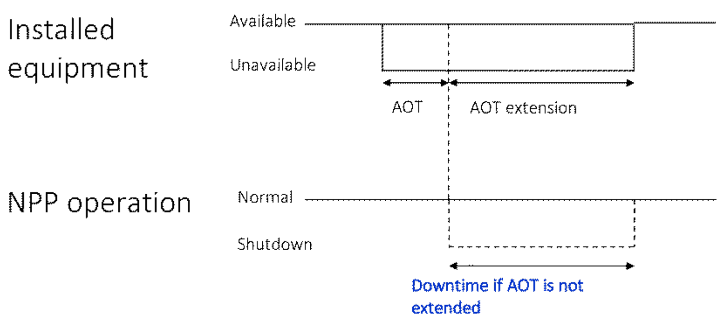

Figure 5. AOT extension.

The steps to extend AOT using FLEX portable equipment are as follows:

1. Incorporate FLEX into plant PRA model, as explained in the previous section (margin expansion). Generate cut sets and calculate the resulting Level 1 plant risk as CDF_1.
2. Identify the target components for which AOT is considered too short and for which AOT must be extended using risk information. Analyze the importance of basic events in cut sets from Step 1 using the risk-achievement-worth (RAW) parameter defined in *Equation (1)*. This equation informs the increase in total risk if the component corresponding to the basic event is unavailable. The RAW parameter can therefore be compared to the risk-acceptance guideline in NRC regulation[6]—i.e., incremental conditional core-damage probability (ICCDP) defined in *Equation (3)*. Shortlist components for which the RAW parameter exceeds the value given in *Equation (4)*.

$$RAW = \frac{CDF_2}{CDF_1} \tag{1}$$

$$\Delta CDF = CDF_2 - CDF_1 = CDF_1 \times (RAW - 1) \tag{2}$$

$$ICCDP = \Delta CDF \times AOT < 10^{-6} \tag{3}$$

$$RAW > 1 + \frac{10^{-6}}{AOT \times CDF_1} \times 365 \tag{4}$$

3. Render a selected component unavailable for maintenance by setting its basic-event probability to 1. Generate the PRA cut sets and calculate the resulting plant risk as CDF_2.
4. Identify the safety functions to reinforce in order to extend the AOT to the new desired completion time (CT). Analyze the importance of basic events in cut sets from Step 3 using the Birnbaum (Bi) measure defined in *Equation (5)*. This parameter informs the rate of change in total risk as a result of changes to the probability of an individual basic event. Therefore, it can be used to estimate the required change in a basic-event probability (P_2), in order to lower the plant risk CDF_2 to a new level CDF_3, which satisfies the NRC acceptance guideline for the specified CT. The new basic event probability, P_3, is given by *Equation (7)*. Calculate P_3 values for each basic event in the cut sets and estimate the required failure probability for FLEX strategies to enable these values—i.e., to change P_2 into P_3. This FLEX-failure probability is given in *Equation (8)*, assuming that the strategy is implemented as a redundant mitigation strategy to the basic events.
5. Shortlist the FLEX-failure probabilities which meet the limits given in *Equation (9)* and sort them ascendingly. Select the lowest FLEX-failure probability from the list and design the FLEX strategy using existing FLEX equipment to meet the required failure probability. Next, implement this strategy as a redundant mitigation strategy to the corresponding installed safety function. It must be noted that there should be a procedure and sufficient time to return the FLEX equipment to their originally intended SBO mitigation functions.

$$Bi = \frac{\Delta CDF}{\Delta P} = \frac{CDF_2 - CDF_3}{P_2 - P_3} \tag{5}$$

$$CDF_3 - CDF_1 = CDF_2 - CDF_1 - Bi \times \Delta P < \frac{10^{-6}}{CT} \times 365 \tag{6}$$

$$P_3 < P_2 - \frac{(CDF_2 - CDF_1) - \left(\frac{10^{-6}}{CT} \times 365\right)}{Bi} \tag{7}$$

$$P_3 = P_2 \times P_{FLEX-FAIL} \rightarrow P_{FLEX-FAIL} = \frac{P_3}{P_2} \tag{8}$$

$$0 < P_{FLEX-FAIL} < 1 - \frac{(CDF_2 - CDF_1) - \left(\frac{10^{-6}}{CT} \times 365\right)}{Bi \times P_2} \tag{9}$$

Figure 6 illustrates the aforementioned steps to extend AOT. Step 1 sets the baseline plant risk CDF1. Step 3 increases the plant risk to CDF2. The ICCDP parameter given in Equation (3) is a product of delta CDF and AOT. Step 5 reduces the plant risk from the supposed CDF2 to CDF3, thereby lowering the delta CDF. This lower delta CDF enables AOT to be extended while complying with the ICCDP guideline of 1E 6.

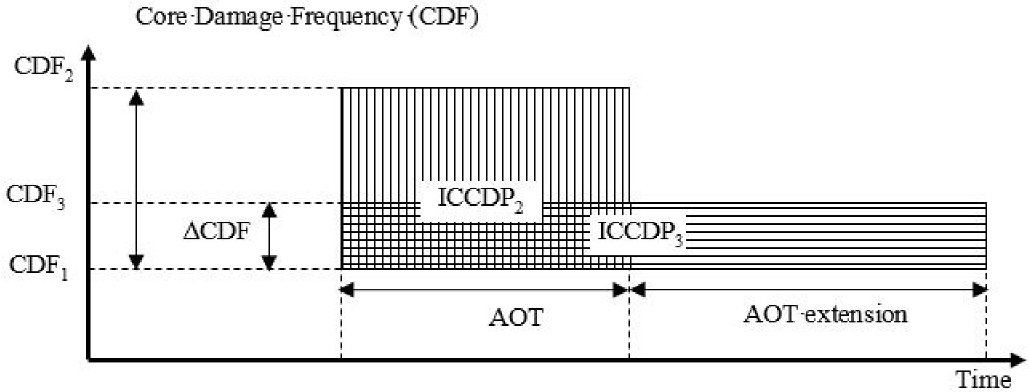

Figure 6. AOT extension in compliance with the risk-acceptance guideline.

Licensees may implement the AOT extension permanently if the change in plant risk complies with the risk-acceptance guideline in Regulatory Guide 1.174.[6] In such a case, the FLEX strategy in Step 5 should follow *Equations (10) and (11)*:

$$CDF_3 - CDF_1 = CDF_2 - CDF_1 - Bi \times \Delta P < 10^{-6} \tag{10}$$

$$0 < P_{FLEX-FAIL} < 1 - \frac{(CDF_2 - CDF_1) - (10^{-6})}{Bi \times P_2} \tag{11}$$

This process was accomplished on a generic PWR model to identify significant components and processes. Collaboration with plant personnel identified a component of significance, as well as one of importance, to their own facility. They also confirmed that the safety systems and functionality were the same as the generic facility.

2.3 Implementation in the Plant PRA Model

This section outlines an implementation of margin expansion using FLEX equipment in the PRA model of a collaborating NPP. Figure 7 shows the SBO-mitigation fault tree that was inserted into the selected plant's SBO logic. This allows for the plant to stage and utilize FLEX diesels to maintain control of their direct current (DC) system and subsequent control systems. This would provide additional mitigation strategies in the instance of an SBO event as it provides a backup system once the plant's batteries deplete. The FLEX strategy in this case study relies either on a diverse feedwater injection using a self-powered FLEX pump or the recovery of a turbine-driven pump (TDP) or motor-driven pump (MDP) in an auxiliary feedwater (AFW) system by using a portable FLEX generator. This generator connects to the existing 480V power bus that also powers the valves required to modulate or cycle secondary-side steam for TDP operation and powers battery chargers connected to the bus.

When assessing FLEX equipment for online maintenance, the self-powered pump and generators were prestaged. This provides the same level of backup, but removes the need for operator actions and some of the redundancy because a single pump is used as a backup to each steam generator, instead of two backups. Figure 8 and Figure 9 show the fault trees used in the plant logic for this strategy. Note: the blank logic represents the plant's own PRA logic; names, descriptions, and probabilities were removed to protect the identity of the facility.

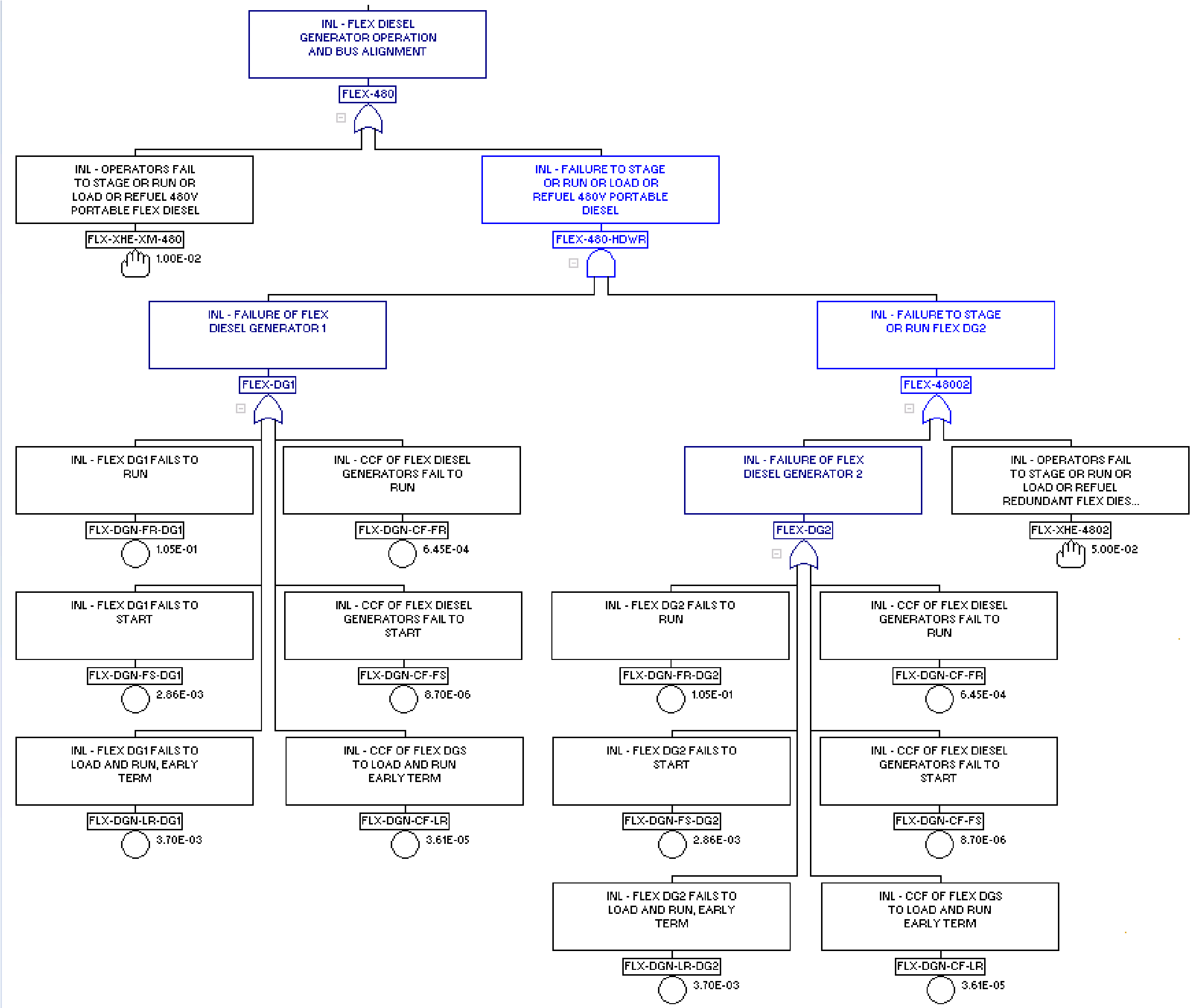

Figure 7. SBO fault tree for FLEX 480V diesel generators.

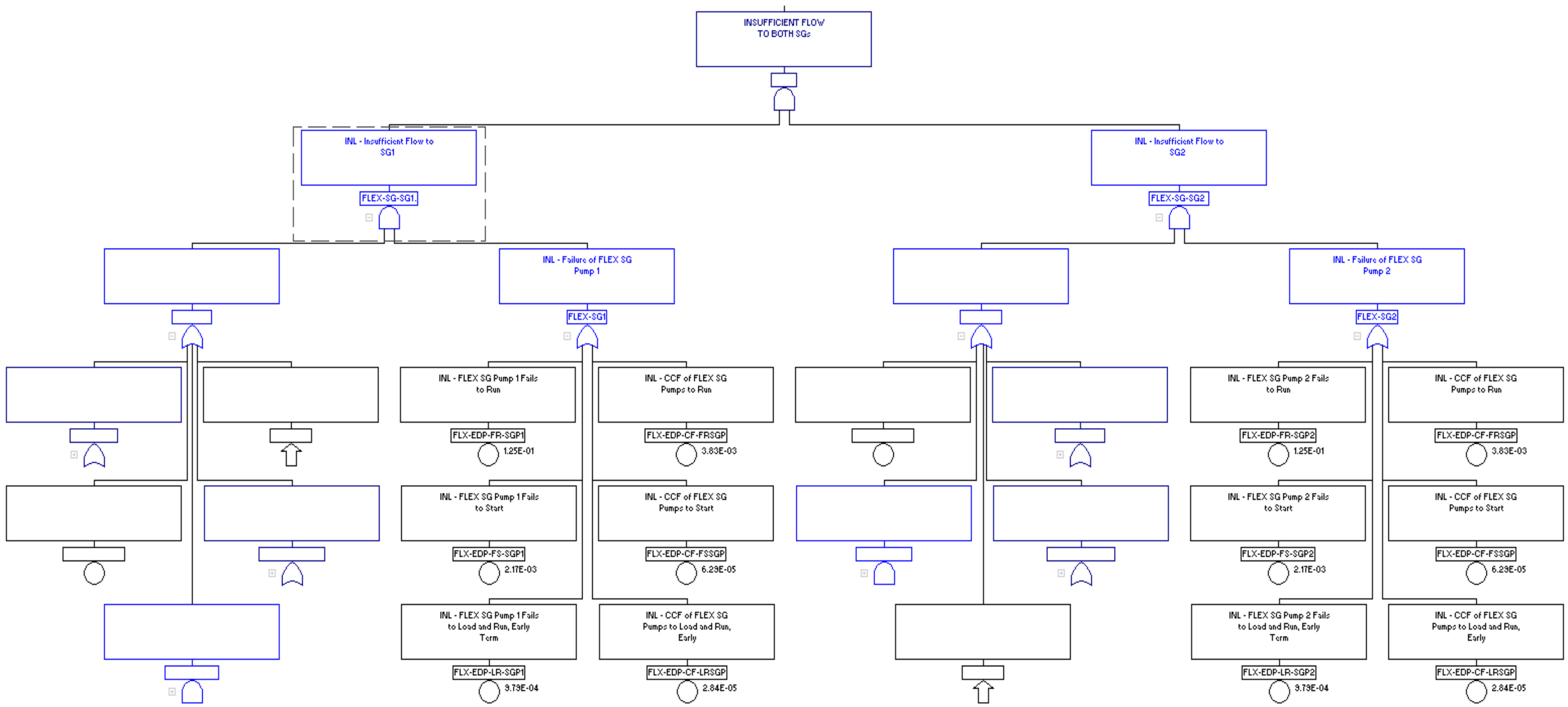

Figure 8. Fault tree for self-powered FLEX pump. Note: The blank logic represents the plants own PRA logic, the names, descriptions, and probabilities were removed to protect the identity of the facility.

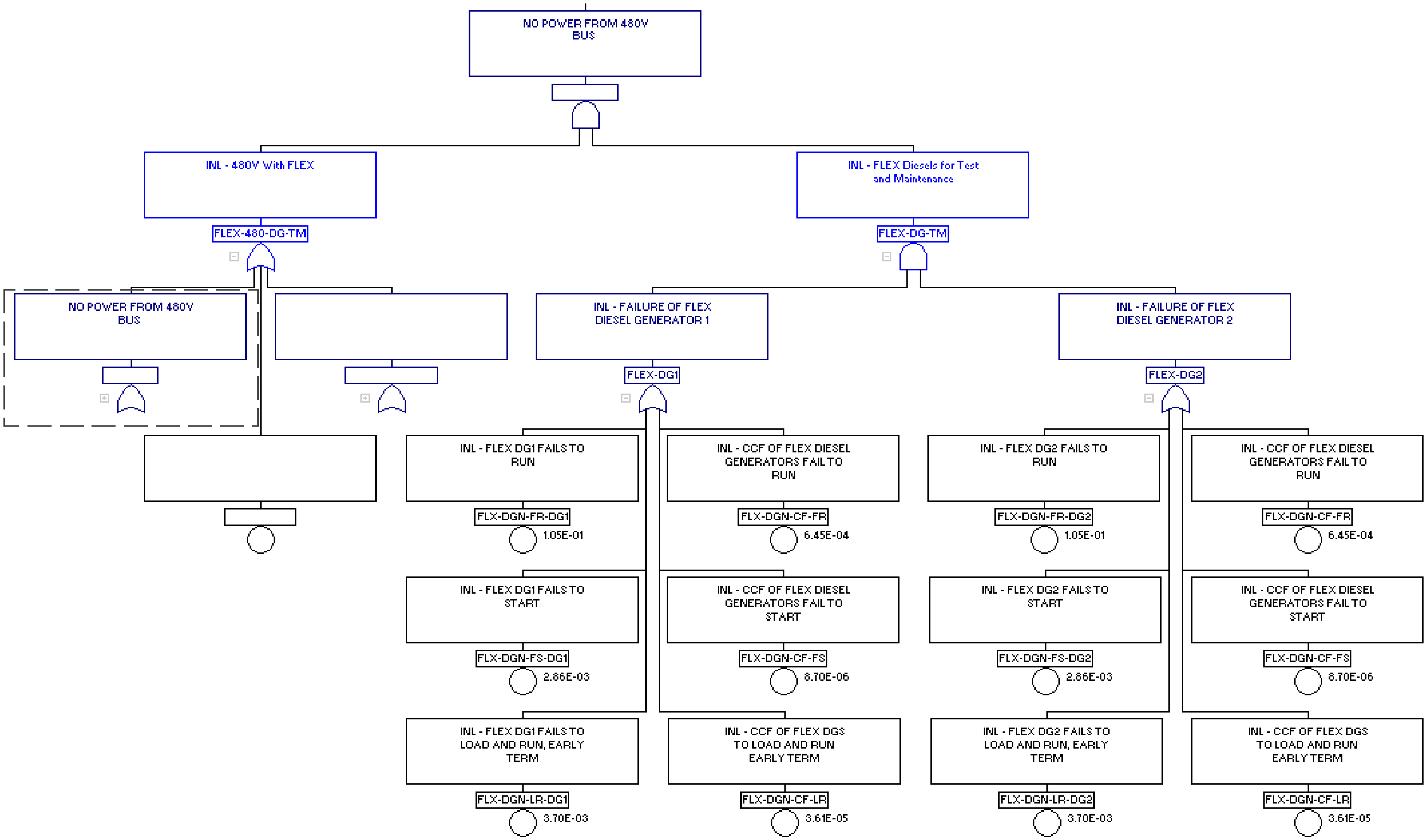

Figure 9. Fault tree for the 480V diesel generators. Note: The blank logic represents the plants own PRA logic, the names, descriptions, and probabilities were removed to protect the identity of the facility.

2.4 AOT Extension Application

An example of AOT extension in a collaborative nuclear power plant's PRA, using the steps described in the previous subsection, is as follows:

1. An AOT of less than 5 days was considered too short in this example. Therefore, the minimum RAW calculated with *Equation (4)* was 2, which is the risk-significant RAW criterion set forth in NUMARC 93-01.[13] One of the components to have a RAW value greater than 2 was the emergency diesel generator.
2. The test and maintenance probability of an EDG was set to 1 in the PRA model to simulate simply the unavailability of the pump, which resulted in an elevated CDF. This was used as CDF_2.
3. The safety functions that might be improved with FLEX strategies, as identified by Birnbaum importance, were emergency power using installed emergency diesel generators (EDGs) and decay-heat removal through the other steam generator (SG), where the TDP is available. Because the FLEX equipment in this case study, as shown in Figure 8 and Figure 9, do not include a 4.16 kV diesel generator to reinforce installed EDGs, the selected FLEX strategy was to provide a diverse means of supplying feed water through the intact SG. The goal was to see if the AOT would see a considerable extension by prestaging the FLEX equipment and including this factor into the plants PRA.
4. This was achieved by prestaging onsite FLEX equipment, as shown in Figure 10, as a redundancy to the existing AFW system and pre-coordinating with offsite FLEX centers. These preliminary actions may lower the chance of human failure to activate and sustain FLEX equipment as a backup provider of feedwater. The new configuration increased AOT by over 24 hours—about 50% increase in overall AOT for the diesel generator out of service—which allows more time for online maintenance.

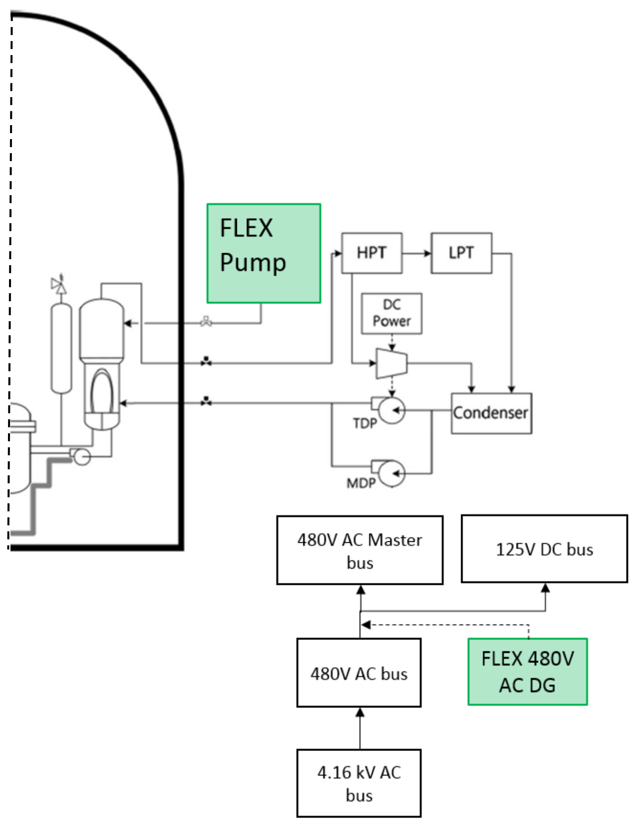

Figure 10. Prestaging secondary-side FLEX equipment.

2.5 FLEX Equipment in Refueling Outage Maintenance

FLEX equipment may also be utilized to provide maintenance flexibility during refueling outages.[7] One example is shown in Figure 11, where a portable FLEX pump is deployed to replace the high-pressure safety injection (HPSI) pump in refilling the safety injection tank (SIT) during an outage. This strategy may reduce wear and tear on the HPSI pump and make it available for maintenance. Another example is shown in Figure 12, where a portable FLEX generator is used to power the SFP pump. A self-powered FLEX pump is additionally staged as a redundant backup pump to further reduce risk. This strategy allows maintenance to be conducted on the electrical bus.

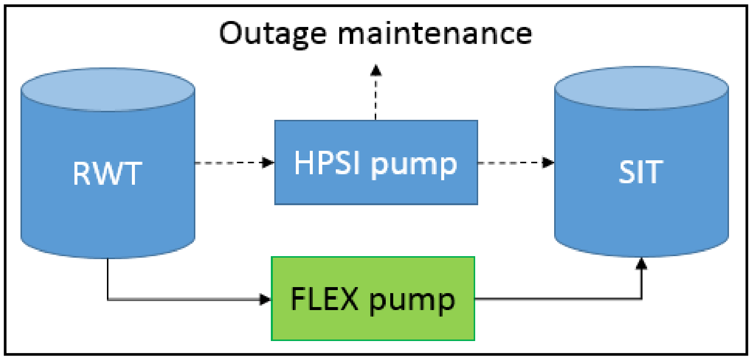

Figure 11. FLEX pump to refill SIT during refueling outage.

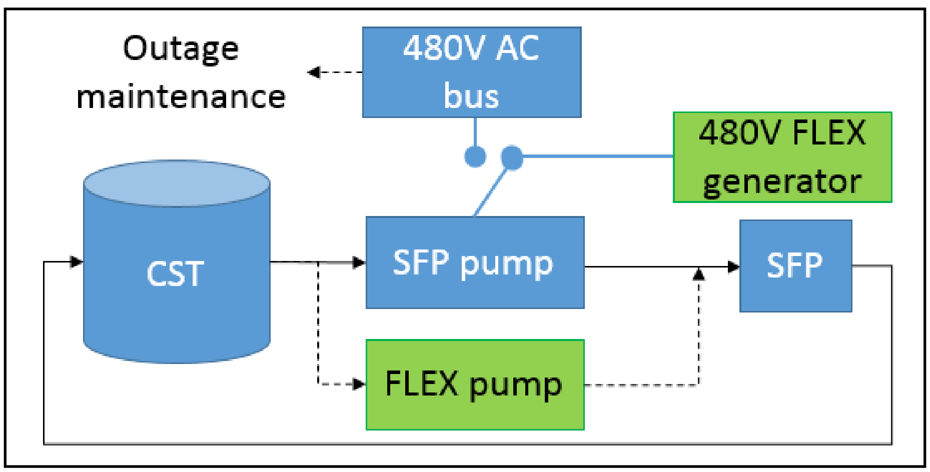

Figure 12. FLEX generator and pump used to cool spent fuel pool during outage.

Figure 13 shows the possible outcome of implementing the FLEX strategy to reduce plant risk and enable maintenance flexibility. The expected plant unavailability due to design-basis events (DBEs) is expected to decrease due to the inclusion of FLEX strategy into the plant PRA model. Incidental plant unavailability due to limiting conditions of operations (LCOs) may be reduced because of AOT extension using FLEX strategies. This AOT extension may also enable some of the maintenance routines in the refueling outage period to be shifted to online maintenance. The reduction of outage-maintenance tasks may, in turn, reduce the outage workload and allows for better outage planning, which reduces outage duration.

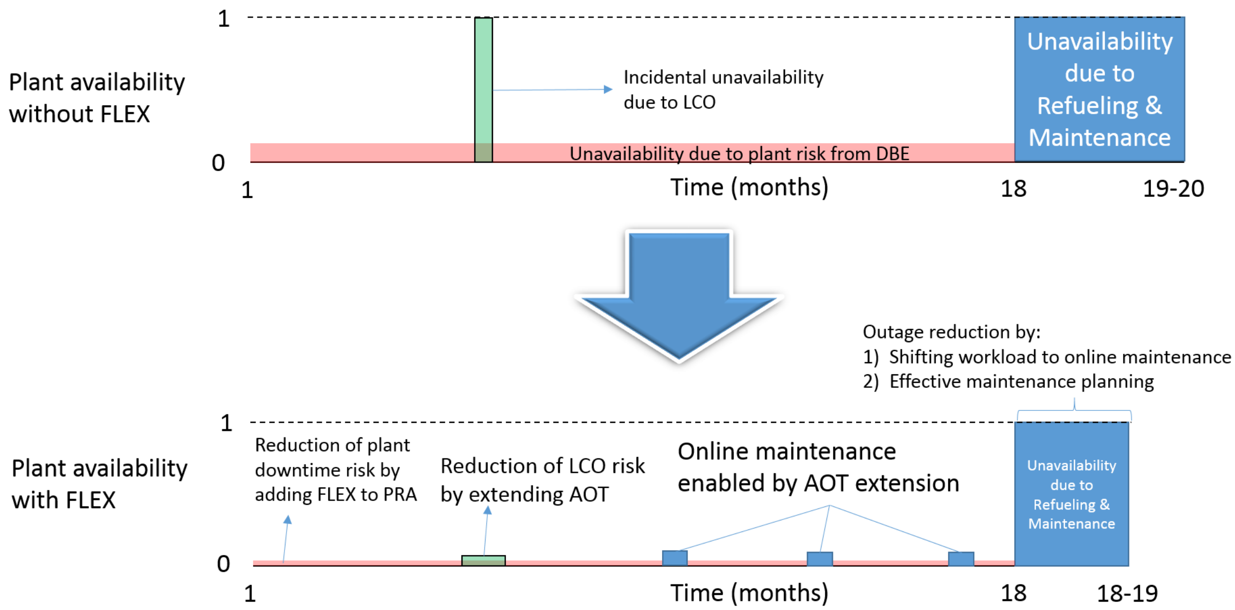

Figure 13. Expected outcome.

Figure 14 shows the various possible scenarios that may happen during maintenance.[8] Maintenance may be planned or unplanned due to unpredicted faults discovered during routine testing or online monitoring. Both scenarios may require a completion time exceeding AOT. When this happens, licensees either file a notice of enforcement discretion to the NRC or shut down the plant. Both options incur either costs or a loss of revenue (or both). This O&M costs may be averted by extending AOT using FLEX equipment. Furthermore, the extended AOT may allow maintenance activities to be conducted thoroughly with better quality compared to a rushed maintenance within a limited AOT. In that sense, this approach reduces the chance for a future equipment fault and a costly unplanned maintenance.

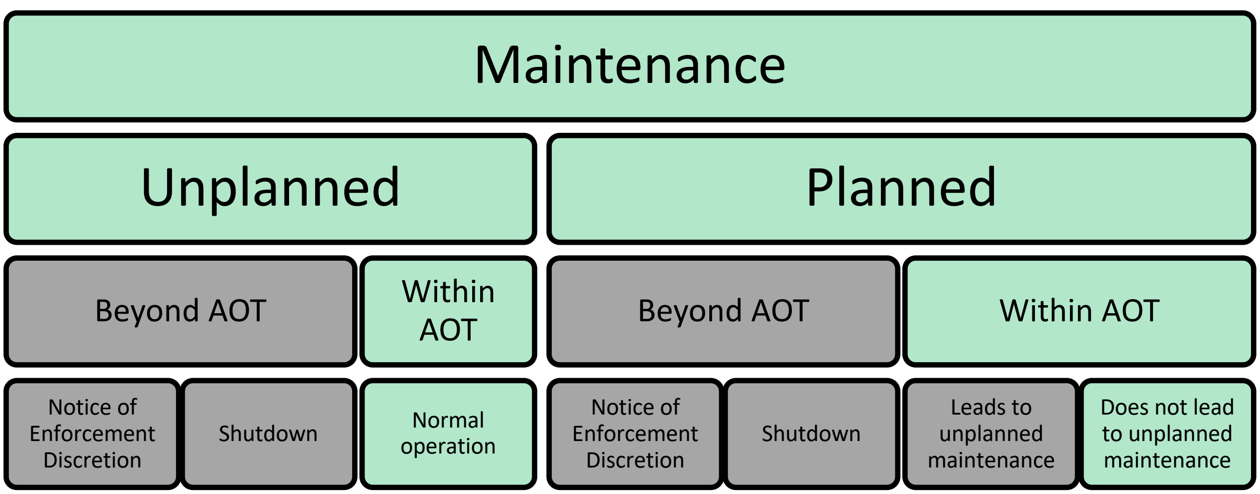

Figure 14. Expected maintenance scenarios.

2.6 Cost Analysis

This analysis is based on the premise that using FLEX equipment can maintain or reduce the CDF such that an NRC inspection is avoided. The example shows what an NRC inspection might cost.

The NRC estimates that the hourly cost of a staff professional is $275/hr.[9] This is the recommended estimate of the cost of NRC staff onsite to conduct an inspection or conduct testing at an NPP facility. It is the basis of the cost estimate illustrated in the example below.

Ball[10] provides guidance on how to estimate costs for various aspects of nuclear operations, including estimating the cost of an NRC inspection. Although it is somewhat dated, the document provides a framework for estimating NRC inspection costs. Ball[10] illustrates the NRC technical-staff requirements for a series of inspections (see Ball[10] Table 7.1 “Summary of Average NRC-Related Costs”). The left-hand column of Table 1 lists the different types of inspection events listed in Ball. Ball next provides factors to add to the technical-staff requirements. That is, for each event type, there are different types of inspectors that may be required to perform the inspection. Table 1 shows the combination of inspection events with inspector types and the estimated cost. Thus, the costs in the table represent staff requirements as outlined in Ball and cost estimates from the hourly staff cost provided by the NRC.

Table 1 shows that, given the inspection event possibilities listed in Ball, inspection costs could range from a low of $36k per event to almost $667k. This provides a sense of benefits NPP might capture if allowed to take credit for FLEX equipment in avoiding technical specification required shutdown.

Table 1. Estimated inspection cost estimates for four inspection event types.

Inspection Events	Resident Inspector ($)	Senior Resident Inspector ($)	Specialized Inspector ($)	Project Inspector ($)
Series F	36,383	43,698	60,253	96,250
Series A-E, G	90,956	109,244	150,631	240,625
Reload Reviews	109,148	131,093	180,758	288,750
Reload Methods	252,079	302,761	417,464	666,875

1. Average cost per professional hour $275 (NRC 2018)
2. Inspector adders and technical staff hours per inspection event from[11]

As was noted previously in the report, a review of the LER database finds as many as 86 technical specification required shutdowns since 2010. When a plant is shutdown, power-plant owners incur another cost: the opportunity cost of shutdown. That is, opportunity cost represents foregone revenue the facility could have generated had it not been shut down. The LER records do not confirm the length of time facilities are shut down. Thus, the opportunity cost is considered on a per day basis.

In July of 2018, the Energy Information Administration (EIA) reported that the average retail sales price of electricity across all user types was 11.02¢/kWh.[12] This equates to $110.2/MWh. Suppose a nuclear power plant is shut down for a 24-hour period. The opportunity cost in the foregone revenue depends on the size of the facility. In terms of $/MWh, a plant with capacity of 800 MWe loses $2.1M per day. A plant with capacity of 1000 MWe loses to $2.6 million per day, and the cost reaches $3.7 million per day for a plant that has capacity to produce 1400 MWe. Adding the opportunity cost to the direct cost reinforces the significant costs that might be avoided through the implementation of FLEX equipment.

3. CONCLUSION

This work presents implementation of the following framework to utilize portable FLEX equipment when a component failure can potentially lead to technical specification required shutdown:

1. Identify the components the failure or unavailability of which would result in 10 CFR 50.73(a)(2)(i)A reportability requirement postulated by the NRC for technical specification required shutdown to be reported in NRC's LER database.
2. Identify the FLEX equipment that could be utilized as a standby to the failed component.
3. Develop a PRA model that incorporates the FLEX equipment within the current plant PRA model.
4. Perform PRA calculations to determine the change in CDF and the change in risk-informed AOT.
5. Perform cost-benefit analysis to determine the economic feasibility of implementing the FLEX equipment.

In this work, PRA is used to model prestaging onsite FLEX equipment as a redundancy to the existing auxiliary feedwater system, and pre-coordination with offsite FLEX centers. The new configuration increases the allowable outage time by about a 50% overall for events that leave the diesel generator out of service. The implementation and analysis presented in this report provides strong technical evidence that FLEX portable equipment can be used to extend the AOT. The framework presented is sufficiently generalizable in that it can be readily implemented by any U.S. commercial utility on its specific PRA model. The results of implementing this framework would provide the utilities a sound and reliable way to file regulatory requests for AOT extension. The cost analysis presents the direct and indirect savings to the NPP on utilizing the portable FLEX equipment. PRA models developed in this work are distinct from the models that incorporate FLEX equipment for their intended use in SBOs, etc., and not during normal plant operation. The benefits to NPP of utilizing the FLEX equipment during normal operations, and performing the PRA developed in this work, include:

1. A risk-informed plant shutdown alternative to current technical specification required shutdowns.
2. Extension of AOT to initiate technical specification required shutdown.
3. Reduced economic impact of component failure, avoidance of plant shutdown, and maximized generation.
4. Direct and indirect cost savings versus those associated with a technical specification required shutdown.

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