Enhancing Realism in Fire Probabilistic Risk Assessment of Nuclear Power Plants

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The Socio-Technical Risk Analysis (SoTeRiA) Laboratory at the University of Illinois at Urbana-Champaign focuses on the advancements of Probabilistic Risk Assessment (PRA), pioneering three key areas of scholarly developments: (1) spatiotemporal coupling of physical failure mechanisms with human/social performance and incorporation of this coupling into PRA by developing a static-dynamic Integrated PRA (I-PRA) methodology, (2) incorporation of big data analytics into PRA, and (3) integration of safety risk and financial risk for socio-technical systems. This paper reports on how the progress in the first key area has improved the realism of Fire PRA of Nuclear Power Plants (NPPs). In this research, the spatiotemporal coupling between fire progression and fire crew performance is advanced in three phases. In the first phase, an explicit unidirectional coupling between the data-driven fire crew model and a Computational Fluid Dynamics (CFD) fire model is developed by modifying the heat release rate curve. This fire-human coupling is implemented in the I-PRA methodology and applied to a critical fire scenario of an NPP that leads to a 50% reduction in the plant risk estimation. In the second phase, a Human Reliability Analysis (HRA)-based approach is developed by generating an explicit bidirectional coupling between an HRA model of the fire crew and the CFD fire model. In the third phase, a spatiotemporal human performance model is developed using Agent-Based Modeling (ABM) and coupled bidirectionally with a fire model in a Geographic Information System (GIS). Although the Fire PRA applications are the primary focus of this paper, the concepts and methodologies presented would also be applicable for the External Control Room (Ex-CR) HRA, in general, that involve other types of hazards.

Keywords: Probabilistic Risk Assessment (PRA), Fire PRA, static-dynamic Integrated PRA (I-PRA), Coupling of Physics and Human Performance, Human Reliability Analysis, Agent-Based Modeling, Nuclear Power Plant.

1. Introduction

The Socio-Technical Risk Analysis (SoTeRiA) Research Laboratory at the University of Illinois at Urbana-Champaign (UIUC) advances Probabilistic Risk Assessment (PRA), pioneering three key areas of scholarly developments:

- Key area (#1): Spatiotemporal coupling of physical failure mechanisms with human/social performance and incorporation of this coupling into plant PRA by developing a static-dynamic Integrated PRA (I-PRA) methodology;

Proceedings of the 30th European Safety and Reliability Conference and
the 15th Probabilistic Safety Assessment and Management Conference
Edited by Piero Baraldi, Francesco Di Maio and Enrico Zio
Published by Research Publishing, Singapore.
ISBN: 978-981-14-8593-0; doi:10.3850/978-981-14-8593-0

- Key area (#2): Incorporating big data analytics into PRA
- Key area (#3): Developing theory and methodology for integrating safety risk with financial risk for socio-technical systems

The focus of this paper is the authors' recent progress of Key area (#1). In PRA, there are two types of physics-human interactions contributing to the plant risk: (i) interactions between human performance and plant system response (e.g., thermal-hydraulic behavior of a reactor); and (ii) interactions between human performance and the surrounding environmental conditions (e.g., fire, radiation). Our research has advanced modeling of the second type of physics-human interactions focusing on the human performance under a hazardous condition where the physics-human interactions are bidirectional; i.e., human actions can mitigate progression of the hazard, while the hazard-induced conditions can impact the human performance. In the existing PRAs of Nuclear Power Plants (NPPs), this type of physics-human interaction is typically treated by a time-based method (e.g., computing the time available and the time required separately and then comparing them) or by expert judgement. These methods, however, can introduce an unquantifiable bias or uncertainty due to a lack of explicit consideration of physics-human interactions over time and space. To improve the realism associated with the modeling of this type of physics-human interaction, our research has developed a simulation-based model of human performance that explicitly simulates spatiotemporal human behavior and couples it with the physical hazard propagation by creating an interface for communicating spatiotemporal information bidirectionally. In the context of PRA for NPPs, there are several studies that have developed a human performance simulation and have connected it to a physical simulation, e.g., simulation-based HRA. Our research, however, is the first to explicitly incorporate space in addition to time into the human performance model and develop the physics-human coupling that is capable of transferring both spatial and temporal information in a bidirectional way.

One of the application areas for Key area (#1) is Fire PRA of NPPs. After the 1975 fire at Browns Ferry Unit 1 [1], fire protection at NPPs emerged as a controversial and complicated area of nuclear safety [2-4]. In 1980, the U.S. NRC issued the deterministic and prescriptive fire protection requirements for NPPs in 10 CFR 50.48 and Appendix R [5]. In 2004, the U.S. NRC modified its fire protection regulation to allow existing NPPs to voluntarily transition to the Risk-Informed, Performance-Based (RIPB) approach, adopting the National Fire Protection Association (NFPA) Standard 805 [6]. In the NFPA-805 transition, Fire PRA is used as a basis for the Fire Risk Evaluation. Guidance on the Fire PRA methodology, based on state-of-the-art techniques, tools, and data, is provided in NUREG/CR-6850, EPRI TR-1011989 [7, 8]. For brevity in the current paper, this document is referred to as "NUREG/CR-6850", and the methodology, therein, is referred to as the "current Fire PRA methodology".

In spite of research and development over the past decades, experts point out that there is still an overestimation of risk in the current Fire PRA methodology due to the excessive conservatism that is introduced in the input parameters and modeling assumptions. A literature review by the authors [9] identified five major domains for improving realism in the current Fire PRA methodology: (a) Fire ignition frequency, (b) Fire progression and damage modeling, (c) Interaction between fire progression and manual suppression, (d) Circuit failure analysis, and (e) Post-fire Human Reliability Analysis (HRA). The authors' research is focused on improving the realism in domains 'b' and 'c.'

2. Fire-Human Interaction in NPP Fire Scenarios

To establish the conceptual background, Subsection 2.1 provides a qualitative overview of the fire-human interactions associated with fire scenarios at NPPs. Subsection 2.2 summarizes the review and categorization of the existing studies on the fire-human interactions, especially focusing on the studies in the nuclear power domain, to highlight the contributions of this line of research.

2.1 *Concepts of Fire-Human Interaction in NPP Fire Scenarios*

To establish the conceptual basis for the fire-human interaction in NPP fire scenarios, the underlying causalities leading to the observable fire-induced damage consequences in the context of NPP fires are shown in Fig. 1. The fire source and its progression in the fire compartment ('Fire Progression') is the driver of the underlying physical mechanisms leading to the Fire PRA scenarios. The safety-related equipment of an NPP can fail due to the fire-induced damage to the critical equipment in the compartment, such as cable trays and electrical cabinet ('Cable Tray/ Cabinet Damage' in Fig. 1). The impacts of fire progression and fire-induced physical environment, such as high temperature and heat flux, on the critical safety equipment are predicted by a fire model.

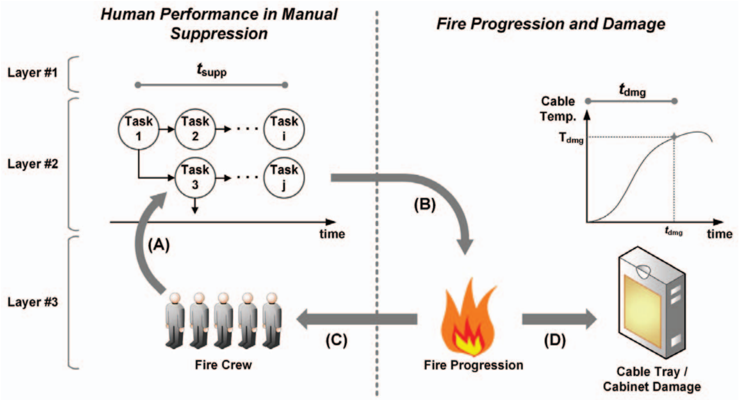

Fig. 1. Concepts of Physics-Human Interactions in the Context of Fire PRA of NPPs

Attempting to prevent and limit fire-induced damage to critical equipment, manual suppression is performed by the onsite fire crew ('Fire Crew' in Fig. 1). The manual suppression involves various tasks, consisting of both cognitive and execution tasks, and is typically performed by a fire crew team consisting of multiple coordinating members. The performance of manual suppression can also be affected by fire-induced conditions, such as visibility and thermal stress (arrow 'C' in Fig. 1). Through time-dependent and location-specific human behavior of the fire crew members ('Layer #3' in Fig. 1), the pivotal manual suppression tasks for suppressing and controlling the fires, such as traveling to the fire location, searching for the fire source, and manually suppressing it using the portable extinguisher, are performed (Layer #2 in Fig. 1). Each manual suppression task can influence the fire progression, for instance, the fire intensity can change when the fire crew opens the cabinet door or when the fire crew starts discharging the suppressant (arrow 'B' in Fig. 1). The interactions between fire progression and manual suppression form a time-dependent feedback loop, represented by arrows 'A', 'B', and 'C' in Fig. 1.

2.2 *Review and Categorization of Existing Studies on the Modeling of Fire-Human Interactions in NPP Fire Scenarios*

In this subsection, a review summary and categorization of the existing studies on the modeling of manual suppression and its interactions with fire progression is provided. The primary focus is on NPP applications, although a complete literature review, covering both nuclear and non-nuclear domains, is provided in the referenced publication [10]. In the manual suppression analysis for Fire PRA, two elements should be addressed: (I) human performance in manual suppression and (II) interactions between fire progression and manual suppression.

Regarding human performance in manual suppression, depending on the scope and resolution of the human model, three layers of causalities in Fig. 1 can be defined:

- 'Layer #1' refers to the time-based performance measure for manual suppression (such as time to detection and time to suppression);
- 'Layer #2' refers to the sequence of manual suppression tasks including the timings and outcomes of each task
- 'Layer #3; refers to the underlying behavior of the human beings (e.g., fire crew members), including the physical movements and cognitive processes, during the manual suppression activity.

For human performance in manual suppression, the existing studies can be classified into three approaches: (a) Data-driven approach, (b) HRA-based approach, and (c) Simulation-based approach [10]. The data-driven approach implicitly quantifies sequencing and timing of the fire crew tasks and human error probabilities (HEPs) by analyzing empirical data. In this approach, only 'Layer #1' of the causations is treated explicitly. The HRA-based approach offers advancements from two angles: it develops more detailed task sequencing and quantifies the HEPs associated with each task using existing HRA techniques, rather than solely relying on empirical data; thus, 'Layer #1 and 'Layer #2' are treated explicitly. The HRA-based approach has key limitations in that the spatial dimension is not explicitly analyzed, and the incorporation of human factors relies on semi-quantitative Performance Shaping Factors (PSFs) that are characterized based on expert judgment. The simulation-based approach improves these limitations by using a computer simulation model for improved modeling of the contextual factors that could influence the human performance, extending the modeling to ‘Layer #3’ in Fig. 1.

Interactions between fire progression and manual suppression has two directions: the influences of fire-induced conditions (e.g., smoke, temperature) on the human performance (arrow ‘C’ in Fig. 1); and the influences of the manual suppression activities (e.g., discharging suppressant, activating smoke purge) on the fire progression (arrow ‘B’ in Fig. 1). In this regard, the existing studies are classified into four types: (i) Implicit time-based, (ii) Explicit one-directional interface from human performance to fire progression (only arrow ‘B’ is explicit), (iii) Explicit one-directional interface from fire progression to human performance (only arrow ‘C’ is explicit), and (iv) Explicit bidirectional (both arrows are explicit) [10]. The Type (i) method is based on competition between “time to damage” with “time to suppression,” as implemented in the current Fire PRA methodology [7, 8]. Type (ii) and Type (iii) methods explicitly model the fire-human interactions during the evolution of these two processes, yet each method type only addresses a single direction of the fire-physics interactions separately. In the Type (ii) method, information from the human performance model is used as input to the fire model, while in the Type (iii) method, information obtained from the fire model is used as input to the human performance model. Type (iv) methods consider both directions of the fire-human interactions concurrently by using a combination of the Type (ii) and Type (iii) methods.

Our review [10] showed that most of the existing studies for the NPP applications used the data-driven approach for fire crew modeling and Type (i) (implicit time-based method) for capturing the fire-human interactions. With a few exceptions, such as NUREG-2180 [11] and Kloos et al. [12-14], studies using the HRA-based approach for fire crew modeling and those using Types (iii) and (iv) methods for addressing the fire-human interactions are not common. Although there are some simulation-based HRAs for Main Control Room (MCR) operators, none have been adopted for modeling human performance in fire scenarios. Moreover, these existing simulation-based HRA models focused on human cognitive behavior and do not incorporate the spatial dimension explicitly. In the non-nuclear domains, simulation techniques such as discrete event simulation, serious games and virtual simulation, and agent-based modeling have been proposed to advance the first responder modeling in fire scenarios. These studies, however, have been conducted on a larger scale than those for enclosure fires and are not directly applicable to Fire PRA of NPPs.

3. Evolution of SoTeRiA Lab’s Research on Fire Crew Modeling and Fire-Human Coupling

To improve the realism of Fire PRA for NPPs, the authors have advanced the fire crew modeling and its coupling with fire progression in three phases as explained in the following subsections.

3.1 *Phase 1: Explicit, One-directional Interface with a Data-Driven Fire Crew Model*

In the first phase of research [9, 15, 16], an explicit one-directional interface from human performance to fire progression (i.e., Type (ii) mentioned above) is developed. In this research, the data-driven probability model (i.e., a non-suppression curve from NUREG-2169 [17]) is used for human performance. Fire progression and damage to targets are simulated by a CFD fire model, i.e., the Fire Dynamics Simulator (FDS) [18]. To create the explicit interface with the data-driven fire crew model, the Heat Release Rate (HRR) curve, which is one of the key inputs to the FDS, is modified using three pivotal timings associated with manual suppression, including the time to detection (t_{det}), the fire crew response time (t_{fb}), and the duration of manual suppression ($t_{\text{fb}\rightarrow\text{sup}}$). The burnout HRR curve (without suppression) is reduced between t_{fb} and $t_{\text{fb}\rightarrow\text{sup}}$ (Fig. 2).

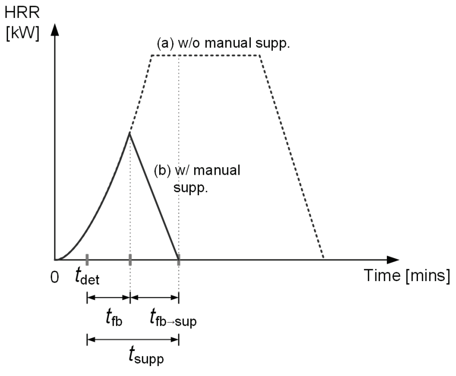

Fig. 2. Type (ii) Fire-Human Interface in Phase 1.

3.2 *Phase 2: Explicit, Bidirectional Interface with an HRA-based Fire Crew Model*

In the second phase [19], modeling of the fire-human interactions is advanced by developing an HRA-based approach. In this research, the existing Fire HRA methods [11, 20] are extended in manual suppression with two key advancements:

(i) adding quantification of the timing of pivotal actions by the fire crew, and (ii) creating the explicit and bidirectional interface between the HRA model and the FDS code. In this fire-human interface, the influence of manual suppression on fire progression is modeled by modifying the HRR curve during manual suppression using an empirical correlation for water-based suppression. The influence of fire progression on manual suppression is modeled by (i) considering the likelihood of fire crew performance based on the FDS outputs (i.e., when the HRR exceeds a threshold value, the manual suppression is assumed to fail), and (ii) modifying the PSFs in the HRA quantification to reflect the fire-induced adverse conditions.

The HRA-based method, however, has key limitations in that the fire-induced dependency, e.g., dependency among the fire crew tasks in terms of human error probabilities and timing, cannot be fully captured. This is because the spatial dimension is not incorporated explicitly when modeling the fire-human interactions, and incorporation of human factors relies on semi-quantitative PSFs that are characterized based on expert judgment. To address these limitations, the simulation-based approach is developed in the third phase.

3.3 *Phase 3: Explicit, Bidirectional Interface with a Simulation-based Fire Crew Model*

In the third phase [10, 21], the authors develop a simulation-based approach for modeling fire crew performance and its spatiotemporal interactions with fire progression. An Agent-Based Modeling (ABM) approach is used to simulate the behavior and decision making by the fire crew during the fire search phase. The ABM is coupled with a fire model, CFAST [22], through a Geographic Information System (GIS) environment (Fig. 3), where the time steps and spatially discretized regions are synchronized between ABM and CFAST to generate a spatiotemporal interface between the two simulations. The ABM-GIS methodology allows for modeling the spatiotemporal behavior of the fire crew considering scenario-specific human factors, including fire-induced environmental stresses (e.g., smoke and heat) and the degree of knowledge of the fire crew (e.g., familiarity with the room settings). The coupling between ABM and CFAST for capturing fire-human interactions generates an explicit, bidirectional fire-human interface of Type (iv). In order to capture the impact of human performance on fire progression, the HRR curve is modified using the time to locate the fire and the time to suppression obtained from the ABM model, in addition to a correlation model for water-based suppression. To capture the impact of fire progression on human performance, this GIS-based coupling transfers temporal and spatial information on the fire-induced smoke density from CFAST to the ABM model to update the fire crew parameters including walking speed and visibility.

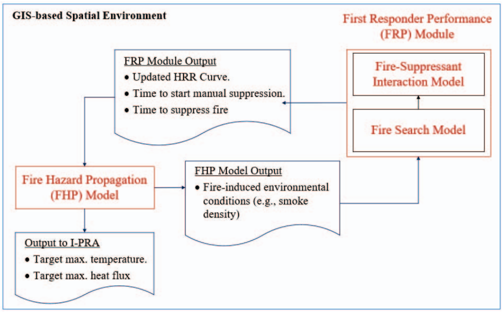

Fig. 3. ABM-CFAST-GIS Coupling in Phase 3.

4. Integration of Advanced Fire-Human Coupling into Fire PRA of NPPs

Another critical aspect of Key area (#1) of SoTeRiA's Scholarly Development (explained in Section 1) is an incorporation of the advanced physics-human coupling into the existing plant PRA. In this research, the advanced fire-human couplings (explained in Section 3) are integrated with the existing plant PRA using a static-dynamic Integrated PRA (I-PRA) methodological framework (Fig. 4) [9, 16].

The fundamental concept of the I-PRA methodological framework is that advanced simulation models of underlying physical and social phenomena are developed and, then, integrated with the existing plant PRA through a probabilistic interface. Compared to existing dynamic PRAs, I-PRA maintains a tractable number of accident scenarios (by using the existing plant ET-FT structure) while capturing the dynamic physics-human interactions through the spatiotemporal simulations of underlying failure mechanisms. I-PRA increases the realism of PRA by explicitly incorporating time and space into underlying models while avoiding significant changes to the existing plant PRA structure and the associated costs (e.g., peer review effort).

In I-PRA, the existing plant PRA model is integrated with underlying simulations in a "unified" computational platform. In the existing Fire PRA methodology, the connection between underlying fire simulation models and the plant PRA is "passive," i.e., the cable damage probabilities (e.g., 'CBD' in Fig. 4) are computed as outputs from the fire model, which are then used as inputs to the PRA software. In contrast, in Fire I-PRA, the spatial and temporal information on input-output relationships between the plant PRA model and the underlying simulations (i.e., the coupling of the fire model and the human

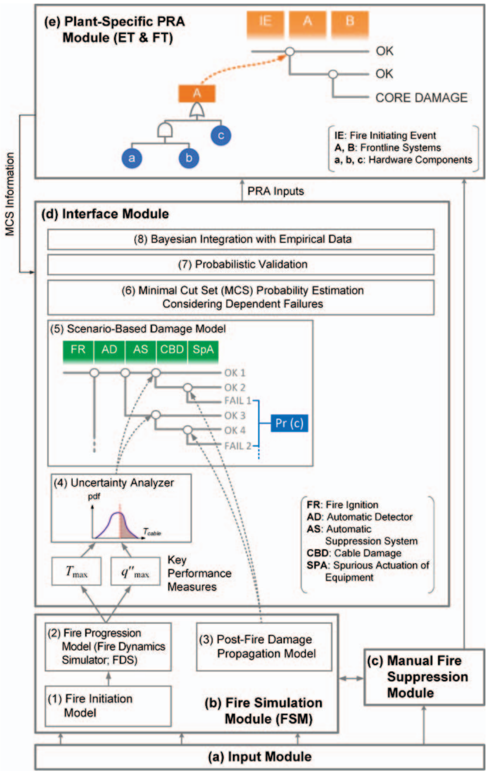

Fig. 4. Integrated PRA (I-PRA) Methodological Framework for Fire PRA of NPPs

performance model) are recorded and analyzed in a unified platform. This unified connection allows the Global Importance Measure analysis to be conducted to generate the risk-importance ranking based on the impact of the fire protection parameters on the plant risk metrics [23, 24].

In Fire I-PRA (Fig. 4), the Fire Simulation Module (FSM) ('b' in Fig. 4) includes models of physical failure mechanisms associated with fire-induced PRA scenarios. The Plant-Specific PRA Module consists of static Event Trees (FTs) and Fault Trees (FTs) in the existing plant PRA. The core of the FSM is the Fire Progression Model (#2 of Fig. 4) simulating spatiotemporal evolution of fire-induced conditions in the compartment. In Fire I-PRA, a CFD fire model, FDS [18], is used. The FDS code numerically solves the transient governing equations for a low-Mach number turbulent reacting flow, including continuity, species mass fraction, momentum, sensible enthalpy, along with the equation of state for an ideal gas. The inputs to the Fire Progression Model include: (i) information on the fire source such as the HRR curve and fire location provided by the Fire Initiation Model (#1 in Fig. 4), (ii) initial and boundary conditions, and (iii) material properties, such as electrical cables. The advanced fire crew model and its coupling with fire progression developed in Section 3 are plugged into modules 'b' and 'c' in Fig. 4. The FSM coupled with the fire crew model predicts physical Key Performance Measures (KPMs) for fire-induced equipment damage, e.g., maximum temperature ($T_{\max}$) and heat flux ($q''_{\max}$) of target cable trays.

The Uncertainty Analyzer (#4 in Fig. 4) performs uncertainty quantification for the FSM and the Manual Fire Suppression Module. By considering damage thresholds for the physical KPMs, the cable damage probabilities (e.g., 'CBD' in Fig. 4) are estimated. Probabilistic Validation (#5 in Fig. 4) characterizes and propagates epistemic uncertainty in I-PRA and constructs the uncertainty bounds for the cable damage probabilities [25]. The cable damage probabilities are then plugged into the Scenario-Based Damage Model (#6 in Fig. 4). The Post-Fire Damage Progression Model (#3 in Fig. 4) provides the conditional probabilities of the component-level failure, given the fire-induced cable damage. The outputs from #3 and #4 are combined by the scenario logic in Model #6 to develop component-level failure probabilities, e.g., Pr (c) in Fig. 4. The Minimal Cut Set probabilities are computed based on the fire-induced component probabilities obtained from #4 and #5 with consideration of dependent failures [25]. If there are any empirical data other than the simulation outputs, Bayesian integration with empirical data (#8 in Fig. 4) is conducted.

The Fire I-PRA methodological framework, along with an advanced fire-human coupling (an explicit coupling between a data-driven fire crew model and the FDS developed in Phase 1) was applied for one of the critical fire scenarios at an NPP (a small loss-of-coolant accident due to the stuck-open pressurizer valve caused by a switchgear room fire). The results showed that, compared to the current Fire PRA methodology, Fire I-PRA could improve the realism of the core damage frequency estimate by 50% [16]. This case study has highlighted the criticality of improving the realism in the fire-human coupling and motivated the authors' further advancements in the fire-human coupling in Phases 2 and 3 (Subsections 3.2 and 3.3) to develop the HRA-based and simulation-based fire crew models and their bidirectional interface with a fire model.

5. Concluding Remarks

The Socio-Technical Risk Analysis (SoTeRiA) Laboratory at the University of Illinois at Urbana-Champaign advances Probabilistic Risk Assessment (PRA), pioneering three key areas of scholarly developments: (1) spatiotemporal coupling of physical failure mechanisms with human/social performance and incorporation of this coupling into PRA using a static-dynamic Integrated PRA (I-PRA) methodology, (2) incorporation of big data analytics into PRA, and (3) integration of safety risk and financial risk for socio-technical systems. This paper reports on how the progress in the first key area has improved the realism of Fire PRA of Nuclear Power Plants (NPPs). Although the Fire PRA applications are the primary focus of this paper, the concepts and methodologies presented would also be applicable for the External Control Room (Ex-CR) HRA, in general, that involve other types of hazards.

The coupling between fire progression and fire crew performance is advanced in three phases. In the first phase, an explicit unidirectional coupling between the data-driven fire crew model and a fire progression model is developed by modifying the Heat Release Rate (HRR) curve using the timings of the fire crew activities. The coupling is integrated with the plant PRA using the Integrated PRA (I-PRA) methodology, and it is applied to a critical fire scenario of an NPP leading to a 50% reduction in the risk estimation. In the second phase, a Human Reliability Analysis (HRA)-based approach for a fire crew model is developed, and an explicit bidirectional coupling between the HRA model and the fire model is developed. In the third phase, a simulation-based human performance model is developed using Agent-Based Modeling (ABM) and coupled bidirectionally with a fire model in a Geographic Information System (GIS).

In practical applications, advanced physics-human couplings should not be developed for all Fire PRA scenarios or fire crew tasks. Instead, the level of detail and accuracy of the fire crew model should be increased gradually based on the risk importance of a specific scenario and the need for explicit fire-human coupling for each fire crew task. In the authors' view, in order to improve the realism of Fire PRA efficiently, the combination of HRA-based and simulation-based approaches should be used. When the fire crew tasks are performed in a fire compartment (and, thus, have a higher degree of fire-human interactions), the simulation-based method is recommended as it can simulate the fire-human interactions more realistically through the spatio-temporal fire-human coupling in the GIS environment. Depending on the nature of the fire scenarios and the fire crew activities, the ABM-CFAST-GIS coupling has a capability of being extended to more complex processes with different time and space scales, e.g., adding explicit modeling of the team interactions and decision-making processes. For the fire crew tasks that are not subjected to strong fire-human interactions (e.g., the tasks outside the fire room), the HRA-based approach is recommended as it can capture the plant- and scenario-specific contextual factors more realistically than the data-driven approach used in the current Fire PRA methodology while reducing the complexity of the human performance model compared to the simulation-based approach. A structured methodology for integrating the HRA-based and simulation-based approaches for fire crew modeling in Fire PRA is developed in the authors' research.

As another application of Key area (#1), i.e., spatiotemporal coupling of physical degradation and human performance, the authors have been advancing the coupling of stress corrosion cracking with maintenance performance. An explicit model of maintenance work processes is developed using an HRA-based approach and then coupled with the physical degradation using a renewal process model to estimate pipe failure rates for advanced nuclear reactors [26].

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