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An integrated methodology for spatio-temporal incorporation of underlying failure mechanisms into fire probabilistic risk assessment of nuclear power plants

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ABSTRACT

In this research, an Integrated probabilistic risk assessment (I-PRA) methodological framework for Fire PRA is developed to provide a unified multi-level probabilistic integration, beginning with spatio-temporal simulation-based models of underlying failure mechanisms (i.e., physical phenomena and human actions), connecting to component-level failures, and then linking to system-level risk scenarios in classical PRA. The simulation-based module, called the fire simulation module (FSM), includes state-of-the-art models of fire initiation, fire progression, post-fire failure damage propagation, fire brigade response, and scenario-based damage. Fire progression is simulated using a CFD code, fire dynamics simulator (FDS), which solves Navier–Stokes equations governing the turbulent flow field. Uncertainty quantification is conducted to address parameter uncertainties. The I-PRA paves the way for reducing excessive conservatisms derived from the modeling of (i) fire progression and damage and (ii) the interactions between fire progression and manual suppression. Global importance measure analysis is used to rank the risk-contributing factors. A case study demonstrates the implementation of I-PRA for a regulatory-documented fire scenario.

1. Introduction

Probabilistic risk assessment (PRA) was developed in the nuclear power domain, where risk information gained from PRA is one of the key pillars in the risk-informed decision-making process by the US Nuclear Regulatory Commission (NRC) [1]. This research is advancing PRA by explicitly incorporating the underlying science of accident causation into Fire PRA. External and internal fires can be the initiating events of cascading failure throughout a system, compromising the existing physical barriers and redundant safety systems. After a major fire at the Browns Ferry NPP in 1975 [2], NPP fire protection has emerged as a controversial and complicated area of nuclear safety [3–6]. In 2004, the US NRC approved a structured Fire PRA methodology that is still not well established in the nuclear community and remains an area of active research. Many experts point out that the main gap in Fire PRA is the overestimation of risk due to the excessive conservatism that is introduced in the input parameters and modeling assumptions [5,7–16]. Literature points out five major sources of conservatism in the current Fire PRA: (1) Fire ignition frequency, (2) Fire progression and damage modeling, (3) Interaction between fire progression and the fire brigade, (4) Circuit failure analysis, and (5) post-fire human reliability analysis (HRA). The results of this research lead to a more accurate estimation of fire risk in NPPs by reducing excessive conservatisms in the second and third areas through the probabilistic integration of simulation-based models

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Abbreviations: CCF, common cause failure; cdf, cumulative distribution function; CFAST, consolidated model of fire growth and smoke transport; CFD, computational fluid dynamics; CFR, code of federal regulations; CI, confidence interval; DBA, design-basis accident; DiD, defense-in-depth; FDS, fire dynamics simulator; FDT, fire dynamics tool; FFT, fast Fourier transform; FIVE-Rev1, fire-induced vulnerability evaluation revision 1; FPP, fire protection program; FSM, fire simulation module; GDC, general design criteria; HRR, heat release rate; HRA, human reliability analysis; IM, importance measure; I-PRA, integrated probabilistic risk assessment; LES, large eddy simulation; LHS, latin-hypercube sampling; MPI, message passing interface; MTR, measure of turbulence resolution; NIST, National Institute of Standards and Technology; NPP, nuclear power plant; NRC, Nuclear Regulatory Commission; PRA, probabilistic risk assessment; RIPB, risk-informed, performance-based; SA, sensitivity analysis; SSCs, structures, systems, and components; UQ, uncertainty quantification; V&V, verification and validation.

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of underlying failure phenomena with the classical PRA model. In this context, a "simulation-based" model is defined as a mechanistic model of the underlying failure mechanisms that numerically solves the physical governing equations and can capture space- and time-dependent phenomena. Temporal aspects are important in Fire PRA since the progression of fire-induced scenarios and interactions between fire physics and plant response are dynamic and complex. The consideration of spatial aspects is also crucial in Fire PRA since equipment damage and fire-induced adverse conditions are associated with a specific zone around the fire source. The integrated framework helps identify, rank, and manage the most important risk-contributing factors and underlying failure mechanisms associated with fire scenarios.

Section 2 provides a theoretical background on NPP fire protection approaches (both deterministic and risk-informed) and the main gaps in the existing Fire PRA. It highlights the main contributions of this research with respect to the reduction of conservatism and the advancements of Fire PRA. Section 3 explains the new I-PRA methodological framework. In Section 4, the new I-PRA methodology and the risk-ranking method (i.e., Global importance measure analysis) are both applied for a NPP fire scenario. Section 5 concludes the paper, highlighting future research directions.

2. Theoretical background on fire protection approaches in nuclear power plants, gap analysis and contributions

The accident at the Browns Ferry NPP led to dramatic changes in fire protection and regulation at U.S.NPPs and, since that time, the FPP at NPPs has been implemented and regulated using the deterministic and prescriptive requirements provided by 10 CFR 50.48 and Appendix R [17]. Deterministic and prescriptive fire protection was developed on the basis of three procedural elements of the defense-in-depth (DiD) philosophy; namely (i) prevent fires from starting, (ii) if a fire starts, rapidly detect and suppress it, and (iii) in case the rapid detection and suppression fail, provide protection for the structures, systems, and components essential for safe shutdown [17]. In general, the deterministic approach is effective in the initial stages of technological development when knowledge of and experience with the system is quite limited. However, as experience in design and operation at NPPs has increased, and as several major nuclear accidents have occurred in the past 60 years, the scope of nuclear regulation has expanded. Therefore, both the licensees and the regulatory agency have recognized that the deterministic and prescriptive approaches have drawbacks such as (a) inflexibility in the fire protection design, (b) a complicated process of granting exemptions and deviation applications, (c) inefficient resource allocations due to inflexible prescriptive requirements [18], and (d) less effectiveness in addressing the low-probability relatively high-consequence events by relying on design-basis accidents (DBAs) instead of utilizing large sets of potential accident scenarios in safety analysis and regulation. These limitations in the deterministic approach have motivated the transition to the risk-informed, performance-based (RIPB) approach in fire protection.

In parallel with deterministic and prescriptive FPP regulations, research on fire risk analysis, initiated in 1977 by the U.S. NRC, aimed at developing a systematic and structured methodology for estimating the fire-induced risk to NPPs. The research was led by PRA researchers at the University of California at Los Angeles, developing a methodology for integrating uncertainty quantification (UQ) with a deterministic fire model to compute the probability of fire damage to equipment based on the competition between two time quantities: time-to-fire-progression and time-to-fire-suppression. The computed damage probability was used as an input to the PRA for calculating plant risk induced by fire [19–23]. This Fire PRA methodology was implemented in utility-sponsored PRA projects in the early 1980s [24,25]. Subsequently, from the mid-1980s until the early 1990s, Fire PRAs were conducted in multiple industry-sponsored and regulatory PRA studies, such as NUREG-1150 [26] and the Individual Plant Examinations of External Events [27]. The Fire PRA approach, developed in the 1980s, was used as a foundation for the "current methodology" NUREG/CR-6850 [28,29], which is an outcome of collaborative efforts by the U.S. NRC's Office of Nuclear Regulatory Research and the Electric Power Research Institute. In this paper, the methodology recommended in NUREG/CR-6850 is referred to as the "current/existing methodology". The recent industry-wide implementation of plant-specific Fire PRA in the U.S. is mainly based on this methodology.

One of the main advantages of the RIPB-FPP is that the uncertainties associated with fire characteristics, fire detection and suppression system performance, and plant response can be explicitly addressed. The explicit treatment of uncertainties means the excessive safety factors in the deterministic approach [30] can be reduced. Furthermore, the RIPB-FPP approach provides an expanded scope of possible fire hazards and fire-induced event sequences, rather than focusing on predetermined representative fire hazards and fire-induced scenarios applied in the deterministic and prescriptive approach. This feature provides decision-makers with valuable information and insights, on a plant-specific basis, about the fire protection features, major risk-contributing factors (e.g., fire locations, design parameters), and the predicted system responses to possible fires [7,18]. In addition, licensing conditions and requirements are less complicated and time consuming than those prescribed in the traditional FPP regulation, based on Appendix R, where many requests for exemption and deviation were submitted by licensees and all had to be reviewed by the U.S. NRC. In 2004, 10 CFR 50.48 was revised to allow licensees to voluntarily transition to the RIPB approach under NFPA 805 [31]. Under this framework, the licensees can adopt the FPP, based on goal-driven performance requirements, without requiring a specific solution in a prescriptive manner.

2.1. Gaps in existing fire PRAs

Despite advances in Fire PRA, many experts have pointed out that risk estimated from the current methodology is unrealistic, and is due mainly to the overly conservative input parameters and assumptions introduced in the models of fire physics and human actions [5,7–16]. The belief is that the degree of conservatism in the current Fire PRA is much larger than that of the internal event PRA [16] and that the fire-induced plant risk calculated by the current Fire PRA is conservative when compared with reality by a factor of 5 to 10 or more [11]. Essentially, the conservatism is introduced in the areas where, rather than using a structured and quantitative UQ, the bounding method has been applied to deal with a large uncertainty [10,11]. The bounding method utilizes conservative input parameters and physical models that are derived from limited experimental data and expert judgment, introducing conservatism in the final outputs of Fire PRA. In addition, the nuclear industry has claimed that fire tests performed by the U.S. NRC were biased toward unrealistically large fires, skewing the outcomes and producing unrealistic and possibly detrimental results with respect to the realism in PRA [8,12,16]. As mentioned in Section 1, literature points out five major sources of conservatism in the current Fire PRA. This research contributes to Area of Conservatism #2, i.e. fire progression and damage modeling, and Area of Conservatism #3, i.e. interaction between fire progression and the fire brigade. The conservatism in these two areas is briefly explained as follows:

- *Conservatism in fire progression and damage modeling:* The modeling approaches of energy release, cable flame spread rate, and fire propagation among cable trays were evaluated and determined to be unrealistic [8,9,11,16]. In recent Fire PRAs conducted under NFPA-805 [31], fire progression and fire-induced physical conditions are mainly modeled by zone of influence (ZOI) models and/or engineering correlations derived from experimental data and expert judgment, or by zone models such as the consolidated model of fire growth and smoke transport (CFAST) [8]. Those correlations were derived from non-realistic and conservative experiments designed