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# Use of PSA Methods to Evaluate Technical Decisions Performed on Unit 5 and 6 on the Kozloduy NPP

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**Abstract.** The PSA enables the application of an integrated approach in the safety analysis of NPPs, being a conceptual and mathematical tool for deriving quantitative estimates regarding the CDF/FDF or the LERF, which are often used as quantitative measures to identify weaknesses in the design or operation of the NPPs.

Maintaining a high level of safety predetermines the implementation of various TDs and determining changes in the project of nuclear facilities (replacement of equipment, implementation of new systems, changes in instructions and/or operating practices, strengthening of buildings and facilities, etc.). The PSA methods allow us to adequately assess the NPP safety affected by each one or a group of TDs, implemented over time. The change in CDF/FDF and LERF is used to determine the impact on the risk by the relevant TDs, while simultaneously providing an estimate of the TDs' significance. Each TD or a group of TDs affects the PSA level 1 model in a different way and accordingly, different techniques can be applied for their assessment. This report presents the basic framework for evaluating TDs while using the PSA methods, implemented in the RiskSpectrum PSA software.

**Keywords:** nuclear power plant, technical decisions, probabilistic safety assessment, CDF/FDF, RiskSpectrum

Nomenclature

| | |
|---|---|
| PSA | — Probabilistic Safety Assessment |
| (K)NPP | — (Kozloduy) Nuclear Power Plant |
| CDF/FDF | — Core/Fuel Damage Frequency |
| LERF | — Large Early Release Frequency |
| TD | — Technical Decisions |
| MCS | — Minimal Cut Sets |
| ET | — Event Tree |
| FT | — Fault Tree |
| BE | — Basic Event |
| IE | — Initiating Event |
| SSC | — Systems, Structures, and Components |
| SFP | — Spent Fuel Pool |
| $N_{nom}$ | — Nominal power |

## 1 Introduction

### PSA: the main indicator regarding the TD impact on the NPP safety

PSA serves as an integrated approach to evaluating the safety of NPPs and serves as a conceptual and mathematical tool for deriving quantitative estimates concerning CDF/FDF or LERF, which conventionally serve as quantitative measures to assess the risk associated with NPP operation. The PSA methodology amalgamates operational practices and history, component reliability, human behavior, NPP response to various events, specific phenomena, and measures taken to mitigate potential impacts on the environment and health.

The maintenance of high safety levels in NPPs is achieved through the implementation of various TDs, which dictate changes in the designs of nuclear facilities. These design alterations in units of NPPs, such as the Kozloduy Nuclear Power Plant (KNPP), are undertaken to enhance operational reliability and efficiency, facilitate repair and control of SSC, comply with evolving regulatory requirements, adopt advanced technologies and equipment, and improve operations based on accumulated experience.

To assess the impact of TDs on NPP safety, various PSA methods are applied. The objective is to discern the strengths and weaknesses of project adjustments and operational characteristics considering the operational risks of NPPs. This assessment entails a sensitivity analysis wherein specific aspects of the base model are modified due to the influence of TDs, followed by quantitative modeling. Correct modeling necessitates the identification of all aspects of the PSA Level 1 model affected by introduced changes.

According to methods utilized for PSA analysis, the main aspects of the model susceptible to the influence of a given TD include:

- Selection of initiating events;
- ET model;
- Success criteria;
- FT model;
- Quantitative indicators of equipment failures;
- Analysis of human error;
- Parameters of seismic fragility of equipment;
- Alteration in combustible load of zones;
- Modification of fire zones;

- Resistance to failure mechanisms induced by internal flooding and spatial interactions.

PSA methods enable the evaluation of TD implementation effects through the ratio between new and old results. Calculations are based on the difference between quantitative results of the base model and the alternative model, expressing the status of NPP systems before and after TD implementation. This approach gauges the impact of TDs on NPP safety, calculated as a percentage change using the formula:

$$\%\text{change} = \frac{\text{MCS}_{\text{BeforeTD}} - \text{MCS}_{\text{BaseModel}}}{\text{MCS}_{\text{BeforeTD}}} \times 100\,,$$

where $\text{MCS}_{\text{BeforeTD}}$ – MCS analysis results for CDF/FDF before the TD realization on Unit 5 and 6 on KNPP; $\text{MCS}_{\text{BaseModel}}$ – MCS analysis results for CDF/FDF after the TD realization on Unit 5 and 6 on KNPP (MCS analysis results for core/fuel damage in the base (actual) model).

The analysis focuses on the updated integrated PSA model level 1 for units 5 and 6 of KNPP. Several PSA methods implemented in the RiskSpectrum PSA software product are employed to achieve objectives. Three examples illustrating different approaches to cover most TDs are represented within this report:

- Technical decisions related to changing equipment reliability parameters;
- Technical decisions related to altering the frequency of IE;
- Technical decisions related to modifying the FT model using a logical operator.

## 2 Analyzing the Impact of TDs on NPP Safety Related to Changing the Equipments' Reliability Parameters

In the context of modernizing NPPs, one of the most common scenarios involves altering equipment to enhance operational characteristics. This typically entails adjusting the reliability indicators of the equipment and modifying parameters related to its seismic fragility. To illustrate the PSA method employed for assessing the impact on NPP safety, we analyzed the effects of a group of TDs that mandated the replacement of supply cabinets and assemblies labeled “HG” in two units of KNPP.

The “HG” power assemblies are integral components of the PSA Level 1 model, categorized under the reliable power supply system Category 1, necessitating any related changes to be accurately incorporated into the current PSA model. All TDs affecting ’HG’ supply cabinets and assemblies entail the substitution of one piece of equipment with another. Upon a comprehensive review of the introduced TDs (related to the replacement of “HG” supply cabinets and assemblies), it was determined that only the BE, as detailed in Table 1, will be altered.

As a standard procedure for accommodating TDs of this nature, reliability parameters sourced from [8] are adopted if they deviate from those utilized in the current model for the affected equipment. Notably, the frequencies of initiating events and seismic failures remain unchanged, as these TDs do not instigate such modifications.

Table 1. Modification of BEs’ reliability parameters used to calculate the quantitative assessment of the effect from TDs associated with the modernization of “HG” power assemblies

| **BE in the PSA model** | **Value of the failure rate of the equipment, 1/h** | |
|---|---|---|
| | **Before TD** | **After TD** |
| Failure of “HG” power cabinet of 0.4 kV assemblies to function<br>Code for the BE in the PSA model: HG##-CH1-CAB3-A-F | 5.83E-07 | 1.89E-08 |
| Failure of the “HG” assembly to function<br>Code for the BE in the PSA model: HG##-RTZ-A-F | 6.35E-07 | 5.85E-08 |

The evaluation was conducted for unit 5, with the assumption of identical results for unit 6.

As evident from Table 1, the failure rate value utilized after the implementation of the TD is notably smaller, resulting in an enhancement of the system’s safety.

The implementation of TDs pertaining to the replacement of equipment from HG power assemblies manifests in improved IP protection of the cabinets, coordinated equipment within supply cabinet 1 with equipment supplying consumers, enhanced equipment power reliability, and other associated improvements. However, analysis of these TDs reveals that they do not exert a significant influence on the values of the Minimal Cut Sets (MCS) Analysis, which includes all categories of initiating events. Similarly, there is no discernible change in risk indicated by the Consequence Analysis list.

The MCS involving the altered cabinets and assemblies fall below the cut-off probability threshold and thus do not contribute to risk formation. Furthermore, systems powered solely by the modified assemblies contribute less than 1% to the CDF/FDF.

## 3 Analyzing the Impact of TDs on NPP Safety Related to Changing the Frequency of the IE

When quantitatively assessing the effect of certain TDs, changes in the system’s elements result in alterations in the frequencies of related IEs. This scenario arises when the reliability parameters of modified elements contribute to the frequency of IEs. This is exemplified by two TDs, which mandate the reconstruction of control panels for compressors labeled as US11,21,31D01 to enhance their operational reliability.

The influence of this group of TDs on the Probabilistic Safety Assessment (PSA) model is manifested through several aspects:

- The TDs impact the reliability parameters of compressors, as control panel failures fall within the compressors’ failure limits. To assess the TDs’ contribution, reliability parameter values for compressors from previous PSA studies are utilized.
- Compressors play a role in determining the frequency of an IE related to internal events: IE-T3-5 “5,6UT system loss”. Hence, modifying the relia-

bility parameters of compressors will alter the value of the IE frequency, which encompasses compressor failures.

- The seismic fragility parameters of compressors US11,21,31D01 will be updated, as compressors are part of the list of SSC considered in seismic PSA. This necessitates changes in seismic failure probability parameters for each input impact level based on fragility parameters.

It has been determined that these TDs do not require changes in the ET and FT logical models. Additionally, no adjustments are needed in the internal fire and internal flood PSA models. Seismic failure of compressors in the PSA model is represented in Table 2, where the seismic fragility parameters[1] used for calculating seismic failure probability at each seismic level are shown.

Table 2. Modification of seismic fragility parameters of compressors US11,21,31D01

| Component | Parameter value | |
|---|---|---|
| | Before TD | After TD |
| Seismic fragility parameters of air compressors US11,21,31D01 | $A_m = 1.70$ g<br>$\beta_r = 0.18$<br>$\beta_u = 0.23$ | $A_m = 1.50$ g<br>$\beta_r = 0.30$<br>$\beta_u = 0.35$ |

The change in reliability parameters used to quantify the contribution of TDs, associated with the reconstruction of the compressors' control panels US11,21,31D01, is presented in Table 3.

Table 3. Modification of reliability parameters for quantification of TD's contribution related to the reconstruction of compressors' control panels US11,21,31D01

| Description of the BE used in the PSA model | Value of the failure intensity of the equipment, 1/h | |
|---|---|---|
| | Before TD | After TD |
| Failure of the air compressor US11,21,31D01 to function | 5.75E-04 | 3.64E-04 |
| | Equipment failure probability value | |
| | Before TD | After TD |
| Failure of the air compressor US11,21,31D01 to start | 1.00E-03 | 2.15E-05 |

To determine the frequencies of IE T3-5 “5,6UT system loss”, the FT model from internal events [2] is utilized. After inserting the new values of the reliability parameters (displayed in the “Before TD” column in Table 3), a calculation of the FT model was conducted to obtain the frequency value for the IE T3-5. The method for calculating the frequency is outlined in item 8.5 of Appendix A6 of Chapter 3 in [2]. The implementation of this IE is considered only in two operational states: POS0, representing the normal operation of the power unit, and POS1, representing the plant operational state. POS1 encompasses the processes of reducing the power of the reactor from 40%$N_{\text{nom}}$ to 1-3%$N_{\text{nom}}$ during unit shutdown, as well as increasing power up to 40%$N_{nom}$ during unit startup and low-power operation modes.

From Table 4, it can be observed that the frequency values of IE T3-5 in the various plant operational states are lower after the implementation of the TD. This suggests that the reconstruction of the compressors' control panels US11,21,31D01, as mandated by the TD, has resulted in a reduction of the frequency of IE T3-5 across different operational states.

Table 4. Comparison of IE frequencies T3-5 before and after implementation of TD related to the reconstruction of control panels of compressors US11,21,31D01

| IE in the PSA model | Value of the IE frequency, 1/year | |
|---|---|---|
| | Before TD | After TD |
| IE-5T3-5-POS0 | 2.09E-03 | 8.90E-04 |
| IE-5T3-5-POS01 | 5.89E-05 | 3.30E-05 |

The implementation of the analyzed TDs has resulted in improvements in the reliability, operating conditions, maintenance, and repair of compressor US11,21,31D01 control panels. Following the implementation of the TDs, the total FDF of Unit 5 for all IE categories (ALL-5UNIT-TOTAL) decreased by 0.61%. This reduction is primarily attributed to the decrease in the frequency of IE T3-5, which plays a significant role in shaping the frequency of failure of the SFP of Unit 5 across all IE categories.

UT system loss leads to closing of the pneumatic valve and isolation of the hermetic structure. The IE T3-5 is defined as a total loss of the system UT, as each of the channels reserves the others. Namely, loss of the UT system and human error in performing function F2 (Diagnostics and decision-making to ensure the supply of coolant in the SFP) lead to fuel failure in the SFP.

The MCS analysis results (see Figure 1) are appropriate because IE T3-5 prevents the implementation of FB3-1 (Removal of the residual heat separation in the SFP with 1/2 TG pumps). Furthermore, the implementation of TDs related to the reconstruction of the control panels of compressors US11,21,31D01 has reduced the frequency of fuel failure IE with loss of cooling of SFP (ALL-5B2-TOTAL) by approximately 10%, while the remaining results remain consistent.

## 4 Analyzing the Impact of TDs on NPP Safety Related to Changing the FT Model Using a Logical Operator

The final case involves a TD affecting the replacement of RT and cross cabinets with new ones in the UKTS - OVATION. The implementation of this measure holds particular significance for maintaining a high level of safety in the KNPP, as the replaced equipment had been in operation for over 30 years, with an expired operational resource,

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[1] One simple but effective fragility model supposes that the entire family of curves representing a particular failure mode can be expressed by median ground acceleration $A_m$ and two random variables $\beta_r$ and $\beta_u$.

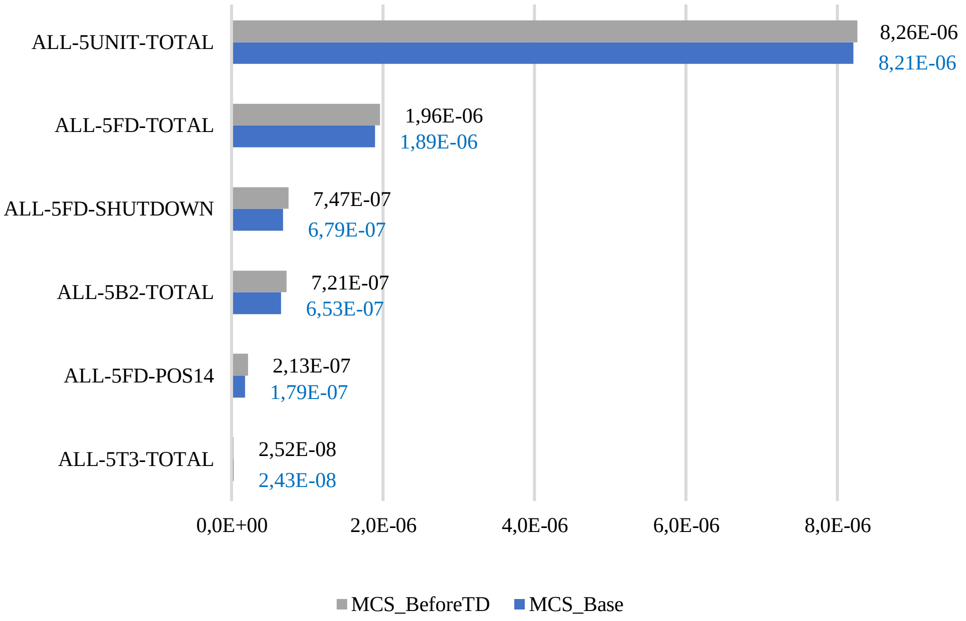

Figure 1. Results of the examined MCS Analysis Case, collecting all categories of IEs, before and after the TDs realization related to the reconstruction of air compressors' control panels US11,21,31D01.

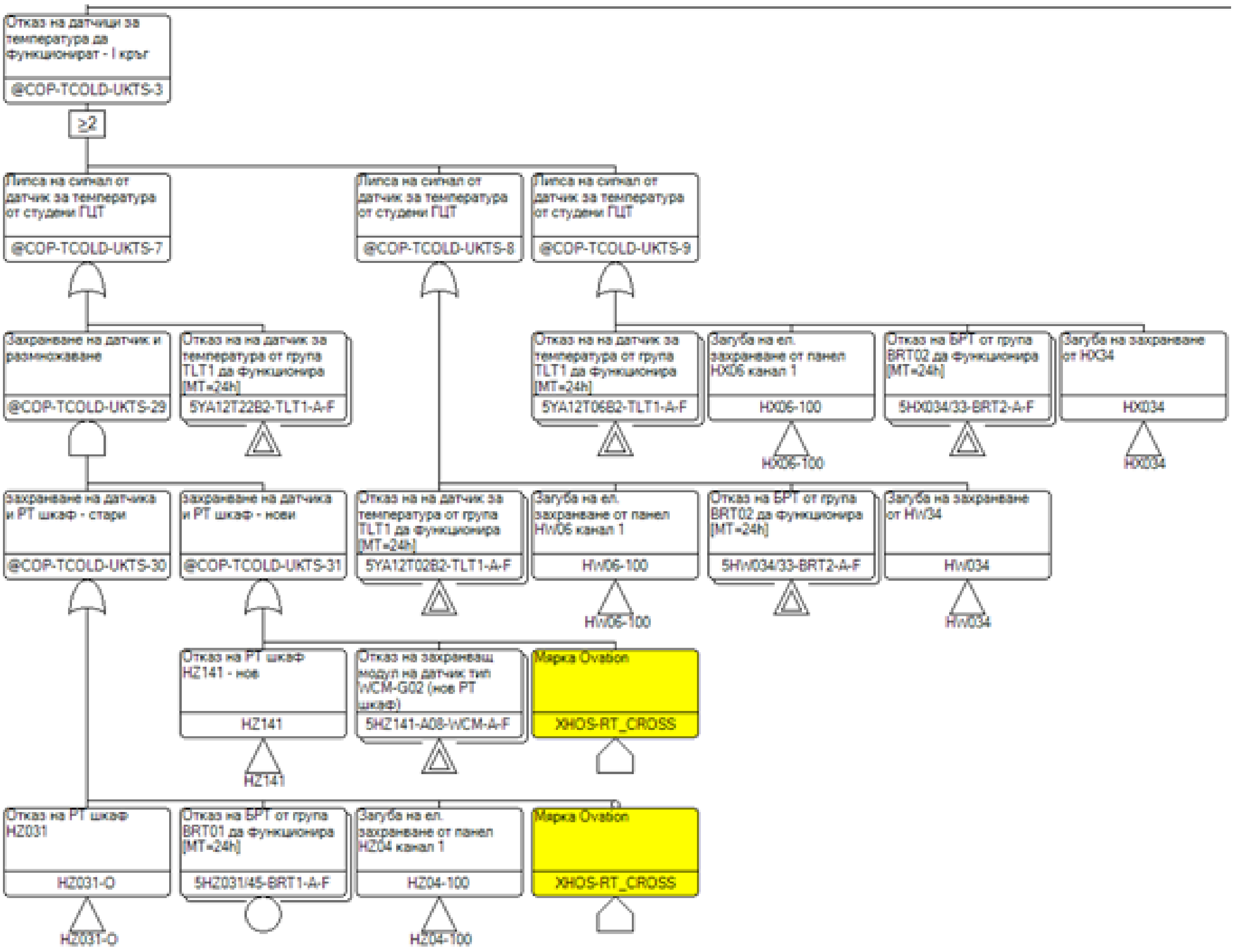

Figure 2. Exemplary use of a logical operator to assess the impact of a group of TDs.

outdated material, and an old element base. Besides the expected significant impact on the outcome, this example is noteworthy because it also illustrates a specific approach to modeling the impact of TDs in the PSA model, related to changes in design decisions rather than equipment replacement.

The influence of the analyzed TDs revolves around the commissioning of electrical cabinets for processing within the managing normal operating systems, implementing control and management functions of technological processes along the I circuit of the two units at the KNPP.

Given the broad impact of the measure on the entire PSA Level 1 model, it was decided to reflect the implemented changes by introducing the logical operator “XHOS-RT_CROSS”. This approach enables the toggling of certain parts of the FT logic without disrupting the rest of the model settings. Thus, a switch is made between the new FT model, depicting power supply from the new cross and RT cabinets, and the old model with the previous cabinets for primary processing and distribution of analog and discrete input signals and power supply panels. This is illustrated in Figure 2.

When the logical operator “XHOS-RT_CROSS” is TRUE (logical 1), the logic of the FT used in the previous PSA study [8] is restored, representing a state where the group of TDs is not reflected. Conversely, a value of FALSE (logical 0) enables the use of the new model, featuring the new cross cabinets involved in controlling the actuators. The logical operator “XHOS-RT_CROSS” is utilized in multiple FTs available in the PSA model.

The implemented TDs related to the replacement of RT and cross cabinets with new ones in UKTS - OVATION significantly alter the risk profile, as they impact the overall result for CDF/FDF. The results of the examined MCS Analysis Case, collecting all categories of IE, are shown in Figure 3. Since the changes are identical for both units, Figure 3 only presents the results for unit 5.

The most notable change is observed in the MCS analysis for “IEs with loss of removal of the residual heat separation from I-circuit” (T9). The implementation of TDs related to the replacement of RT and cross cabinets with new ones in UKTS - OVATION results in a CDF reduction of 90.39%. This reduction is primarily due to the impact of internal fires, where more Category II sections are lost. Specifically, the analysis of the MCS identifies fires in fire zones PZ119, PZ118, and PZ603, leading to the inability of the cold press protection to perform function F2-1 (Protection of I-circuit from overpressure). Consequently, this accounts for the observed difference in CDF of unit 5 for all IE categories in POS14. In other words, the implementation of the measure reduces the CDF of unit 5 for all IE categories in POS14 by 89.5%. The remaining results exhibit similar trends.

In certain analyses of MCS, the result after the implementation of a TD group related to the replacement of RT and cross cabinets with new ones in UKTS - OVATION may increase. However, this does not indicate a deterioration in the safety of the NPP. Physically, with the integration of the new RT and cross cabinets in the UKTS - OVATION, new elements are added to the structures of the control systems for normal operation, providing power supply, processing of unified analog signals, and participation in the management of executive mechanisms and technological signaling in the I circuit. These elements were not present in some safety-critical systems before the implementation of the TDs, and similarly, they were not modeled in the FTs illustrating failures of the same systems.

Essentially, the implementation of TDs related to the replacement of RT and cross cabinets with new ones in UKTS - OVATION requires the introduction of new elements, which leads to introduction of new failures in the FTs (part of the RiskSpectrum PSA Model). This is evident

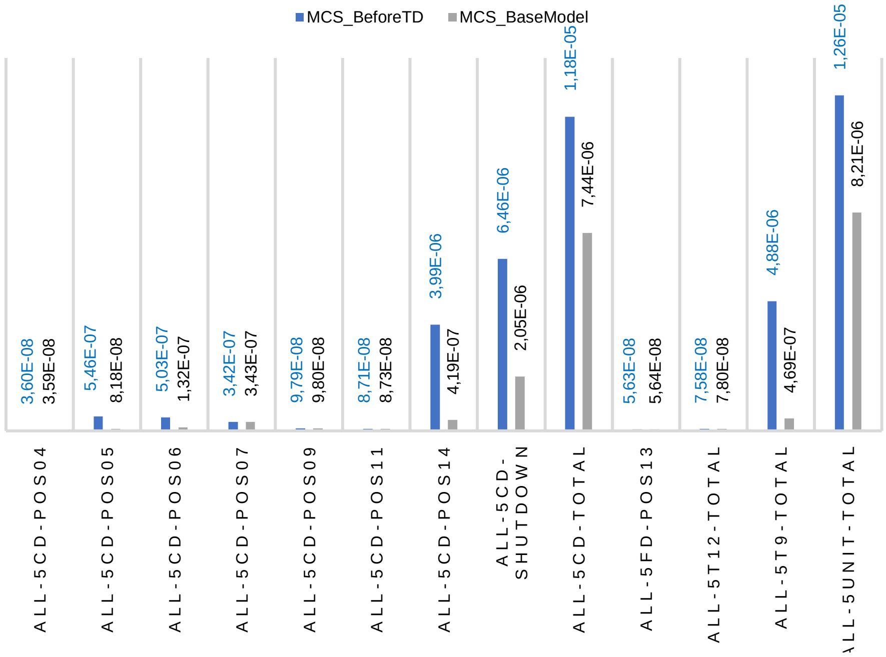

Figure 3. Results of the examined MCS Analysis Case, collecting all categories of initiating events, before and after the TDs realization, related to the replacement of RT and cross cabinets with new ones in UKTS – OVATION.

in the MCS analysis ALL-5T12-TOTAL, where the number of MCS in the analysis, showing the state before the implementation of the TD, is 384 sets less compared to the number of MCS in the current model. This discrepancy originates from the Failure of the TK system's shut-off and control valves (FT: TK00-31-32), crucial for providing deep sub-criticality in emergency conditions associated with boron depletion IEs. Specifically in FT TK00-31-32, the implementation of the specified TDs introduces new equipment failures, which, when combined with other failures, lead to an increase in the number of MCS. This approach is consistent across other analyzed results.

## 5 Conclusions

The modifications made to the KNPP units encompass various aspects of the PSA Level 1 model. Identifying the model aspects affected by a given TD is crucial for assessing the TD's impact on NPP safety and for selecting the appropriate approach for TD analysis. In this report, three PSA methods are analyzed, allowing for an adequate assessment of the safety impact of implemented TDs:

- PSA method for analyzing TDs related to equipment reliability parameter changes: This method enables the analysis of TDs associated with modifications in the reliability parameters of equipment.
- PSA method for analyzing TDs related to changes in IE frequency: This method enables the analysis of TDs linked to alterations in the frequency of IE.
- PSA method for analyzing TDs related to changes in FT model using logical operators: This method allows for the analysis of TDs concerning changes in the FT model through the use of logical operators.

The assessment of the impact on risk by the relevant TDs is based on changes in CDF/FDF and LERF, providing an estimate of the TDs' significance. Quantitatively evaluating the TDs' impact facilitates the creation of a "TD's priority list", which holds economic significance. Prioritizing TDs in this manner streamlines the decision-making process regarding the implementation sequence of TDs on the NPP.

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