



Research on Implementing a Risk-Informed, Performance-Based Fire Protection Program for Nuclear Power Plants

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Abstract. Fire protection management constitutes an essential part of the defense-in-depth system for nuclear safety in nuclear power plants. With the advancement of Probabilistic Safety Assessment (PSA) and risk-informed decision making (RIDM), nuclear facilities in the United States, among other, have taken the lead in transitioning from deterministic fire protection management system to a risk-informed one, of which the most critical step is the establishment of a risk-informed, performance-based (RI-PB) fire protection program. Based on a comparative analysis of the Chinese and U.S. nuclear fire protection regulations and standards, this article examines the feasibility of implementing such a fire protection program in Chinese nuclear power plants, and proposes the substitution of fire vulnerability analysis (FVA) for safe shutdown analysis during the transition process, thereby offering a possible approach for the transition of fire protection programs in China.

Keywords: Nuclear Power Plant, Fire Protection Program, Risk-Informed, Performance-Based, Probabilistic Safety Assessment

1 Introduction

Fire is one of the major risk sources threatening the safe operation of nuclear power plants. Consequently, fire protection is regarded as a vital part of the nuclear safety defense-in-depth system. For a long period, nuclear power plants worldwide have generally adopted deterministic fire protection design methods, which prescribe fire compartmentalization, fire barrier installation, fire detection and suppression, separation of redundant equipment to ensure safety, etc. Although these prescriptive requirements provide a fundamental level of fire safety to a large extent, they lack flexibility in certain scenarios and are often difficult to implement. Additionally, they cannot quantify fire risks and tend to adopt uniformly conservative designs for the entire plant, potentially leading to resource inefficiency.

Take the United States as an example. Following the fire at Browns Ferry Nuclear Plant in 1975, Appendix R to 10 CFR 50 was issued for plants operating prior to January

1, 1979 and set forth fire protection features required to satisfy Criterion 3 of Appendix A to 10 CFR 50, i.e., “Structures, systems, and components important to safety shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions.”[1] However, the industry encountered considerable difficulties in complying with the detailed requirements in Appendix R, which were based on deterministic fire safety analysis. With the advancement of probabilistic safety assessment (PSA, a.k.a. probabilistic risk assessment, PRA) and risk-informed decision making (RIDM), the National Fire Protection Association (NFPA) issued *Fire Protection for Light Water Reactor Electric Generating Plants* (NFPA 805)[2]. In 2004 the U.S. Nuclear Regulatory Commission (NRC) amended 10 CFR part 50.48 “Fire Protection” to add a new subsection, 10 CFR 50.48(c), which endorses, with exception, NFPA 805, allowing licensees to choose an alternative method to demonstrate compliance with 10 CFR 50.48(b) and section (f). Subsequently, the Nuclear Energy Institute (NEI) issued *Guidance for Implementing a Risk-Informed, Performance-Based Fire Protection Program under 10 CFR 50.48(c)* (NEI 04-02)[3], which provides guidance for implementing the requirements of the rule change and represents methods for implementing a risk-informed, performance-based (RI-PB) fire protection program. Since then, U.S. nuclear facilities have been gradually transitioning to an RI-PB fire protection program.

Currently, the fire protection design in China’s nuclear facilities mainly follows the regulations and standards based on deterministic approaches, such as *Safety Regulation for Design of Nuclear Power Plants* (HAF 102-2016)[4], *Nuclear Power Plant Fire and Explosion-proof Design* (HAD 102/11-2019)[5], *Code for Fire Protection Design of Nuclear Power Plants* (GB/T 22158-2021)[6], etc. Fire protection management largely relies on the prescriptive measures set forth by these documents. With the progress of risk-informed technologies, particularly that of internal fire PSA for nuclear power plants, calls for implementing risk-informed fire protection management have been growing. Undoubtedly, the U.S. experience offers a lot that can be learned from, but there are differences among the regulation, codes and practices conducted by the facilities in the two countries (e.g., safe shutdown analysis is generally not conducted for Chinese plants). Therefore, further study is necessary to adopt the NFPA 805 methodology and develop an applicable implementation process.

Through the analysis of the differences and potential obstacles, this article discusses the feasibility of implementing a risk-informed, performance-based fire protection program in nuclear power plants in China. Specific discrepancies were analyzed, demonstrating adjustments required to the technical method and process. It aims to provide a practically feasible technical pathway for the transition of the deterministic fire protection programs to RI-PB ones.

2 Feasibility Analysis of a Risk-Informed, Performance-Based Fire Protection Program

2.1 Performance Criteria

A performance-based approach is an approach where goals are established and objectives are identified to achieve the goals. It's employed in various fields, including the design of buildings, structures, facilities, equipment and processes [7].

Criteria, analyses and assessment are employed in order to demonstrate how the goals are achieved. Four performance objectives are set forth in NFPA 805[2], i.e., Nuclear Safety (maintaining reactivity control, decay heat removal, and reactor coolant pressure boundary integrity), Radioactive Release (maintaining containment integrity and limiting source terms), Life Safety (protecting personnel), and Plant damage / Business interruption (limiting economic losses). Corresponding performance criteria are established to measure compliance.

Similarly, GB/T 22158-2021 sets forth general requirements for fire protection design in nuclear power plants in China. The basic objectives are: a) to ensure the effectiveness of reactivity control, decay heat removal and radioactive containment during and after a fire, b) to ensure the monitoring of plant status and the performance of safety functions, c) to limit and promptly extinguish fires that could lead to long-term unavailability, and d) to ensure personnel safety and evacuation, and, preferably, accommodate firefighting and rescue[6].

Although certain requirements regarding radioactive release and life safety might differ, some key fire protection elements are comparably similar between Chinese and US regulations. Examples are shown in Table 1. Besides, when performing PSA, the acceptance guidelines for CDF (core damage frequency) and LERF (large early release frequency) provided in RG 1.174 on changes to licensing basis are applicable in both US and China.

Table 1. Examples of similar requirements of key fire protection elements

Key Elements	Requirements in NFPA805	Requirements in GB/T 22158
Fire resistance rating of fire barriers	3-hour for separation of required cables and equipment of redundant success paths.	2-hour for fire zones of nuclear safety functions/equipment.
Fire protection water supply	Not less than two separate supplies of 300,000 gal (1,135.5 m ³) or the 2-hour fire flow rate for 2 hours shall be calculated.	At least two separate supplies of 1,200 m ³ and the 2-hour max demand shall be calculated.
Automatic sprinkler systems in cable spreading rooms and galleries	A density of 0.30 gpm/ft ² (12.2 L/min·m ²) over the most remote 2500 ft ² (232.2 m ²).	A density of 10 L/min·m ² over the most remote 260 m ² .

Since the general objectives of fire protection design prescribed in GB/T 22158 largely overlap with those of NFPA 805, corresponding performance criteria can be established: Nuclear Safety (maintaining the three fundamental safety functions),

Radioactive Release (maintaining containment integrity and limiting source terms), Fire Response Effectiveness (limiting and promptly extinguishing fires), and Life Safety (ensuring personnel safety and evacuation), as shown in Fig. 1.

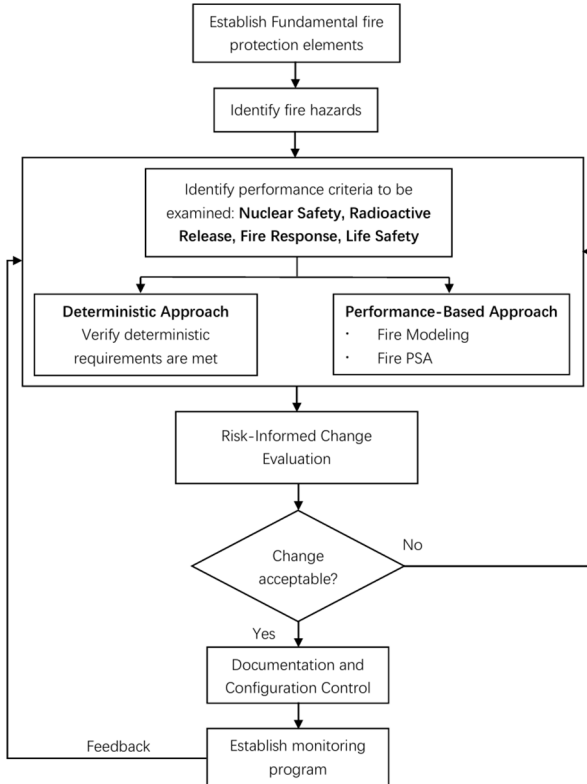


Fig. 1. NFPA 805 Process (with Adjusted Performance Criteria)

2.2 Probabilistic Safety Assessment

NFPA 805 requires that the applicable performance criteria be applied to the structures, systems, and components (SSCs) within each fire area to demonstrate compliance with 10 CFR 50.48(b) or plant-specific fire protection licensing conditions. Licensees may employ a deterministic approach or a performance-based approach. The risk impact of the changes to the approved design basis should be evaluated to examine if the changes are acceptable, which would be documented and controlled. A monitoring program should be established to keep track of the changes and configurations. The use of performance-based approaches is the most distinctive feature of NFPA 805 compared to the traditional deterministic requirements in fire protection design, and the most commonly employed methods are fire modeling and fire PSA.

Although PSA started relatively late in China, the advancements in recent years have led to the development of internal fire PSA models at most nuclear plants, and these

models have been used in some pilot application projects. Meanwhile, research facilities are already proficient in fire modeling, which is often a supporting step in fire safety analysis, including internal fire PSA development. With the help from the regulatory authorities and the industry, hopefully there would soon be peer reviews on the existing internal fire PSA models to demonstrate their technical adequacy, and they can provide technical support to the implementation of RI-PB fire protection programs.

3 Transition to an RI-PB Fire Protection Program

3.1 Practice in the U.S.

NFPA 805 clearly specifies the minimum requirements for fire protection design and provides a methodology for establishing a RI-PB fire protection program, but it does not give details on how to transition from an existing deterministic fire protection program, where NEI 04-02 provides sufficient guidance.

According to NEI 04-02, the transition process from an existing fire protection program to an RI-PB one is divided into three phases, namely Preliminary Assessment and Letter of Intent, Analysis and License Amendment Request, and Completion of Transition[3].

The preliminary assessment is essentially a self-assessment conducted by the plant. After the decision to proceed with the transition, the plant establishes a tentative transition schedule and submits a Letter of Intent to the NRC.

Phase 2 is where the analysis and evaluation area conducted to demonstrate compliance. Based on the transition schedule, the plant carries out four major transition reviews: Fundamental Fire Protection Program and Design Elements Transition Review, Nuclear Safety Performance Criteria Transition Review, Non-Power Operational Modes Transition Review, and Radioactive Release Transition Review. Among these four reviews, the Fundamental Fire Protection Program and Design Elements Transition Review mainly verifies compliance of the current fire protection program, including previously approved alternatives, with the corresponding requirements of NFPA 805. The Nuclear Safety Performance Criteria Transition Review focuses on how the current fire protection program complies with the post-fire safe shutdown requirements in Sections III.G and III.L of 10 CFR 50 Appendix R. The Non-Power Operational Modes Transition Review considers the differences between functional requirements and time dependencies on decay heat removal system operation during low-power/shutdown operations and power operations, where risk during non-power conditions is evaluated. The Radioactive Release Transition Review focuses on risks of potential releases that could result from fire suppression activities. Where performance criteria are not met, risks are evaluated using methods and tools such as internal fire PSA, fire modeling and safety margin evaluations. If the risk is unacceptable, compensatory measures or modifications are required, and a license amendment request (LAR) must be prepared.

Among the above-stated four reviews, the Nuclear Safety Performance Criteria Transition Review evaluates the technical compliance of the plant's current safe

shutdown analysis against *Guidance for Post-Fire Safe Shutdown Circuit Analysis* (NEI 00-01)[8]. Safe shutdown analysis is an important part of the U.S. nuclear safety regulatory framework. Plants in the U.S. have generally completed such analyses, which provide detailed lists of cables and equipment that must remain functional within each fire area to ensure shutdown, decay heat removal, and radioactive material confinement, paying special attention to the effects of fire-induced circuit failures.

Phase 3 is where the transition is completed and maintained. At this stage, the plant may implement changes without prior NRC approval. Concurrently, the plant should update procedures and training programs, establish comprehensive documentation and tracking mechanisms, and continuously monitor the fire risk of the plant.

3.2 Substitution for Safe Shutdown Analysis

Currently, fire protection design for nuclear plants in China is primarily governed by HAF102, HAD 102/11, GB/T 22158, etc. These regulations and codes require the establishment of fire areas, physical separation of redundant safety systems, rated fire barriers, installation of fire detection and suppression systems. In terms of fire safety analysis, HAD 102/11-2019 requires that plants conduct a fire hazard analysis (FHA), while GB/T 22158-2021 requires that plants perform fire safety analysis including FHA and fire vulnerability analysis (FVA) or safe shutdown analysis. In practice, most plants have performed FHA and FVA, while few have conducted safe shutdown analysis. Due to the unavailability of safe shutdown analysis, the Nuclear Safety Performance Criteria Transition Review, where compliance to NEI 00-01 is examined, is not applicable to the majority of plants in China.

Before the development of PSA methods, safe shutdown analysis had long been an important tool for safety evaluation and assurance for U.S. nuclear plants. However, compliance of safe shutdown analysis to the guidance of NEI 00-01 is not the sole option for demonstrating nuclear safety performance. For instance, the results of FVA can also be used to evaluate and ensure safe shutdown capabilities.

FVA originates from the 1997 fourth edition of the French Code, *Règles de Conception et de Construction des centrales nucléaires REP applicables à la protection Incendie* (RCC-I 97)[9]. RCC-I 97 defines the concepts of fire area and fire zones and requires the identification of potential common-mode failures induced by fires for each fire area or fire zone, i.e., the performance of a fire vulnerability analysis. In FVA, potential common-modes are identified within each fire area or fire zone, i.e., redundant equipment (including electrical connections) of safety functions that could simultaneously fail due to a fire. A functional analysis of these potential common-modes is conducted. If the consequences of the potential common-mode failures are unacceptable, the common-mode must be eliminated, i.e. fire protection (wrapping) or compensatory measures be taken. At least one train of safety function equipment within the fire area or fire zone must remain available in the event of a fire. GB/T 22158-2021 has already listed FVA as one of the approved methods of fire safety analysis.

Based on the above analysis, during the transition to an RI-PB fire protection program, if a plant has not yet performed a safe shutdown analysis, it may choose to review the already completed FVA when conducting the Nuclear Safety Performance Criteria

Transition Review. By examining the technical adequacy of the FVA (steps are shown in Fig. 2), the plant can assess the compliance with nuclear safety performance criteria. During this process, particular attention should be paid to confirming that it systematically identifies fire-induced common-mode failure and evaluates the effectiveness of compensatory measures, so that the results can be considered equivalent to those of safe shutdown analysis.

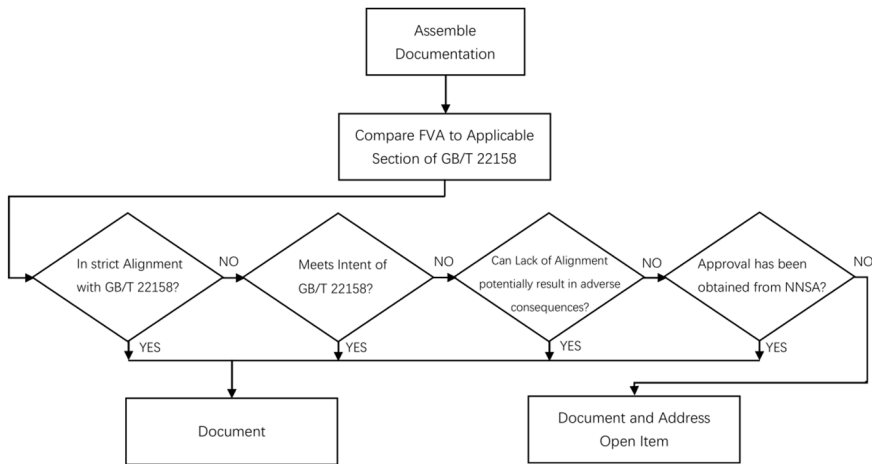


Fig. 2. Process of Examining Technical Adequacy of FVA Against GB/T 22158

4 Conclusions and Outlook

RI-PB approaches are already widely used in the nuclear industry, from fire protection system management[10], reactor concepts and designs[11] to emergency planning[12] and nuclear safety regulation. The American Nuclear Society is also incorporating RI-PB approaches/attributes in developing standards[13].

Through a comparative analysis of the Chinese and U.S. nuclear fire protection regulations, this article demonstrates a feasible implementation of an RI-PB fire protection program in the nuclear power plants in China. Although the current fire protection management in China is predominantly prescriptive, the advancement of internal fire PSA and the prospects of peer reviews have laid the technical groundwork for transitioning to an RI-PB approach. By comparing the fire protection design objectives of NFPA 805 and GB/T 22158, it is recommended to establish the performance criteria of Nuclear Safety, Radioactive Release, Fire Response Effectiveness, and Life Safety. Moreover, in the Nuclear Safety Performance Criteria Transition Review during the transition, given the prevailing absence of safe shutdown analysis, it is proposed to take the alternative of FVA and examines its technical adequacy, thereby effectively circumventing the institutional barriers that would arise from directly adopting the NEI 04-02 process.

Fire safety management in nuclear power plants encompasses many aspects of nuclear safety, and the implementation of a risk-informed, performance-based fire

protection program is a comprehensive and systemic endeavor. Only two elements of the methodology and implementation process are selected and addressed in this article. Further research is needed to steadily advance the evolution of fire protection programs in nuclear plants from prescriptive requirements toward a risk-informed and performance-based management.

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