Implementation of Performance-Based Fire Protection at Operating US Nuclear Power Plants

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Abstract – *Both the traditional deterministic fire protection regulatory approach and the newer risk-informed performance-based approach provide adequate protection of public health and safety. About half of the U.S. operating nuclear power plants are transitioning to the risk-informed performance-based alternative rule, 10 CFR 50.48(c), "National Fire Protection Association Standard NFPA 805." The risk-informed performance-based approach requires a reassessment of plant fire protection using state-of-the-art methods. A vigorous application of these methods at two US nuclear power plants piloting the transition to NFPA 805 has led to opportunities for the enhancement of fire safety. Furthermore, the approach will provide greater regulatory consistency and clarity, and provide more flexibility for licensees to address very low risk issues without prior NRC staff approval.*

I. INTRODUCTION

In June 2004, the United States (U.S.) Nuclear Regulatory Commission (NRC) amended its regulations to provide nuclear plant licensees a new option for complying with fire protection requirements. U.S. nuclear plants currently have fire protection programs based on deterministic regulations. With the publishing of the new rule, licensees may voluntarily choose to change to a risk-informed performance-based fire protection program based on the National Fire Protection Association (NFPA) standard NFPA 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants" (2001 edition).[1]

Title 10, Section 50.48, of the *Code of Federal Regulations* (10 CFR 50.48), "Fire Protection,"[2] requires each licensee to have a fire protection plan that satisfies the following:

> "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 … Fire detection and fighting systems of appropriate capacity and capability shall be provided and designed to minimize the adverse effects of fires on structures, systems, and components important to safety. …"[3]

The deterministic means for meeting these requirements come from 10 CFR 50, Appendix R, "Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979,"[4] or from plant-specific requirements incorporated into the operating license of plants licensed after that date. For simplicity, this paper refers to the NRC's deterministic fire protection requirements as the "Appendix R" approach, because the same technical requirements are applied to the newer plants as well.

Paragraph (c) of 10 CFR 50.48, "National Fire Protection Association Standard NFPA 805," incorporates the 2001 edition of NFPA 805 into the NRC regulations, with certain exceptions, and allows licensees to adopt and maintain a fire protection program that meets the requirements of NFPA 805 as an alternative to the Appendix R requirements. Licensees who choose to comply with 10 CFR 50.48(c) must submit a license amendment application to the NRC and receive approval to implement the new fire protection program. Also for simplicity, when this paper refers to an NFPA 805 fire protection program, it means one that meets the requirements of 10 CFR 50.48(c) and the applicable portions of NFPA 805.

Although the requirements of NFPA 805 differ from those in Appendix R in a number of areas, most notably in the allowance of performance-based alternatives to deterministic compliance, the NRC determined that either approach satisfies the requirements of 10 CFR 50.48(a). The *statements of consideration* for 10 CFR 50.48(c)[5] noted that the new regulations are acceptable because achieving the nuclear safety goals, objectives, and performance criteria of NFPA 805 provide controls for maintenance of the reactor fuel and the plant condition that ensure adequate protection of public health and safety. The NRC concluded that the criteria and methodologies contained in NFPA 805 provide acceptable alternatives to the requirements in Appendix R.

Issuing 10 CFR 50.48(c) is consistent with the NRC's ongoing transition to risk-informed, performance-based regulation, which began in the early 1990's. Also, the new rule addressed comments from the nuclear industry and some members of the public that the prescriptive, deterministic fire protection regulations represented a significant regulatory burden that was unnecessary to achieve an acceptable level of safety. The rulemaking effort was aided by NFPA publishing, in 2001, its consensus standard on performance-base fire protection, NFPA 805.

There are several benefits to licensees that choose to implement the performance-based fire protection program as allowed by 10 CFR 50.48(c). NFPA 805 provides flexibility in meeting its requirements while providing adequate protection of the public from nuclear plant fires. Where the deterministic requirements are not met, the licensee may use performance-based methods to demonstrate that the risk of the alternative is acceptable. This flexibility allows licensees to optimize their allocation of resources by focusing on risk-significant fire areas when making changes to their fire protection program. NFPA 805 also has criteria for assessing the acceptability of changes to a licensee's approved fire protection program – the *plant change evaluation* discussed later in this paper. The NRC intends to allow licensees to "self-approve" certain fire protection changes using the plant change evaluation approach. This means that, provided specified acceptance criteria are met, the licensee may implement the change to its fire protection program without prior review and approval by the NRC. One additional benefit is that, as a result of implementing NFPA 805, the plant has a clear and well-understood fire protection licensing basis.

At the time this paper was written, 50 of the 104 operating U.S. nuclear units had committed to change their existing fire protection program to a risk-informed performance-based program using NFPA 805. Two plant sites (representing four operating nuclear units) volunteered to pilot the implementation of NFPA 805 at their plant. Both pilot plants have been granted a license amendment to implement the NFPA 805 fire protection program. Lessons learned throughout the pilot process have been shared with the industry on an ongoing basis. The NRC staff expects that subsequent license amendment requests will incorporate these lessons, resulting in a more efficient NRC review and approval.

II. PERFORMANCE-BASED FIRE PROTECTION

NFPA 805 is a performance-based standard, as contrasted with approaches that prescribe requirements that are assumed or deemed to provide an acceptable level of fire protection. Before proceeding further, it is useful to describe exactly what is meant by a "performance-based" approach to regulation.

A regulation can be either prescriptive or performance-based. A prescriptive requirement specifies particular features, actions, or programmatic elements to be included in the design or process, as the means for achieving a desired objective. The traditional, prescriptive approach to regulating nuclear power plants in the U.S. has been referred to as "deterministic" or the "traditional engineering" approach; the term deterministic is used in this paper. The deterministic approach to regulation establishes requirements for engineering margin and for quality assurance in design, manufacture, and construction.

In addition, it assumes that adverse conditions can exist, establishes a specific set of design basis events, and requires that the design include safety systems capable of preventing or mitigating the consequences of those design basis events in order to protect public health and safety.

As mentioned in the introduction, Appendix R to 10 CFR 50 is the NRC's deterministic fire protection regulation. NFPA 805 includes both deterministic requirements and performance-based methods. The deterministic requirements in NFPA 805 related to barriers, separation, detection and suppression are almost identical to those in Appendix R. The NFPA 805 performance-based methods allow evaluation of alternatives to the deterministic requirements. The primary differences between Appendix R and NFPA 805 are as follows. The performance-based rule allows the licensee to choose the "safe and stable" end state that must be achieved and maintained following a fire, whereas Appendix R specifies hot shutdown initially and cold shutdown within three days. Also, Appendix R does not allow operator manual actions in lieu of barriers, separation, detection and suppression requirements without prior approval by the NRC. NFPA 805 allows feasible operator actions as part of the performance-based approach, provided the acceptance criteria for the chosen approach are met (e.g., as demonstrated by an assessment of risk using a fire probabilistic risk assessment (PRA) model of acceptable quality).

NFPA 805 defines a performance-based approach as one that "… relies upon measurable (or calculable) outcomes (i.e., performance results) to be met but provides more flexibility as to the means of meeting those outcomes. A performance-based approach is one that establishes performance and results as the primary basis for decision-making and incorporates the following attributes: (1) Measurable or calculable parameters exist to monitor the system, including facility performance; (2) Objective criteria to assess performance are established based on risk insights, deterministic analyses, and/or performance history; (3) Plant operators have the flexibility to determine how to meet established performance criteria in ways that will encourage and reward improved outcomes; and (4) A framework exists in which the failure to meet a performance criteria, while undesirable, will not in and of itself constitute or result in an immediate safety concern. The NRC uses identical attributes for defining performance-based regulation.[6]

A licensee that chooses to implement the requirements in NFPA 805 may use the deterministic approach in that standard or a performance-based approach to demonstrate that the appropriate performance criteria are met. The steps that a licensee takes to implement a fire protection program under NFPA 805 are discussed in the next section.

In both NFPA 805 and Appendix R, the deterministic approach utilizes barriers, separation, detection and suppression to protect one success path of required cables and equipment to achieve and maintain the nuclear safety performance criteria. Operator actions are not allowed for the protection of this equipment and cables. For each fire area where the deterministic approach is used, the licensee must demonstrate that the physical conditions (e.g., barriers, separation) exist such that the success path equipment and cables are free from fire damage. The deterministic approach is deemed to meet the nuclear safety performance criteria by virtue of the physical protection of the necessary hardware.

The performance-based approach uses engineering analyses to demonstrate that nuclear safety performance criteria are satisfied. There are two performance-based methods in NFPA 805: fire modeling and fire risk evaluation. The NRC regulation, 10 CFR 50.48(c), allows licensees to propose additional risk-informed or performance-based methods and, upon approval by the NRC, to use these methods to demonstrate compliance with NFPA 805.

The *fire modeling* performance-based approach determines the maximum expected fire scenarios for a given fire area and demonstrates that there is sufficient margin to the limiting fire scenario. The "maximum expected fire scenarios" represent the most challenging fires that could be reasonably anticipated for the given fire area. The "limiting fire scenarios" are postulated fires in the fire area that would be just severe enough to preclude meeting the performance criteria. The fire modeling approach is to demonstrate adequate margin between the maximum expected fire and the limiting fire scenario. Ensuring that there is adequate margin between these two fires provides reasonable assurance that the nuclear safety performance criteria will be met for any fires in that fire area.

The fire risk evaluation is an integrated assessment of the acceptability of risk, defense-in-depth, and safety margins. It compares the risk from fires of a configuration in a fire area that does not meet the NFPA 805 deterministic criteria with what the risk would be if the deterministic criteria were met. The difference in risk between the deterministically compliant fire area and the alternative, in terms of both core damage frequency (CDF) and large early release frequency (LERF), must meet published NRC acceptance guidelines. For a plant with total CDF below 1×10^{-4} per year and total LERF below 1×10^{-5} per year, the total *increase* in risk for all fire areas that use the fire risk evaluation performance-based method should be less than 1 x 10^{-5} per year CDF and less than 1 x 10^{-6} per year LERF.

NFPA 805 defines fire protection defense-in-depth as maintaining an adequate balance among: (1) preventing fires from starting; (2) rapidly detecting any fires that do occur and extinguish them promptly; and, (3) providing an adequate level of fire protection for structures, systems, and components important to safety, so that a fire that is not promptly extinguished will not prevent essential plant safety functions from being performed. Sufficient safety margins are deemed to exist when the existing calculated margin between the analysis results and the performance criteria compensates for the uncertainties associated with the analysis and data. Another way that safety margins are maintained is through the application of codes and standards, which are typically written to ensure adequate margins exist.

In summary, NFPA 805 provides deterministic requirements that are very similar to those in Appendix R, but also includes performance-based methods for evaluating plant configurations that may not meet those deterministic requirements. The performance-based methods use engineering analyses to demonstrate that the risk of these plant configurations is acceptably small compared to meeting the deterministic requirements and that fire protection defense-in-depth and adequate safety margins are maintained. This provides the licensee a great deal of flexibility regarding how to implement its fire protection program while maintaining an acceptable level of fire safety.

III. IMPLEMENTING A PERFORMANCE-BASED FIRE PROTECTION PROGRAM

NFPA 805 specifies the process for establishing a fire protection program at a light water nuclear reactor; this process is shown in Fig. 1. (The Chapter references in the figure refer to NFPA 805, 2001 edition.) The first step is to establish the fundamental fire protection program. The fundamental fire protection program includes development of a fire protection plan, establishing a fire brigade, and providing a water supply, pumps, standpipes, hose stations, and fire extinguishers. The requirements applicable to fire alarm and detection systems, suppression systems, and passive fire protection features (e.g., fire barriers) are also included in this part of the NFPA 805 standard.

The next step is to identify fire areas and associated fire hazards within the plant, and then to identify the performance criteria that apply to each fire area. For U.S. reactors, these are the nuclear safety and the radiation release performance criteria. (The NRC regulation did not incorporate the life safety or plant damage/business interruption goals that are also part of NFPA 805.) The nuclear safety performance criteria involve maintaining reactivity control, inventory and pressure control, decay heat removal, and vital auxiliaries to support these functions. The radiation performance criterion restricts radiation release to any unrestricted area due to the direct effects of fire suppression activities.

Once this step is complete, the licensee must identify systems, structures, and components in each fire area to which the performance criteria apply. In other words, for any fires that could occur within a fire area, the licensee must identify the equipment that will be relied upon to meet the performance criteria. For each of the fire areas, the licensee must then select the NFPA 805 deterministic approach or a performance-based approach for demonstrating that the performance criteria are met. (The deterministic and performance-based methods were discussed in the preceding section.) A combination of these approaches may be used in a given fire area, and the standard allows the performance-based approach to utilize deterministic methods for simplifying assumptions within the fire area. For example, if a particular fire area meets the deterministic requirements with one minor exception, a performance-based approach may be applied to just the exception.

The next step in implementing NFPA 805 is to perform a *plant change evaluation* to demonstrate that changes in risk, defense-in-depth, and safety margins are acceptable. The plant change evaluation is similar to the fire risk evaluation performance-based method described in the preceding section. The difference is that the plant change evaluation compares the proposed change to the previously-approved fire protection program, whereas the fire risk evaluation compares a configuration to the deterministic criteria. If the risk, defense-in-depth, or safety margins are not acceptable, NFPA 805 requires additional fire protection features or other alternatives to be implemented to provide acceptable levels of each attribute. For initial implementation of NFPA 805, since the licensee does not yet have a fire protection program that has been approved under NFPA 805, the NRC staff considers the results of the fire risk evaluations to bound the plant change evaluation requirement.

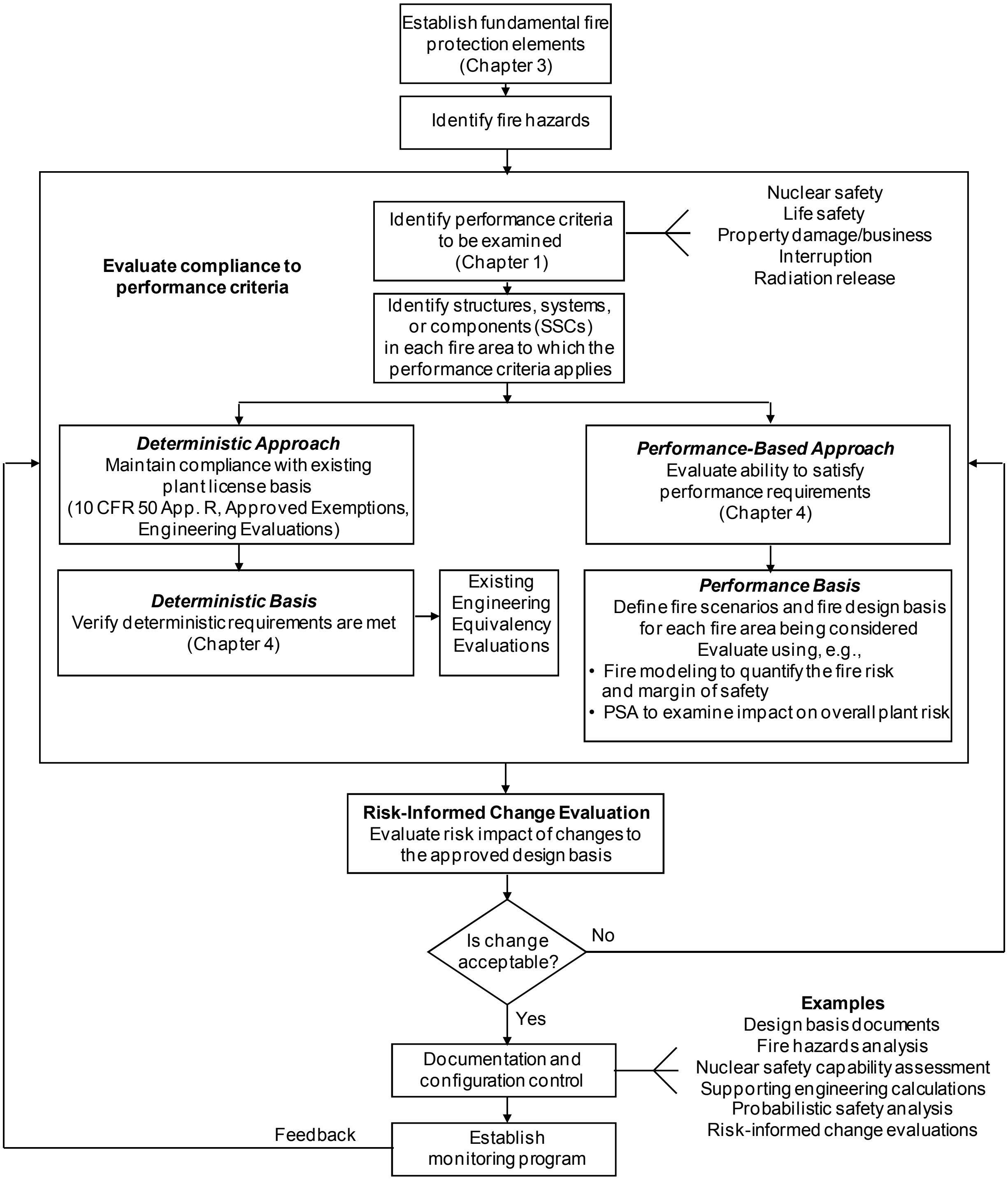

Fig. 1. NFPA 805 Methodology (reproduced from NFPA 805 figure 2.2)

The final two steps for NFPA 805 implementation are to develop a monitoring program and configuration control process. The purpose of the former is to monitor plant performance as it applies to fire risk and provide feedback for adjusting the fire protection program as necessary. The monitoring program is to ensure that the assumptions in the engineering analysis remain valid. Configuration control includes adequate levels of documentation of the fire protection program, a formal process for maintaining that documentation up-to-date, and requirements for quality of the engineering analyses that support the fire protection program.

By the end of the process, the licensee will have reviewed its entire fire protection program and documented its compliance with NRC fire protection regulations. The licensee also has a much better understanding of the fire risk at the facility and, if it has made plant modifications as a result of this understanding, is a safer plant from a fire perspective. The licensee will have implemented a monitoring program to ensure that the fire protection program remains effective over time, and will typically have the ability to self-approve certain fire protection program changes that meet specified criteria.

IV. SAFETY IMPROVEMENTS FROM IMPLEMENTING THE PERFORMANCE-BASED APPROACH

Each NFPA 805 pilot plant performed an assessment of its existing fire protection program using the methods discussed above. This assessment was an in-depth review of all aspects of the fire protection program using state-of-the art methods and information. In addition, both licensees developed fire PRA models of the entire plant. As a result of these reviews and analyses, each licensee identified instances where safety improvements could be made to reduce plant risk from fires.

The pilot plant licensees committed to make modifications to their plants to improve safety. As a result of these modifications, implementation of NFPA 805 will result in a net risk decrease for these plants. The scope of the modifications ranged from protecting certain electrical cables to installation of new systems for mitigating plant events resulting from a fire. The modifications include:

- Moving or wrapping electrical cables or installing fireproof cables;
- Improving electrical raceway fire barrier systems;
- Adding very early warning fire detection systems (“incipient detection”) to critical instrumentation cabinets;
- Providing new or additional fire detectors in key fire areas;
- Installing an additional control on the alternate shutdown panel;
- Adding a new pump and related engine-driven generator to provide alternate source of injection to reactor coolant pump seals; and,
- Adding a new high-pressure pump to provide make-up water to the steam generators.

The pilot plants also improved their fire plans and procedures in order to implement NFPA 805. The fire protection programs were extended to include shut down conditions and to comply with the NFPA 805 requirements for controlling radiological releases.

The net results of all the hardware and procedure changes, coupled with verification by the licensee that its fire protection program is in compliance with NFPA 805, are enhanced safety and reduced risk. Both pilot plants demonstrated that implementation of NFPA 805 can be a net safety benefit as well as establishing regulatory compliance.

V. INSIGHTS FROM TWO PILOT PLANTS

One purpose for piloting a new method or approach is to test out how well it works in practice and learn what enhancements can be made. At the time the two licensees volunteered their plants as NFPA 805 pilots, the NRC regulations had been revised to permit plants to adopt a performance-based fire protection program and initial guidance documents had been written. An NRC Regulatory Guide[7] had been issued that endorsed an industry document telling licensees how to systematically review their existing fire protection licensing basis and transition into one based on NFPA 805. NRC and industry had jointly published a document on how to perform a fire PRA.[8] The pilot plants would be the first to apply the performance-based fire protection approach and the first users of those guidance documents.

Numerous meetings were held among the pilot plant licensees, the NRC, and interested stakeholders to discuss issues that surfaced as the pilot plants went through the transition to their new fire protection program. The issues included both regulatory and technical aspects of the rule and the associated guidance documents. NRC staff participated in several industry conferences and made presentations on regulatory and technical aspects associated with implementing the new rule at the pilot plants. A number of insights were gleaned from resolving the issues and working through the pilot process.

One insight is that the performance-based fire protection program set forth in NFPA 805 can be successfully implemented and can result in improvements to plant safety. The in-depth review of a licensee's existing fire protection program as part of implementing NFPA 805 provides confidence that any conditions adverse to safety were identified. Where a licensee chooses to use a performance-based approach instead of the deterministic requirements of NFPA 805, the level of risk associated with the alternative is quantified and must be acceptably small. As discussed in the preceding section, both pilot plants identified plant modifications to improve plant safety as part of their implementation of the performance-based fire protection program.

Another insight is that fire PRA methods are sufficient to support the NFPA 805 fire risk evaluation performance-based method. Both pilot plant licensees developed fire PRA models for their plants that were capable of estimating CDF and LERF from internal fire events. In both cases, the NRC staff was able to conclude that the licensee had reasonably estimated the risks associated with fires at their plants and had appropriately used fire risk evaluations when the NFPA 805 performance-based approach was used. However, the fire PRA methods are still maturing and new methods being developed in order to address new analysis needs arising from implementing NFPA 805. For example, one pilot plant committed to install incipient fire detectors in critical instrumentation cabinets. The existing guidance on fire PRA methods did not include modeling incipient fire detectors, so an approach had to be developed. As another example, the published assumptions for treating spurious circuit actuations in the fire PRA may be overly conservative; i.e., not realistic. Additional research is being performed in this area and others in order to refine the methods and improve realism.

A third insight is that a large amount of resources must be expended to transition from an existing fire protection program to the NFPA 805 performance-based program. Both pilot plants underestimated the resources required. For example, the pilot plants had to update and extend the scope of their cable routing databases. Analysis of circuits to identify potential spurious actuations requires a great deal of analysis time. The fire PRA development required analysis of thousands of fire scenarios. The plants performed fire modeling of selected ignition sources and targets, which is also resource-intensive. Two licensees provided to the NRC cost estimates for their implementation of NFPA 805: around $15 million for a two-unit nuclear reactor site and $80 million for a licensee having five reactors.[9]

The pilot approach to implementing the performance-based fire protection program was extremely beneficial. A number of technical and regulatory questions arose during the pilot process. In addition to holding frequent meetings with interested stakeholders as discussed above, the NRC instituted a "frequently asked questions" (FAQ) process to provide a formal means to capture the questions, work through their resolution, and document the resulting NRC answer to the FAQ. The answers to these questions represented interim staff positions, which were incorporated into the regulatory guide when it was later revised. The FAQ approach allowed licensees to proceed with some degree of certainty without waiting for the regulatory guide to be changed, which is a longer lead-time process.

IV. CONCLUSIONS

NFPA 805 provides deterministic requirements that are very similar to those in the NRC's traditional fire protection regulations (Appendix R), but also includes performance-based methods for evaluating plant configurations that may not meet those deterministic requirements. The performance-based methods use engineering analyses to demonstrate that the risk of these plant configurations is acceptably small compared to meeting the deterministic requirements and that fire protection defense-in-depth and adequate safety margins are maintained. This provides the licensee a great deal of flexibility regarding how to implement its fire protection program while maintaining an acceptable level of fire safety. As of this writing, 50 of the 104 operating U.S. nuclear units had committed to implement NFPA 805.

Two licensees participated in a piloting of NFPA 805 implementation at their plants. As a result of the detailed review of their fire protection programs, each pilot plant identified plant modifications to reduce fire risk. The scope of the modifications ranged from protecting certain electrical cables to installation of new systems for mitigating plant events resulting from a fire. The pilot plants also improved their fire plans and procedures and extended their fire protection programs to include shut down conditions. The modifications and programmatic changes will result in substantial safety improvements at each plant.

There were several key insights that came out of the piloting of NFPA 805 implementation at the two sites. One insight is that the performance-based fire protection program set forth in NFPA 805 can be successfully implemented and can result in improvements to plant safety. Another insight is that fire PRA methods are sufficient to support the NFPA 805 fire risk evaluation performance-based method. A third insight is that a large amount of resources must be expended to transition from an existing fire protection program to the NFPA 805 performance-based program. Throughout the pilot process, all stakeholders benefited from frequent communications in the form of public meetings, presentations at industry conferences, and the FAQ process.

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NOMENCLATURE

The following definitions are adapted from references 1 and 6:

Core Damage Frequency (CDF) is the frequency of the combinations of initiating events, hardware failures, and human errors leading to core uncovery with reflooding of the core not imminent.

Defense-in-Depth (fire protection) is providing an adequate balance among: (1) preventing fires from starting; (2) rapidly detecting, controlling, and extinguishing promptly any fires that do occur; and, (3) providing an adequate level of fire protection for structures, systems, and components important to safety, so that a fire that is not promptly extinguished will not prevent essential plant safety functions from being performed.

Deterministic Approach is a regulatory approach that establishes requirements for engineering margin and quality assurance in design, manufacture, and construction. It involves implied, but unquantified, elements of probability in the selection of the specific accidents to be analyzed as design basis events.

Fire Area is an area that is physically separated from other areas by space, barriers, walls, or other means in order to contain fire within that area.

Fire Model is a mathematical prediction of fire growth, environmental conditions, and potential effects on structures, systems, or components based on the conservation equations or empirical data.

Large Early Release Frequency (LERF) is the frequency of core damage events leading to a significant, unmitigated release from containment in a time frame prior to effective evacuation of the close-in population such that there is a potential for early health effects.

Performance-Based Approach is an approach that establishes performance and results as the primary basis for decision-making and incorporates the following attributes: (1) Measurable or calculable parameters exist to monitor the system, including facility performance; (2) Objective criteria to assess performance are established based on risk insights, deterministic analyses, and/or performance history; (3) Plant operators have the flexibility to determine how to meet established performance criteria in ways that will encourage and reward improved outcomes; and (4) A framework exists in which the failure to meet a performance criteria, while undesirable, will not in and of itself constitute or result in an immediate safety concern.

Probabilistic Risk Assessment (PRA) is a comprehensive evaluation of the risk of a facility or process; also referred to as a probabilistic safety assessment (PSA)

Risk is the set of probabilities and consequences for all possible accident scenarios associated with a given plant or process.

Risk Informed Approach is a philosophy whereby risk insights are considered together with other factors to establish performance requirements that better focus attention on design and operational issues commensurate with their importance to public health and safety.

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