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Key Considerations for Probabilistic Safety Assessment under Flexible Operation

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1. Introduction

The share of Variable Renewable Energy (VRE), such as solar and wind power, is rapidly increasing worldwide to achieve the goal of carbon neutrality by 2050. However, the high variability and unpredictability of VRE output pose challenges to maintaining a stable power supply and the balance between supply and demand. Consequently, the introduction of load-following operation is being demanded for Nuclear Power Plants (NPPs), which have traditionally been responsible for baseload operation, to help maintain the grid's supply-demand balance.

Currently, efforts are underway to introduce flexible operation in existing large Light Water Reactors. Additionally, Small Modular Reactors (SMRs), designed for local power generation, inherently require flexible operation capabilities to effectively meet regional electricity demands. While some existing domestic NPPs incorporate load-following capabilities in their design, they have predominantly been operated as baseload plants. Load-following operation entails frequent power fluctuations and transients. This imposes additional thermal and mechanical loads on plant systems and components and increases the complexity of operating procedures. This may introduce new risk factors that fall outside the assumptions and scope of existing Probabilistic Safety Assessments (PSA), which were performed based on full-power and Low Power and Shutdown operation scenarios.

Therefore, this study aims to analyze the impact of flexible operation on the integrity of the reactor core, systems, and components. Based on this analysis, the study identifies key factors that must be considered during the full-power PSA process for the implementation of load-following operation, categorized by technical elements such as initiating events, success criteria, data, and Human Reliability Analysis (HRA).

2. Technical Characteristics and Potential Safety Impacts of Flexible Operation

2.1. Definition of Flexible Operation

Flexible operation is a concept contrasting with baseload operation, referring to all operation modes that vary electrical output in response to the demands of the power grid. The output is adjusted based on technical requirements and commercial agreements for grid frequency and power flow control. The types of flexible operation include load following, frequency control, and extended low-power operation (ELPO). Load following alters power generation to closely match anticipated electricity demand. Frequency control finely tunes the output in response to automatic or remote control signals to ensure grid frequency stability. Meanwhile, ELPO reduces power levels for a substantial period in accordance with long-term demand forecasts.

2.2. Effects on Fuel and Core

Rapid power variations during flexible operation can induce Pellet-Cladding Interaction (PCI) [1]. This phenomenon threatens the integrity of the nuclear fuel cladding. During a power ramp, the expanded pellet exerts strong tensile hoop stress on the cladding, causing a mechanical interaction. Furthermore, corrosive fission products, such as iodine, can accumulate at these stress concentration points. Consequently, the risk of cladding failure due to iodine-induced Stress Corrosion Cracking (SCC) could increase significantly.

Frequent insertion and withdrawal of control rods for power regulation disrupt the equilibrium of ^{135}I and ^{135}Xe concentrations within the core. This disruption primarily has the potential to induce and amplify xenon oscillations in the axial direction of the reactor. These oscillations abruptly alter the local power density and increase the core power peaking factor. As a result, the safety margin can be reduced, heightening the risk of violating Limiting Conditions for Operation (LCO) [2].

Control rod maneuvering rapidly changes reactivity. Simultaneously, it can cause severe perturbations and distortions in the axial and radial power distributions within the core. Drastic power deviations and redistribution phenomena may occur between the rodded and unrodded regions. These phenomena might elevate the peak power density and linear power density. Ultimately, this can generate critical risk factors directly linked to major safety criteria, such as a reduction in the Departure from Nucleate Boiling Ratio (DNBR).

2.3. Effects on System and Equipment Integrity

Flexible operation can also induce frequent thermal and mechanical cycling in the major components of the primary and secondary systems, directly affecting the long-term integrity and safety margins of the power plant.

In the primary system, the frequency of use of the Control Rod Drive System (CRDS) and Control Rod Drive Mechanism (CRDM) increases sharply. This tends to accelerate component fatigue and wear, which can lead to control rod operation failures or unplanned outages [3]. Zircaloy guide tubes, being in close proximity to the control rods, may suffer localized shadow corrosion, potentially impeding control rod insertion. Furthermore, piping around the pressurizer, such as the surge line and spray line, as well as the Chemical and Volume Control System (CVCS), experience frequent temperature and volume fluctuations. These changes can cause temperature and pressure imbalances, potentially leading to thermal stratification and high-cycle fatigue within the piping [4]. Additionally, the heat transfer tubes and nozzles of the steam generator are continuously exposed to variable thermal loads, significantly elevating the risk of thermal fatigue cracking compared to baseload operation.

The secondary system is also susceptible to prominent fatigue, wear, erosion, and aging across the turbine, condenser, and overall feedwater system. Load following increases the operation frequency of turbine control valves, stop valves, and throttle valves, exacerbating wear and shortening maintenance intervals. During low-power operation, increased moisture content in the lower stages of the low-pressure turbine induces wear and increases seal clearances. Furthermore, power reductions may require operating the steam bypass system to divert steam to the condenser, applying excessive thermal loads to the condenser shell, tubes, and steam spargers, causing substantial damage. Finally, large-capacity heat exchangers and feedwater piping are affected by continuous changes in temperature, pressure, and flow rate, leading to feedwater nozzle fatigue and thermal fatigue cracking in heaters and dryers.

2.4. Effects on Operational Programs and Long-term Operation

The introduction of flexible operation requires changes in the physical systems of the power plant. It also necessitates comprehensive modifications across the operational programs that manage these systems. Standard Operating Procedures (SOPs) must be developed for new operation modes, such as load following and frequency control. Existing operating procedures, including Emergency Operating Procedures (EOPs), must also be revised to account for diverse initial conditions.

Operators must undergo enhanced training utilizing simulators. This training ensures they understand complex core phenomena and can accurately respond to various transient states. Additionally, the increased fatigue and wear of specific equipment must be considered. Preventive maintenance cycles, inspection items, and surveillance programs for these components must be readjusted accordingly.

3. Identified Key Factors in PSA

Existing PSA has been fundamentally premised on baseload operation, where the NPP operates consistently at rated power [5]. However, since flexible operation encompasses diverse and dynamic operating modes, including frequent power fluctuations and operation at low-power levels, PSA must be performed reflecting these specific characteristics.

3.1. Initiating Event Analysis

The initiating event analysis in existing PSA was performed based on baseload operation maintained consistently at full power. In a flexible operation environment, however, the dynamic operational characteristics of frequent power fluctuations and intermediate/low-power levels must be reflected in the analysis. Considering these operational characteristics, new transient phenomena that were not previously evaluated may be derived, or the frequency of existing transients and unexpected reactor trips may increase.

In particular, the increase in repetitive thermal and mechanical loads accompanying flexible operation can accelerate the fatigue, wear, corrosion, and aging of major structures, systems, and components (SSCs), which can consequently increase the frequency of initiating events. As a representative example, frequent control rod insertion and withdrawal for power regulation may increase the mechanical wear of the CRDM, which can induce new initiating events such as reactivity control failure due to CRDM malfunction [6].

Furthermore, in addition to hardware factors, changes in risk from human and operational perspectives must be considered. Upon introducing flexible operation, existing operating procedures, protection and control systems, and LCOs may be revised or newly added to execute planned and unplanned power variations. Consequently, this can increase the cognitive load and stress on operators compared to baseload operation, potentially causing new types of human errors and ultimately leading to initiating events such as unexpected reactor trips.

3.2. Accident Sequence and Success Criteria Analysis

Unlike conventional full-power operation, flexible operation encompasses various power levels and transient states; thus, the initial conditions at the time of an accident and the decay heat levels based on prior operating history are different. Therefore, to accurately evaluate the physical progression of the accident and the time available for operator actions, thermal-hydraulic analyses (e.g., MARS-KS) covering the entire range of flexible operation must be performed to redefine specific success criteria and event trees. In this process, tasks to evaluate flexible operation-specific phenomena such as

PCI and xenon oscillations, or to screen them out through bounding analysis, are required.

However, even during flexible operation, the Critical Safety Functions (CSFs) and the configuration of safety systems from full-power operation are expected to remain valid. Additionally, considering that the NPP operates at lower power levels compared to full power, it can be considered a conservative approach to assume that the core damage prevention functions and success criteria based on existing full-power standards bound the conditions of flexible operation.

3.3. System Analysis

System analysis following the introduction of flexible operation requires a comprehensive preliminary review of newly added or design-modified systems, setpoint changes in protection and instrumentation systems, adjustments to periodic maintenance intervals, and revisions to operating procedures. In particular, flexible operation significantly increases the number of demands for specific components such as the CRDM, turbine control valves, and pumps compared to baseload operation. These frequent operation demands have the potential to accelerate mechanical wear and fatigue accumulation in the components, and the thermal loads accompanying frequent power fluctuations can also directly affect component performance. As a result, the failure probabilities of these components may increase, and there is a possibility that new types of failure modes not previously seen may emerge. Therefore, when modeling systems, it is necessary to either demonstrate that new failure types do not appear due to flexible operation, or, if new failure modes exist, to integrate them into existing failure models or reflect them independently as separate failure modes.

3.4. Human Reliability Analysis (HRA)

The introduction of flexible operation entails new operating modes such as load following, requiring complex activities from operators like xenon oscillation control and thereby aggravating their cognitive load. As this increases the potential for unprecedented human errors or abnormal situations, it is necessary to identify the Performance Shaping Factors (PSFs) of new human actions through simulator observations and interviews, and based on this, re-evaluate the existing HRA or add new models [7]. In addition, the impacts of all newly identified testing and maintenance activities, such as CRDM maintenance following design changes, must also be integrated into the analytical model.

Operator response risks following an accident must also be re-evaluated. Due to the nature of flexible operation, the initial conditions and decay heat levels during transients or low-power periods differ from those in full-power operation, resulting in variations in the physical progression of accidents and the time available for operator actions. Therefore, flexible operation-specific operating procedures and thermal-hydraulic analysis results must be actively utilized to realistically recalculate operator response times and situational judgment capabilities under changed accident conditions.

3.5. Data Analysis

In terms of data analysis, the characteristics of increased initiating event frequencies and component failure probabilities, as well as more frequent maintenance activities due to repetitive mechanical and thermal loads and changes in operating procedures, must be quantitatively reflected. In particular, when components of the same type are exposed to repetitive loads, the probability of Common Cause Failures (CCFs) due to mechanical and thermal stresses may increase. Furthermore, since the thermal fatigue of steam generator tubes can increase with higher thermal loads, these factors must be considered when evaluating specific damage probabilities, such as Consequential Steam Generator Tube Ruptures (Consequential SGTR).

However, in the early stages of introducing flexible operation, it is difficult to secure NPP-specific reliability data due to the lack of unique operating experience. Moreover, since it takes a considerable amount of time for component degradation to manifest as actual failures, existing baseload data alone cannot represent the flexible operation environment, introducing uncertainty into the risk assessment. To overcome this, in the initial stages, conservative values based on overseas plant reliability data, similar equipment data, or expert judgment should be utilized, and the impact on risk should be evaluated through sensitivity analysis. Once plant-specific operating data is accumulated in the future, statistical techniques such as Bayesian updating must be applied to establish plant-specific data. Furthermore, during data collection and processing, the full-power baseload mode and the flexible operation mode must be clearly distinguished to calculate initiating event frequencies and failure rates, thereby accurately projecting the differences in reliability characteristics between operating modes into the model.

3.6. Associated Facilities and External Event Analysis

Flexible operation is highly likely to be integrated with Heat Extraction Systems (HES) for hydrogen production, seawater desalination, and process heat supply. This means that new industrial facilities will be located near the NPP, introducing safety degradation factors that did not previously exist [8]. Therefore, the impact of potential fires, explosions, and toxic chemical leaks from these associated facilities on plant safety must be evaluated and modeled either as new initiating events or as factors that increase the frequency of existing accidents. Representative risks to be comprehensively reviewed include the potential for pressure waves and missiles from explosions at hydrogen production facilities to damage the plant's SSCs, or the cascading effects on the frequency of Main Steam Line Break (MSLB) accidents if the HES is connected to the main steam line.

Additionally, the unique physical impacts of flexible operation must be closely re-evaluated when analyzing existing external events such as fires, earthquakes, and flooding. In particular, since the repetitive mechanical and thermal loads accompanying flexible operation are likely to increase the fatigue of major components, their quantitative impact on the fragility—which determines the failure probability of the components during external shocks like earthquakes—must be analyzed and reflected in the risk assessment.

4. Conclusions

This study analyzed the comprehensive impacts of implementing flexible operation in NPPs and identified the key factors that must be addressed when performing PSA for such operational modes. In the future, we intend to develop a flexible operation PSA model that incorporates the factors presented in this study.

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