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Revision 0

Light Water Reactor Sustainability Program

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

Vaibhav Yadav, Jason K. Hansen, Shawn St. Germain and Robby Christian

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EXECUTIVE SUMMARY

Economic or financial causes have led to closure or announcement of early retirement of several US nuclear reactors in 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 63 of the 79 studied nuclear power plants (NPP) 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 accounts for about 70% of total operating expenditures for an NPP. The Light Water Reactor Sustainability (LWRS) Program conducts research and development, sponsored by the US Department of Energy, that provides a technical foundations for licensing and managing the long-term safe and economical operation of current nuclear power plants, 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, economical, and long-term operation.

There are many ways of reducing the O&M costs; this work presents an innovative framework of reducing O&M costs by utilizing the 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 the onsite Flex asset that stands unutilized most of the time. Recently there have been active efforts to develop strategies through which NPPs can take credit for the Flex equipment. This work 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.

Two areas that have potential to utilize portable Flex equipment includes 1. Technical specification required shutdown due to component failure, and 2. Scheduled maintenance during a refueling outage. This report presents the risk- and cost-analysis framework for the technical specification required shutdown due to component failure. The licensee event report (LER) database of the NRC shows that the commercial NPPs in the US reported 86 technical specification required shutdowns since year 2010. When a component failure or unavailability leads to a technical specification required shutdown, the NPPs suffers both direct costs in terms of loss of revenue arising from the loss of generation and indirect costs in 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, postulated

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

2. Identify the Flex equipment that can be utilized as a standby to the failed component.
3. Develop a probabilistic risk assessment (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

In this work, a demonstration probabilistic risk assessment (PRA) model is developed that incorporates a portable Flex pump when a turbine-driven pump has failed to start. The cost analysis presents the 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 black out, but not during normal plant operation. 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. Reducing economic impact of component failure, avoiding plant shutdown, and maximizing generation. 4. Save the direct and indirect costs associated with technical specification required shutdown.

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FIGURES

TABLES

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 US nuclear reactors in 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 63 of the 79 studied nuclear power plants (NPP) 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 accounts for about 70% of total operating expenditures for an NPP (Figure 2). This work presents an innovative framework of reducing direct and indirect maintenance costs by utilizing the onsite FLEX equipment at an NPP.

There are many ways of reducing the O&M costs; this work presents an innovative framework of reducing O&M costs by utilizing the 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 reactor core, maintain containment integrity, and cool a spent-fuel pool (SFP) (Figure 3). Further details on the required safety functions from FLEX equipment for pressurized water reactor (PWR) and boiling water reactor (BWR) are available in the Nuclear Energy Institute (NEI) FLEX implementation guide.[4] In the past years, several NPPs have invested in procuring and maintaining the onsite FLEX asset that stands unutilized most of the time. Recently there have been active efforts to develop strategies through which NPPs can take credit of the FLEX equipment. This work focuses on identifying areas where FLEX equipment can be utilized during normal plant operation and develop a framework to reduce O&M costs without impacting plant safety.

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

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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.

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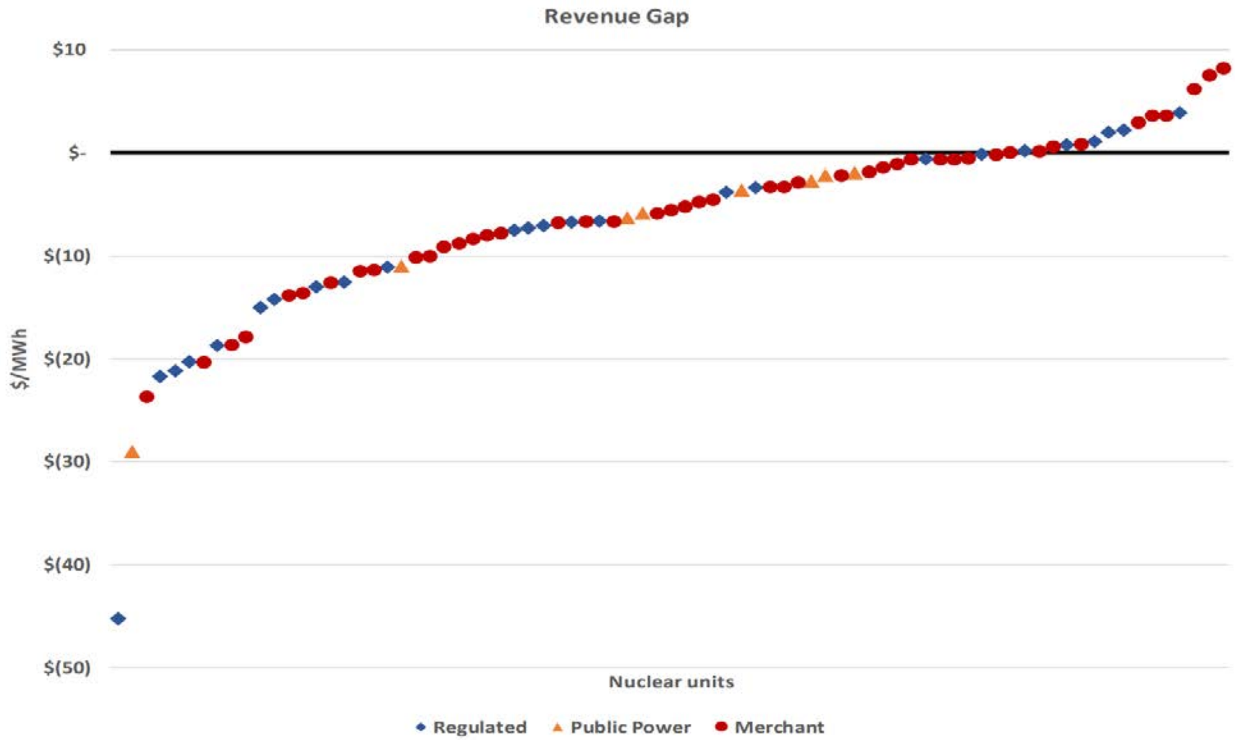

Figure 1. Revenue gap of NPPs in USA.[2]

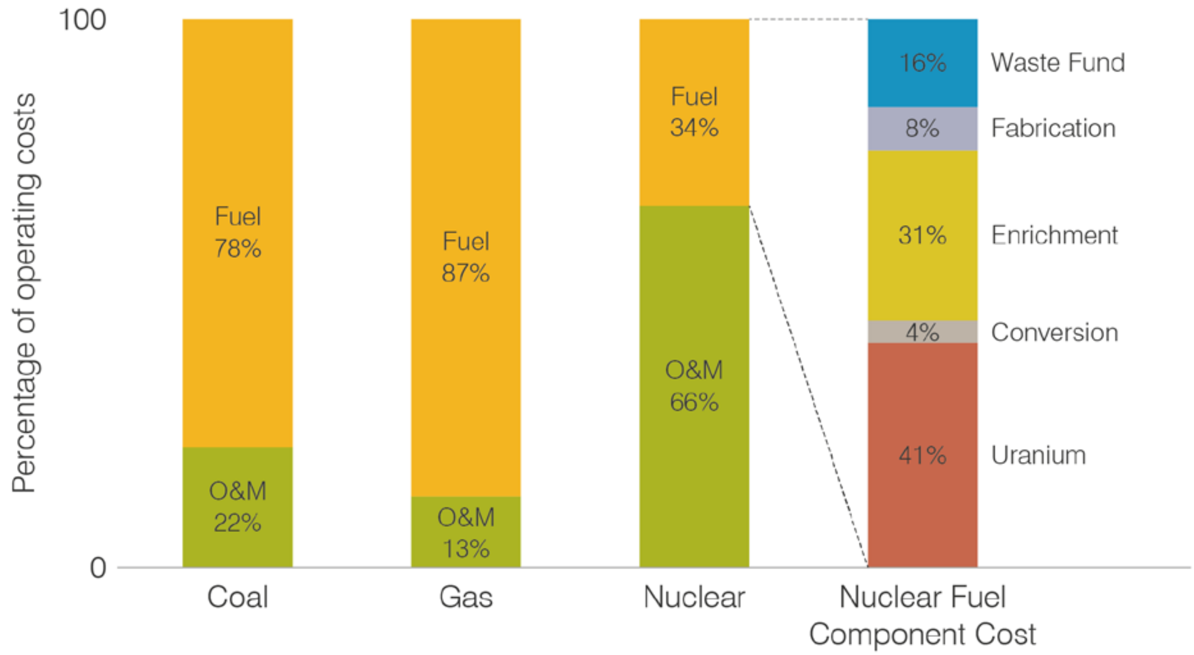

Figure 2. Contribution of O&M costs and fuel costs in coal, gas, and nuclear power plants. Source: NEI.

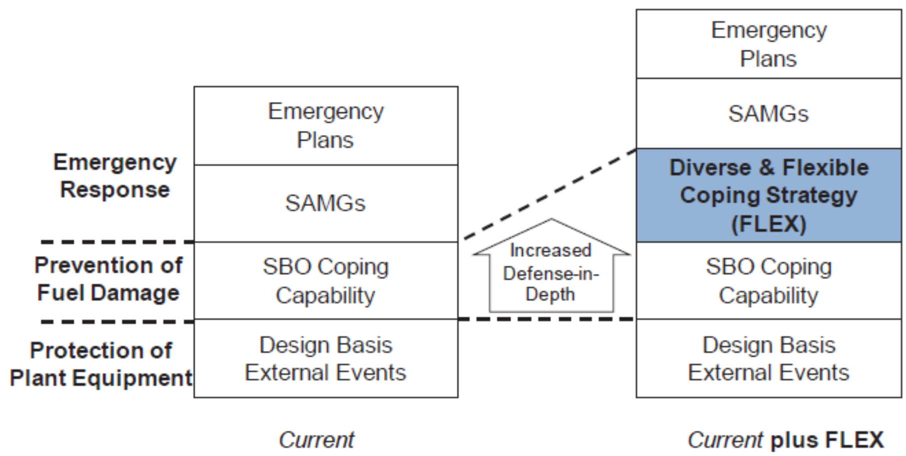

Figure 3. FLEX strategy.[8]

2. METHOD

The general approach of this research is shown in Figure 4. The first stage is to incorporate existing FLEX strategy into the NPP risk model to expand the plant risk margin.[5] The second stage leverages the portable 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 a lower risk compared to the original plant configuration with a reduced O&M cost.

Several key guidelines[4] need to 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, can be implemented in mitigating strategies where they provide a safety function or be implemented in efficiency strategies to provide improvements in plant operations. Another important guideline is that there should 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 SBO event.

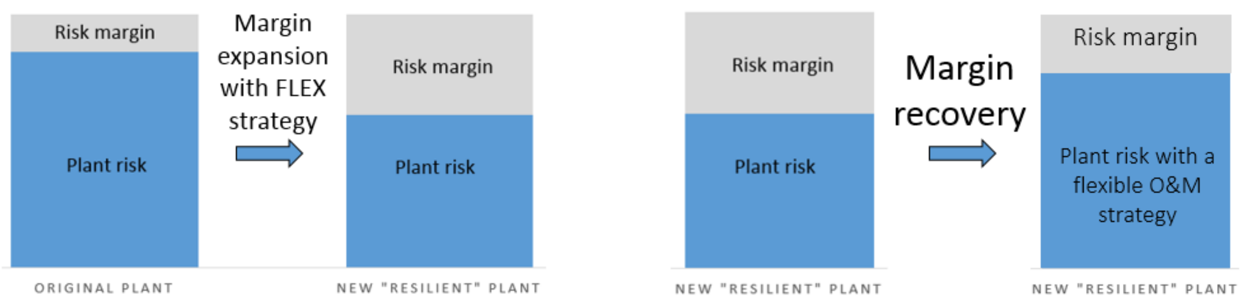

Figure 4. Research approach.

2.1 FLEX 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 a guidance to perform this task, which is 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 to the 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 need to be addressed to credit FLEX strategy into a PRA model compliant 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 the HEP in human actions 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 ASME/ANS PRA standard. NRC also underlined that the technical bases for HEP to initiate mitigating strategies should be submitted for a regulatory review. NRC highlights the need for an acceptable guidance for identifying and assessing pre-initiator human failures in maintenance of FLEX equipment, which may render the equipment unavailable during an event.

NRC emphasized that realistic failure rates for FLEX equipment should be used in lieu of using failure rates of permanently installed equipment. The failure estimates for permanent equipment should not be used because limited information available for FLEX equipment indicates a potential significant difference from permanent plant equipment. In order to obtain realistic values for FLEX equipment, plant-specific of 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.

Table 1. SBO core damage sequence.

Original SBO core damage sequences (Figure 5)		Corresponding SBO sequences when FLEX strategy is implemented (Figure 9)	
Sequence Number	End status	Sequence Number	End Status
3	Core damage	3	OK
		4	Core damage
		5	Core damage
5	Core damage	7	OK
		8	Core damage
		9	Core damage
6	Core damage	10	Core damage
9	Core damage	20	Core damage
10	Core damage	14	OK
		15	Core damage
		16	Core damage
		17	OK
		18	Core damage
		19	Core damage
		20	Core damage
11	Core damage	21	OK
		22	Core damage
		23	Core damage
		24	OK
		25	Core damage
		26	Core damage
		27	Core damage

2.2 Case Study

This section outlines a case study of margin expansion using FLEX equipment. Figure 5 shows an SBO mitigation event tree for a PWR reactor. There are six sequences leading to core damage in this event tree, as shown in Table 1 where FLEX strategy is implemented as an additional mitigation effort in four sequences. The table indicates that FLEX may reduce plant risk by creating several new scenarios to safely shutdown the reactor. The FLEX strategy in this case study relies on a diverse feed-water injection using a self-powered FLEX pump, or the recovery of a turbine-driven pump (TDP) or motor-driven pump (MDP) of an auxiliary feed-water (AFW) system by using a portable FLEX generator. This generator connects to the existing power bus, which also powers the valves required to modulate or cycle secondary-side steam for TDP operation and charges batteries connected to the bus. Figure 6 and Figure 7 show the fault tree for this strategy. The modified SBO event tree crediting FLEX strategy is shown in Figure 9. Sequence Number 1, in both the original and modified SBO mitigation event tree, is considered separately in a general-transients event tree. Plant core damage frequency (CDF) before and after incorporation of FLEX is shown in Figure 8. The figure shows that FLEX strategy in this study significantly reduces CDF due to SBO events.

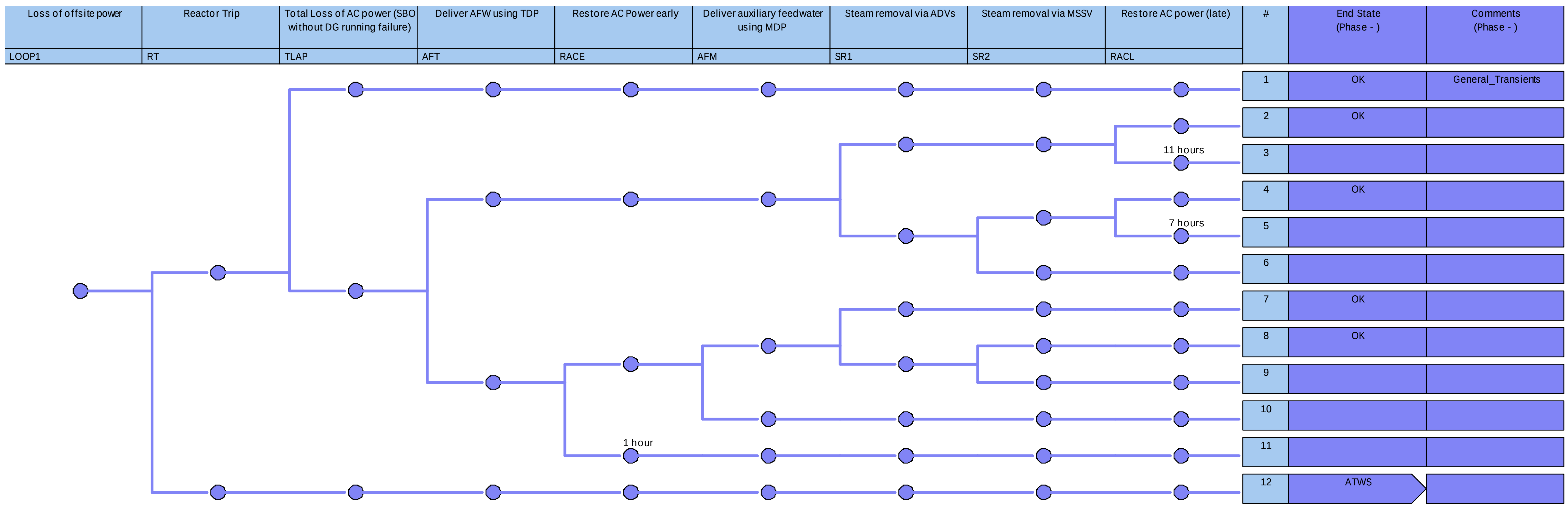

Figure 5. SBO event tree for a PWR reactor.

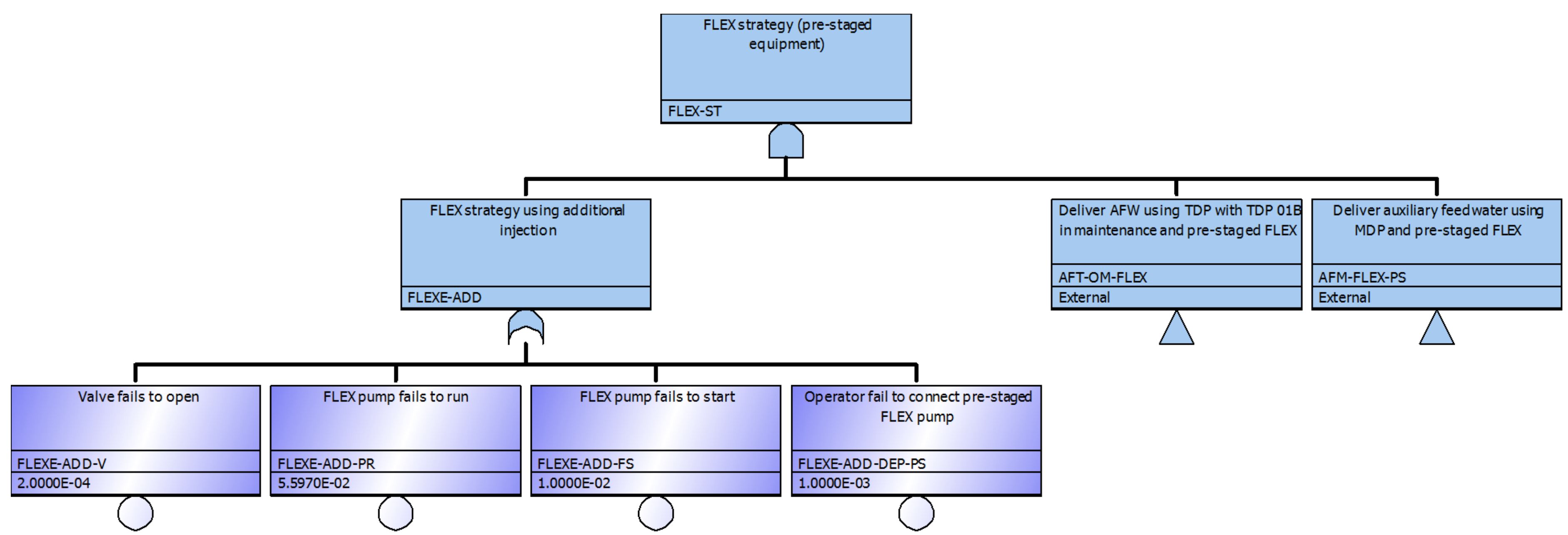

Figure 6. Fault tree for FLEX strategy.

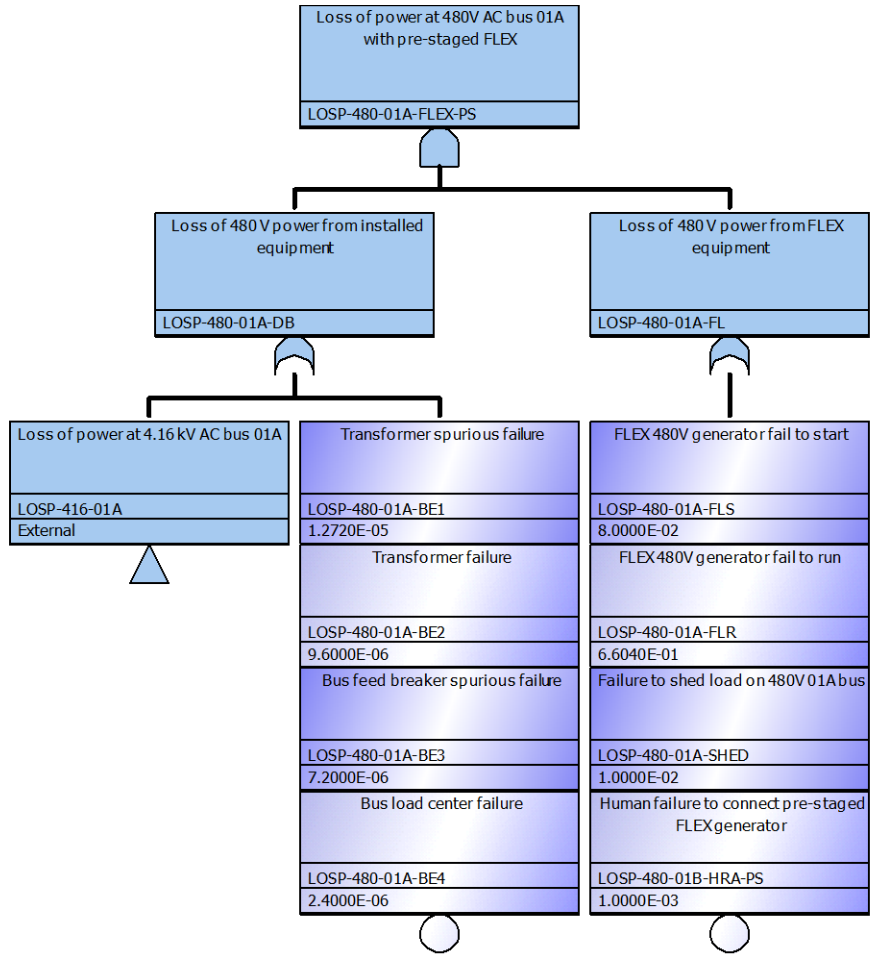

Figure 7. FLEX strategy using portable generator.

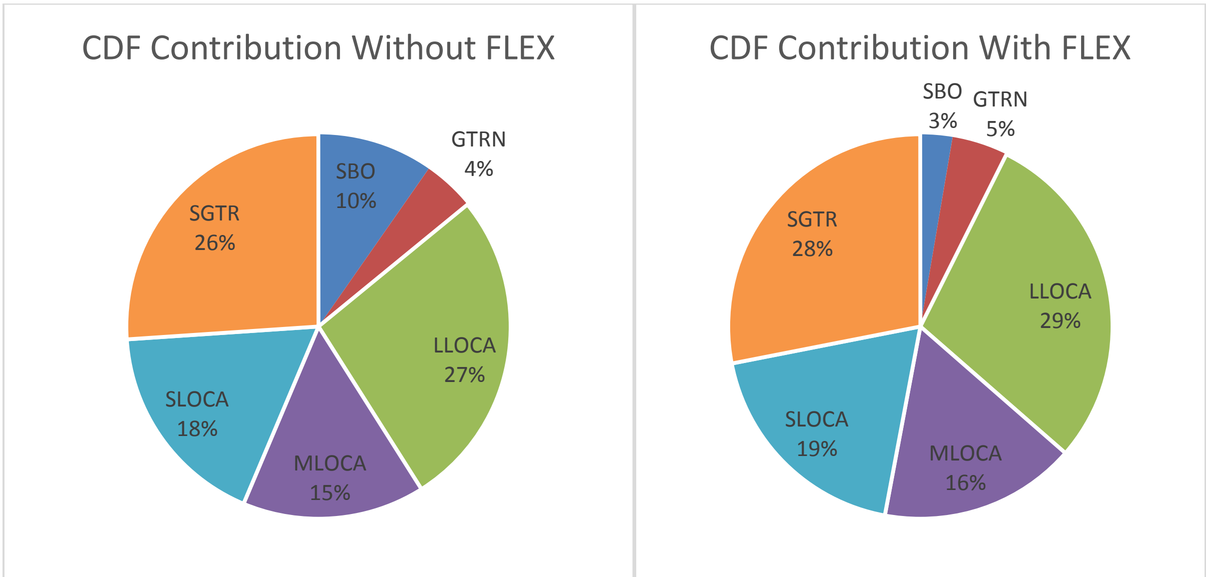

Figure 8. Plant risk change with FLEX introduction.

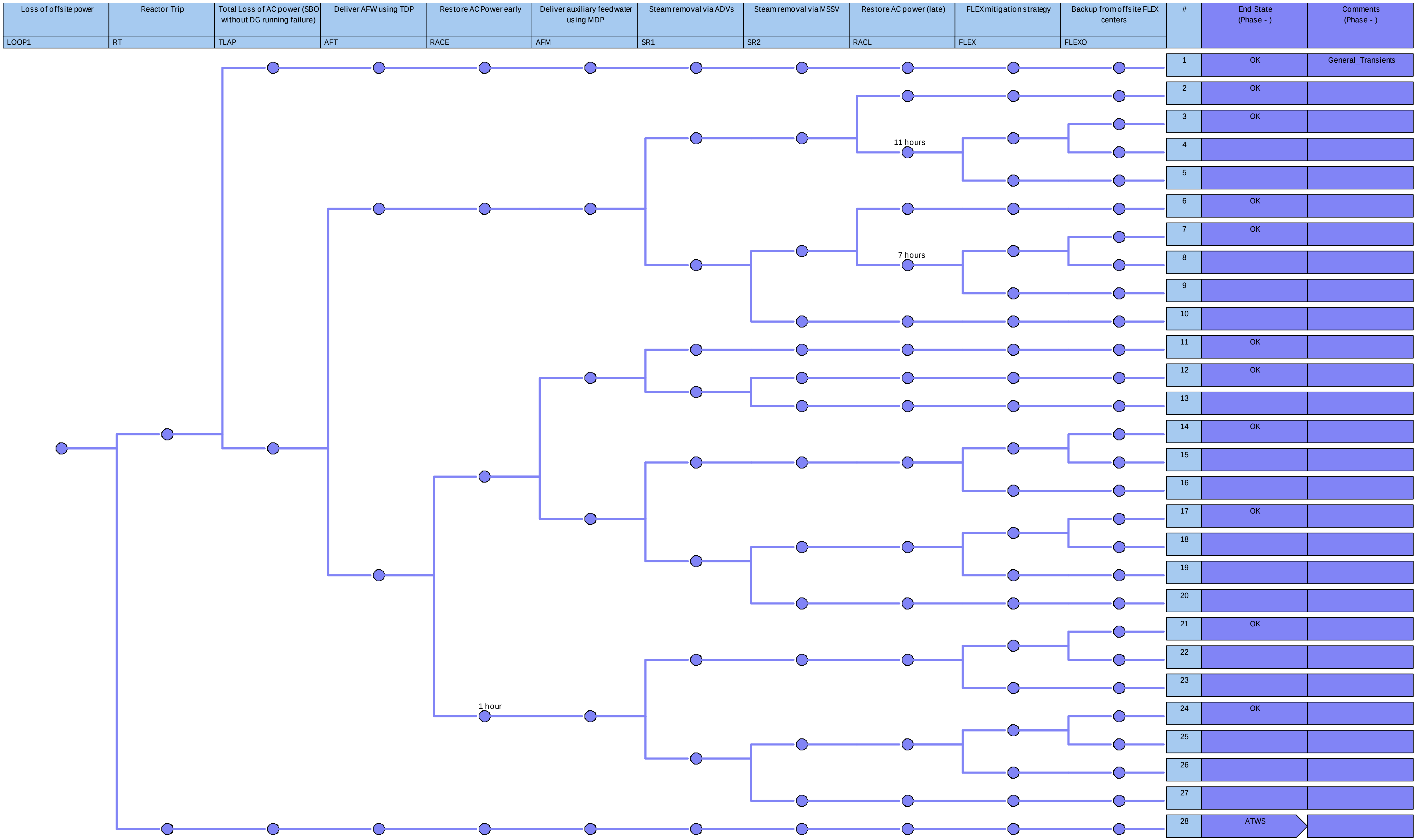

Figure 9. SBO mitigation with FLEX strategy.

2.3 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 technical specifications (TSs). This regulation can be used to estimate how long an installed equipment can be taken out of service, i.e., allowed outage time (AOT), without shifting to the lower plant-operation mode (e.g., shutdown) as illustrated in Figure 10. 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 NPP's capacity factor.

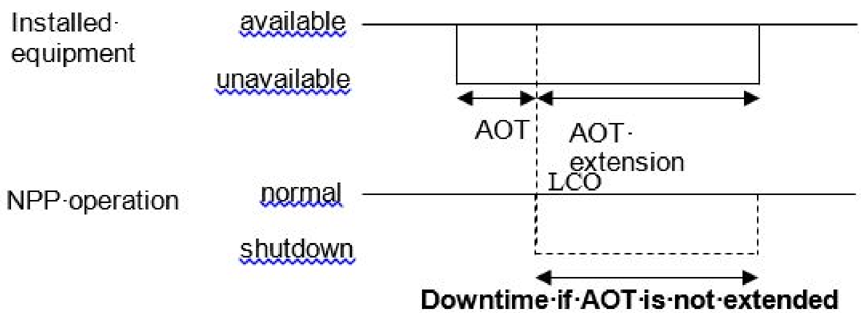

Figure 10. AOT extension.

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

6. 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.
7. Identify the target components for which AOT is considered too short and for which AOT may need to be extended using risk information. Analyze the importance of basic events in cut sets from Step 1 using 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)*.

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

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

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

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

8. 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.

9. 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 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 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.
10. 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. Now, implement this strategy as a redundant mitigation strategy to the corresponding installed safety function. It should 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 11 illustrates the aforementioned steps to extend AOT. Step 1 sets the baseline plant risk CDF_1. Step 3 increases the plant risk to CDF_2. The ICCDP parameter given in *Equation (3)* is a product of delta CDF and AOT. Step 5 reduces the plant risk from the supposed CDF_2 to CDF_3, thereby lowering the delta CDF. This lower delta CDF enables AOT to be extended while complying with the ICCDP guideline of 1E-6.

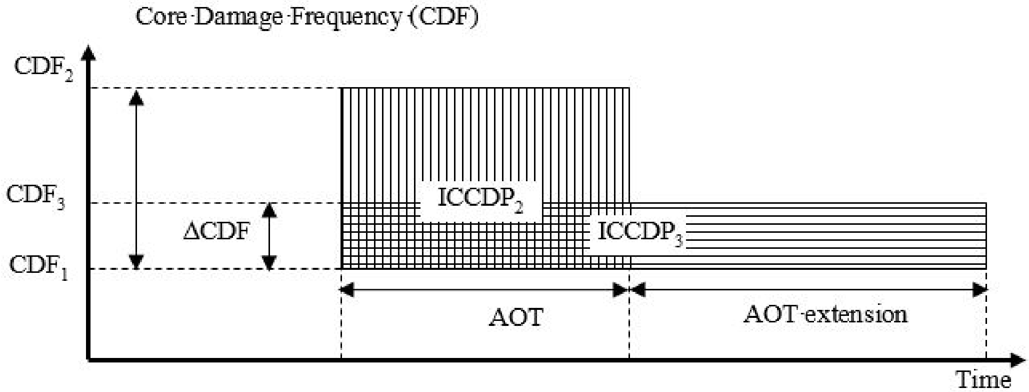

Figure 11. AOT extension in compliance to allowed risk acceptance guideline.

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 case, the FLEX strategy in Step 5 should follow the following equations:

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

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

2.4 AOT Extension Case Study

An example of AOT extension in a 1000 MWe PWR plant using the steps described in the previous subsection is as follows:

1. CDF_1 with the incorporation of FLEX strategy as shown in Figure 9 was at the order of 1E-5.
2. AOT less than 5 days was considered too short in this example. Therefore the minimum RAW calculated with *Equation (4)* was 4.25. Approximately 160 basic events were found having RAW values above 4.25, including valve and TDP failures. TDP, with RAW values ranging from 4.3 to 4.5, was selected for further investigation, since a TDP maintenance may take longer than 5 days.
3. The fail-to-start probability of a TDP was set to 1 in the PRA model to simply simulate unavailability of the pump, which resulted in a CDF_2 of 1E-4. This risk increase corresponded to an AOT of 4 days.
4. It was considered to extend the AOT to a total of at least 10 days. The safety functions which may 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 6 and Figure 7, 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 required failure probability value (P_3) for this combined feed-water supply means was less than 4E-4.

5. The failure probability for the FLEX strategy in order to achieve the P_3 value should be less than 2.8E-2. This was achieved by prestaging onsite FLEX equipment, as shown in Figure 12, 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 to provide feed water. The resulting CT with this strategy was found to be 10 days.

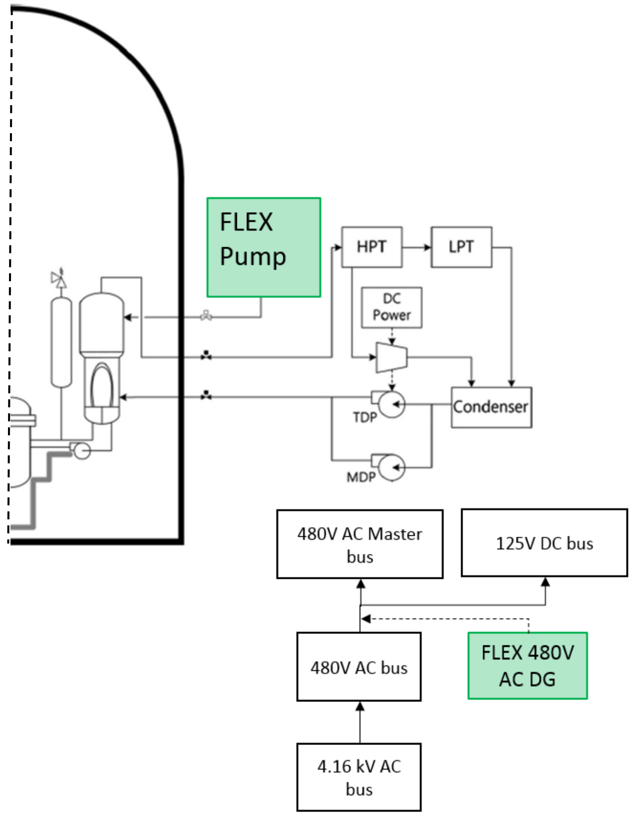

Figure 12. Pre-staging secondary side FLEX equipment.

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 13, 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 the wear and tear of the HPSI pump and makes it available for maintenance. Another example is shown in Figure 14, 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 risks. This strategy allows maintenance to be conducted on the electrical bus.

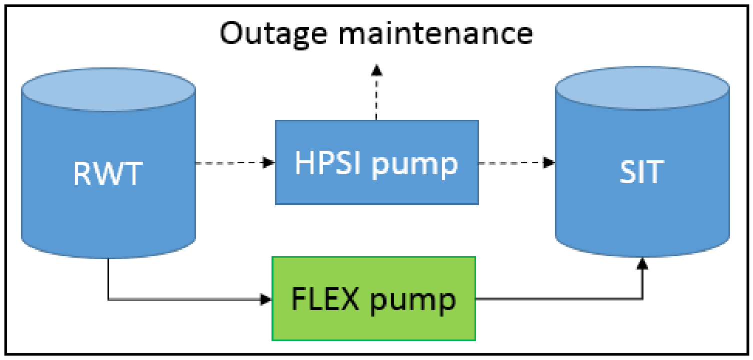

Figure 13. FLEX pump to refill SIT during refueling outage.

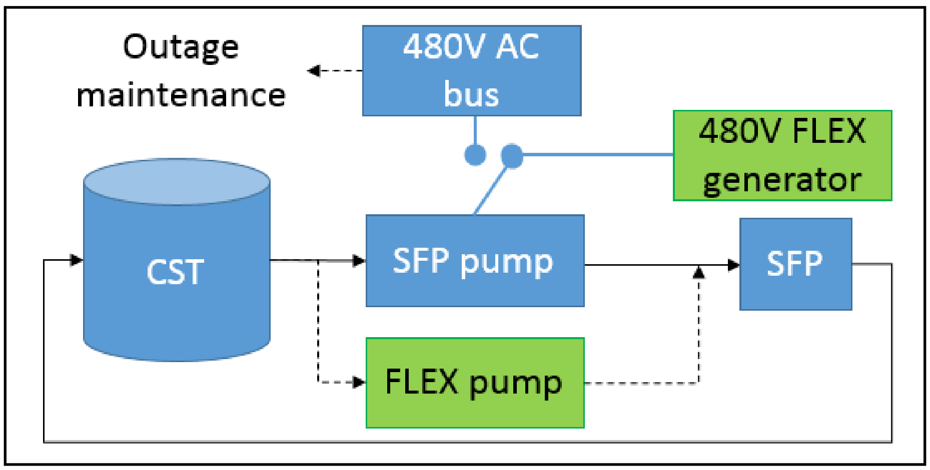

Figure 14. FLEX generator and pump used to cool spent fuel pool during outage.

Figure 15 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.

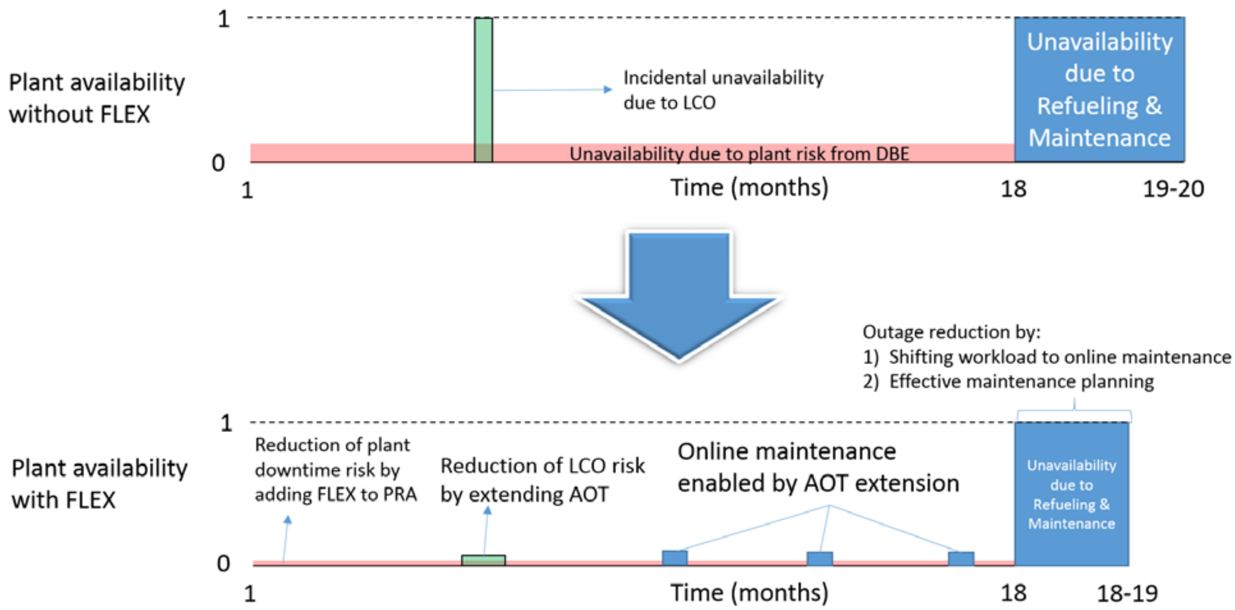

Figure 15. Expected outcome.

Figure 16 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 costs and/or a loss of revenue. 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 a 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.

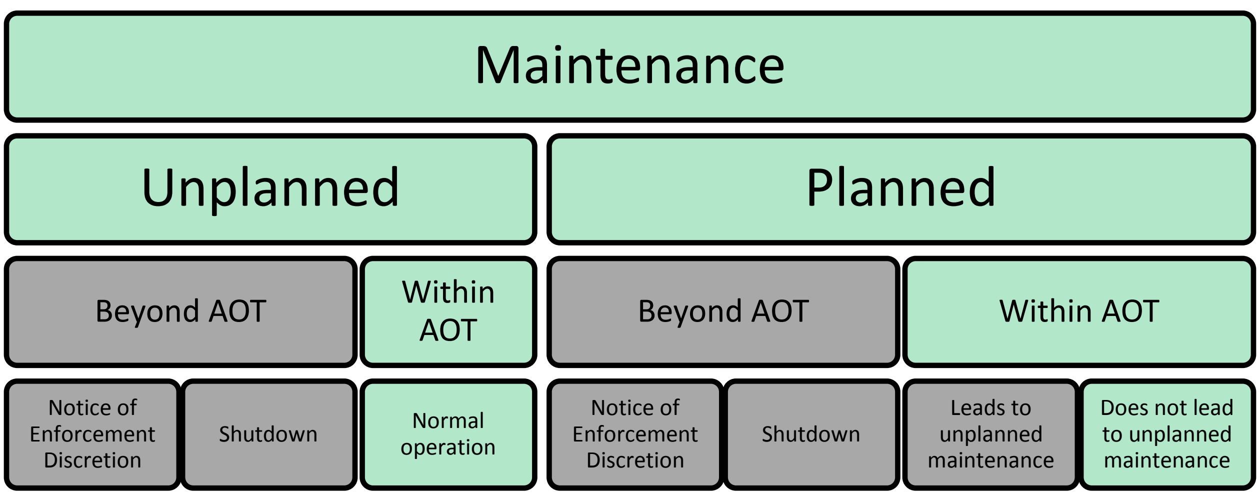

Figure 16. Expected maintenance scenarios.

2.6 Cost Analysis

The 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 2 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 2 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 2 shows that, given the inspection event possibilities listed in Ball, inspection costs could range from a low of $36 thousand per event to almost $667 thousand. This provides a sense of benefits NPP might capture if allowed to take credit for FLEX equipment in avoiding technical specification required shutdown.

Table 2. 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]

Noted previously in the report, a review of the LER database finds that as many as 86 technical specification required shutdowns since 2010. When the 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 consider the opportunity cost on a per day basis.

In July of 2018 the Energy Information Administration (EIA) reports 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 amount of the opportunity cost, the foregone revenue, depends on the size of the facility. At this rate in terms of $/MWh a plant with capacity of 800 MWe loses $2.1 million per day. For a plant that is 1000 MWe it rises to $2.6 million per day and reaches $3.7 million per day for a plant that is 1400 MWe. Adding the opportunity cost to the direct cost results in significant cost savings that might be avoided through the implementation of FLEX equipment.

3. CONCLUSION

This work develops the following framework to utilize the portable Flex equipment when a component failure can potentially lead to technical specification required shutdown: 1. Identify the components whose failure or unavailability resulted in 10 CFR50.73(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 can be utilized as a standby to the failed component. 3. Develop probabilistic risk assessment (PRA) model that incorporates the Flex equipment within the current plant PRA model. 3. Perform PRA calculations to determine the change in core damage frequency (CDF) and the change in risk-informed allowable outage time. 4. Perform cost-benefit analysis to determine the economic feasibility of implementing the Flex equipment.

In this work, a demonstration probabilistic risk assessment (PRA) model is developed that incorporates a portable Flex pump when a turbine driven pump has failed to start. The cost analysis presents the direct and indirect savings to the NPP on utilizing the portable Flex equipment. The PRA models developed in this work are distinct from the models that incorporate Flex equipment for their intended use like station black out etc., and not during normal plant operation. The benefits to NPP of utilizing the Flex equipment during normal operations, and performing PRA developed in this work, include: 1. 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. Reducing economic impact of component failure, avoiding plant shutdown, and maximizing generation. 4. Save direct and indirect costs associated with technical specification required shutdown.

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