Developing a New Fire PRA Framework by Integrating Probabilistic Risk Assessment with a Fire Simulation Module

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Abstract: Recently, the fire protection programs at nuclear power plants have been transitioned to a risk-informed approach utilizing Fire Probabilistic Risk Assessment (Fire PRA). One of the main limitations of the current methodology is that it is not capable of adequately accounting for the dynamic behavior and effects of fire due to its reliance on the classical PRA methodology (i.e., Event Trees and Fault Trees). As a solution for this limitation, in this paper we propose an integrated framework for Fire PRA. This method falls midway between a classical and a fully dynamic PRA with respect to the utilization of simulation techniques. In the integrated framework, some of the fire-related Fault Trees are replaced with a *Fire Simulation Module (FSM)*, which is linked to a plant-specific PRA model. The FSM is composed of simulation-based physical models for fire initiation, progression, and post-fire failure. Moreover, FSM includes the uncertainty propagation in the physical models and input parameters. These features will reduce the unnecessary conservativeness in the current Fire PRA methodology by modeling the underlying physical phenomena and by considering the dynamic interactions among them.

Keywords: Nuclear Power Plants, Fire PRA, Integrated PRA Framework

1. BACKGROUND

After a fire event at the Browns Ferry nuclear power plant (NPP) in 1975 [1], fire protection began to be recognized as one of the important elements of nuclear safety. Conventionally, the fire protection program (FPP) at NPPs has been implemented by a deterministic approach based on Title 10 of the Code of Federal Regulations, Part 50, Section 48 (10 CFR 50.48) [2], and Appendix R [3]. In 2004, the U.S. NRC revised 10 CFR 50.48 to allow licensees to voluntarily shift to risk-informed fire protection under NFPA 805 [4]. As of 2012, 47 reactors in the U.S. (out of a total of 104 reactors operating in the country) plan to shift (or are in the process of shifting) to the risk-informed and performance-based (RI-PB) approach [5].

1.1. Deterministic vs. Risk-informed Fire Protection Program

The transition from a deterministic to a risk-informed approach in the fire protection program at NPPs should be regarded as part of the general effort by the U.S. NRC and the nuclear industry to expand the use of the probabilistic risk assessment (PRA) technique for the improvement of safety at NPPs. According to U.S. NRC PRA Policy Statements [6], the usage of PRA in the nuclear safety arena contributes to (i) decision-making that is enhanced by the use of PRA insights, (ii) more efficient use of resources, and (iii) reduction in unnecessary burdens on licensees. In order to benefit from these advantages, PRA should be used "to reduce unnecessary conservatism" and the PRA output "should be as realistic as possible" [6].

In the context of fire protection at NPPs, the benefits from PRA as compared to those of the deterministic approach are summarized as follows [5]. First, the nuclear operators can obtain a better understanding

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of plant risk by quantitatively identifying the risk-significant fire compartment and event sequences. It will allow nuclear operators to effectively allocate their limited resources to risk-significant factors, and allow them flexibilities in areas that have been assessed as insignificant with respect to plant risk. Second, the licensing conditions and requirements become less complicated. If a licensee transitions to risk-informed FPP under NFPA 805 [7], the licensee can obtain fire protection licensing amendments based on a single standard, NFPA 805. This is considerably simpler than the conventional deterministic FPP, where licensing conditions are subject to a number of guidance documents, communications, and regulatory issue summaries. Transition to a risk-informed FPP can eliminate a significant resource burden, both on the U.S. NRC and the nuclear industry, that is caused by complicated exemption and deviation approval processes in the fire protection program under the deterministic approach [4]. These will help the NRC staff and plant operators focus their available resources on risk-significant issues. Third, according to some licensees and experts, plant safety has actually been improved through the process of transition to fire PRA by the extensive fire analyses and modifications [5]. Due to these benefits, the risk-informed approach has the potential to lead to more effective fire protection at NPPs, outperforming the traditional deterministic approach.

1.2. Limitation in Current Fire PRA Methodology

The current methodology for Fire PRA, established by NUREG/CR-6850, was issued in 2005 [8,9]. NUREG/CR-6850 provides state-of-the-art methods, tools, and data for Fire PRA at operating NPPs. This document aims at consolidating the existing state-of-the-art methods and technical bases into one standard methodology. In addition, the new methods were developed in several areas such as a post-fire plant-safe shutdown response model, fire event data and fire frequency analysis, detection and suppression analysis, circuit analysis, Human Reliability Analysis (HRA), etc.

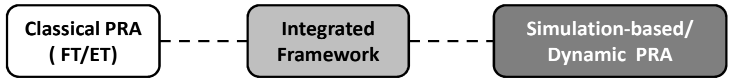
Despite these advancements, it has been recently recognized that the current Fire PRA methodology, established in NUREG/CR-6850, has some limitations. The reported limitations in the literature include (i) an unexpectedly high transition cost reported by pilot plants [5], (ii) lack of human resources familiar with fire modeling [5], and (iii) overly conservative assumptions and unrealistic output [5,10]. Among them, from the technical point of view, the limitation that is frequently pointed out is conservatism [5] [8,10]. The overly conservative assumptions are considered in two areas: First, the data necessary to develop the model of fire phenomena and damage to equipment are insufficient. As one example, NUREG/CR-6850 [8] itself states that spurious actuation likelihood caused by cable damage, which has been derived from expert elicitation, is considered to be generally conservative, while the extent of conservatism remains unidentified. The second cause of overly conservative output is the fact that fire damage and operator response are modeled in a static context [8]. According to NUREG/CR-6850 [8], although the impact of this assumption is judged to be conservative for most fire scenarios, the extent of conservatism has not been identified either qualitatively or quantitatively.

The overly conservative output can result in the misallocation of available resources to areas that have been evaluated as risk-significant by current Fire PRA, in spite of actually being insignificant with respect to actual risk [5]. Thus, in order to reduce the plant risk more effectively, it is necessary to improve the current methodology to reduce the unnecessary conservatism and to produce an “as realistic as possible” result. To achieve this, modeling based on physical simulation techniques should play a key role. A simulation-based model can contribute to overcoming the causes of unnecessary conservatism in the current methodology by modeling time-dependent fire phenomena and damage [8], and by compensating for the lack of data on failure probabilities of equipment and human reliability [11].

2. INTEGRATED FIRE PRA FRAMEWORK

Although a simulation-based/dynamic PRA is the ideal goal for nuclear power risk analysis, it is, on a short-term basis, impractical and can be quite costly. Currently, NPPs utilize classical PRAs and changing them to fully simulation-based PRAs would require significant time and resources. In this paper, we are proposing an *integrated* framework that, with respect to modeling techniques, stands between classical PRA and simulation-based/dynamic PRA (See Figure 1). In other words, the classical

Figure 1: Modeling state of the integrated framework with respect to PRA evolution.



PRA of the plant would be used, but the fire phenomena would be modeled in a simulation-based module (separate from PRA) and the module would then be linked to the classical PRA of the plants. The goal is not to translate the fire phenomena into a fault tree (FT) and event tree (ET) context, but instead to model them in a simulation-based environment up to the last point of events of interface with the plant-specific PRA. Similar *integrated* approaches have been developed, by several of the authors of the current paper, for the incorporation of the effects of organizational factors into PRA [12] and for the risk-informed resolution of Generic Safety Issue 191 (GSI-191) [13].

The major features of the proposed *integrated* Fire PRA approach (Figure 2) are:

(1) *Plant-specific PRA Module* composed of ET/FT used in the classical plant-specific PRA. This module will be explained in Section 2.1

(2) *Fire Simulation Module (FSM)* which includes the simulation and uncertainty quantification of realistic phenomenological models for fire initiation, dynamic progression of fire effects, and post-fire damage .The elements of FSM will be explained in Section 2.2 ,

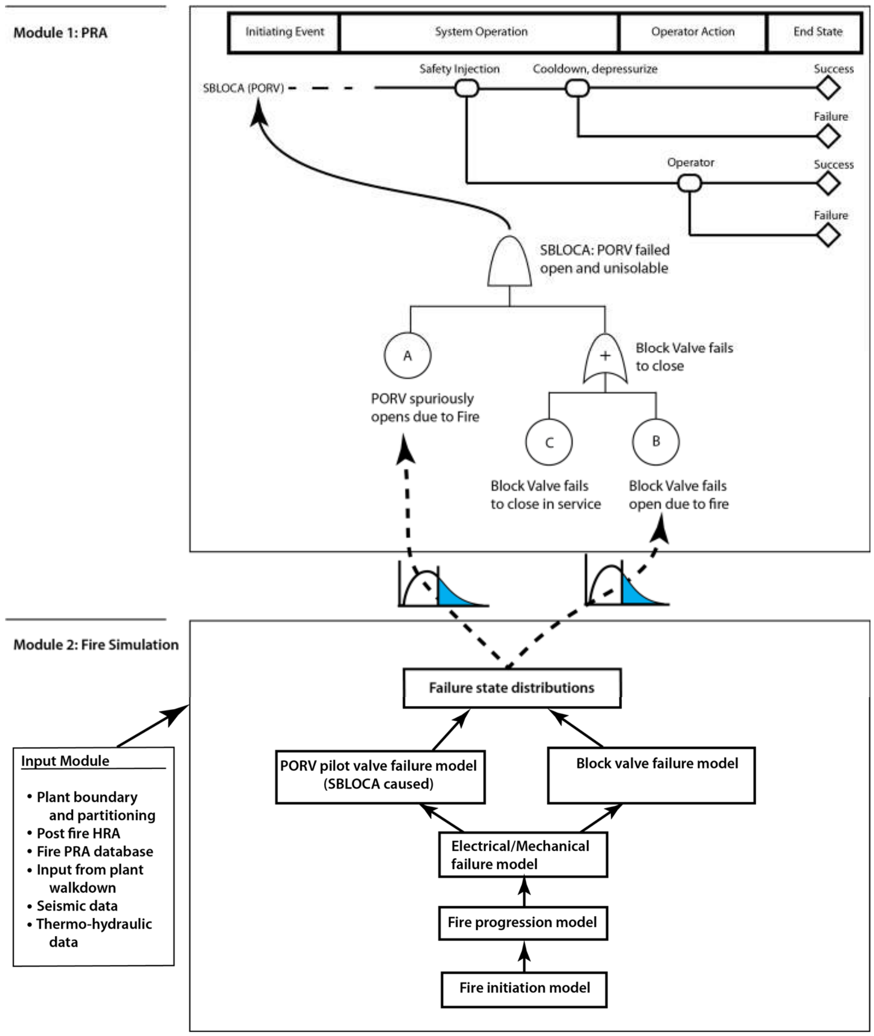
(3) *Input Module* (explained in Section 2.3), which provides the required input for the *Fire Simulation Module.*

The FSM replaces some part of FTs in the current PRA methodology and produces the conditional probabilities of basic events that are input to *Plana-Specific PRA Module*. Using this *integrated* approach would allow us to "simulate" the fire phenomena and would create the possibilities of (a) advancing quantification of dynamic interactions, (b) more adequate depiction of contextual factors (e.g., physical factors and human performances), and (c) advancing propagation of uncertainties involved in the physical phenomena. These three features would lead to more "realistic" modeling of fire that, ultimately, could reduce the unnecessary conservatisms. Another advantage of the *integrated* approach is that it is a step toward having a fully simulation-based PRA. When, and if, NPPs are ready to switch to simulation-based PRAs, the *FSM* developed in this work would be an appropriate engine for their PRAs.

This research project consists of two phases. In Phase I, we will develop a *FSM* by integrating the existing experimental, statistical, and physical models (related to fire initiation, progression, and post-fire failure modeling) that have been proposed as a result of research activity over the past three decades. In this process, we will use the simulation-based model everywhere possible. In addition to those models used in the current Fire PRA methodology [9], we will search for models having the potential for applicability as proposed in existing literature in both the nuclear and non-nuclear arenas. Then, the *FSM* will be connected to the *Plant-specific PRA Module*. The connection provides the conditional failure probability distribution of interface of basic events computed by *FSM* to the *Plant-specific PRA Module.* The target risk metric (i.e., core damage frequency) is calculated using the *Plant-specific PRA Module*.

After obtaining the primary results from Phase I, which would contribute to the development of a dynamic and realistic fire risk analysis, for Phase II of the project, we would advance some of the physical models in the FSM, especially in areas currently dominated by statistical and expert elicitation methods. This would, thereby, create an even more accurate quantification of risk.

Figure 2: An integrated Fire PRA framework for a hypothetical fire-induced fault tree resulting in a SBLOCA.



The primary contributions from Phase I of this project would be to:

(1) Change quantification techniques of the Fire risk analysis for NPPs from FT/ET to a simulation-based approach in a *FSM*: The plan is to extract the majority of fire-related fault trees from PRA and, instead, cover them in a simulation-based context. Our purpose is to integrate the existing time-dependent physical fire models into a simulation module so that their dynamic interactions can be more adequately covered.

(2) Propagate uncertainty in the *FSM*: The *FSM* integrates the physical phenomena and propagates uncertainty in physical models and input parameters from fire initiation to potential core damage precursors. Uncertainty propagation can be accomplished by sampling the input parameters assuming that the input parameters are random variables with epistemic distributions derived from historical data, experimental data, expert elicitation, physics, or a combination of these sources. These values would be propagated through the *FSM* to provide an estimator of a key performance measure, such as the probability of a subsystem failure, which is passed to the *Plant-specific PRA Module*.

(3) Link the *FSM* to the *Plant-specific PRA Module:* In Phase I, the purpose is to use the existing experimental and physical models and to mainly focus on integrating them into a simulation module and, ultimately, into the *integrated* framework. However, in Phase II of this research project, if necessary, some of the elements of the *integrated* framework, such as the physical models that apply to fire initiation and target damage, will be advanced.

Next sections explain the elements of the modules of Figure 2 and map them into the tasks of the current Fire PRA methodology in NUREG/CR-6850 [9]. Note that all elements of the *integrated* framework are not necessarily mapped into the current methodology. This is because the proposed framework is simulation-based and the fire-induced phenomena are stated in the classical PRA language using FT/ET. We will also summarize several simulation-based approaches from literature that are candidates for sub-modules of the *Fire Simulation Module*.

2.1. *Plant-specific PRA Module* (Module 1 in Figure 2)

1.A) <u>Identifying the dominant fire-induced PRA scenarios</u>:

First, we would need to determine on which fire-related scenarios we would develop the *FSM*. We will categorize all the possible fire-related scenarios into several groups based on the similarity in the failure modes of basic events and then develop the *FSM* for each group of scenarios. This step will be related to Task 1 (Plant Boundary & Partitioning) and Task 2 (Fire PRA Component Selection) defined in [9]. A hypothetical example would be a fire in an area that would cause the pressurizer Pilot-Operated Relief Valve (PORV) to spuriously open and would result in a Small Break Loss of Coolant Accident (SBLOCA) until the block valve could be closed (Figure 2).

1.B) <u>Identifying the key basic events of interface between PRA and the *FSM*</u>:

Another element would focus on finding the basic events of the PRA, which are the interfaces between the *Plant-specific PRA Module* and the *FSM.* For example, in this simplified fire-induced scenario (Figure 2), the basic events A and B are the interfaces. This step is similar to Task 4 (Qualitative Screening) as defined in NUREG/CR-6850 [9].

1.C) <u>Calculating total risk</u>:

The ultimate risk for the plant will be calculated by a *Plant-specific PRA Module* (Module 1) using the conditional probabilities calculated by the *FSM* for the basic events of interface. For instance, the core damage frequency (CDF) is mathematically expressed by

$$\text{CDF} = \sum_i f_i \left(\sum_j P_{j|i} \left(\sum_k P_{CD:k|i,j} \right) \right) \tag{1}$$

where f_i denotes the frequency of postulated fire i, $P_{j|i}$ denotes the conditional probability that the postulated fire causes damage to equipment j, and $P_{CD:k\,|\,i,j}$ denotes the conditional probability that the operator fails to recover the plant which results in core damage given the postulated fire i and fire-induced damage to the equipment j [9] [14]. In our *integrated* framework, f_i and $P_{j|i}$ are estimated in *FSM* using the mechanistic simulation-based models to the full extent, while $P_{CD:k\,|\,i,j}$ is provided in the *Input Module*, based on the post-fire HRA.

This step relates to Task 14 (Fire Risk Quantification), Task 15 (Uncertainty & Sensitivity Analysis), and Task 16 (Fire PRA Documentation) in NUREG/CR-6850 [9].

2.2. *Fire Simulation Module* (Module 2)

The main elements of the *FSM* (in Figure 2) include: (3.2.A) Fire initiation model, (3.2.B) Fire progression model, (3.2.C) Post-fire failure model, and (3.2.D) Failure state distributions. The purpose of this module is to integrate the models of the physical phenomena leading to basic events of interface with the *Plant-specific PRA Module*, and to propagate uncertainties in these physical models and input parameters in order to estimate the probability distribution of the basic events of interface (e.g., A and B in Figure 2).

We have reviewed the literature concerned with the models of fire physical phenomena that were published after the issuance of NUREG/CR-6850. Those models are categorized into three groups:

- Category I. Deterministic simulation of fire physical phenomena based on deterministic physical equations (e.g., Fire Dynamic Simulation [15] and CFAST [16]).
- Category II. Probabilistic model of fire physical phenomena (e.g., [17])
- Category III. Integration of deterministic simulation of fire physical phenomena with probabilistic model (e.g., coupling of CFAST with Monte Carlo simulation [18,19]).

The models grouped in Category III [18,19] are conceptually the most similar to the *FSM* being developed in this research. However, the *FSM* differs from Category III models in several aspects. The main differences are in the following:

a) They are not linked to a Plant-specific PRA model. Their target outputs include the cumulative distribution function of physical variables (e.g., maximum heat release rate, maximum temperature of cables [19]) and the failure probability of individual electrical cable caused by fire-induced environmental conditions [18], rather than the total risk (e.g., core damage frequency) or the fire-induced failure probability of safety-related systems.
b) Their scope is limited to one or two fire scenarios. Both references [18] and [19] compute the scenario of electrical cable fire inside the cable tunnels. They do not account for any other type of fire scenarios such as fuel tank fire and battery fire.
c) They only deal with intermediate phases of fire events (i.e., fire ignition, fire progression, and post-fire failure). For instance, both references [18] and [19] do not take into account the fire ignition process and its probability since they focus on the conditional probability or fire-induced environment given a certain fire ignition. In addition, their scope is limited to the cable-level analysis, and the post-fire failure (e.g., spurious operation of equipment) is not considered [18,19].

In the following, the conceptual design of each sub-module in *FSM* is summarized as well as the current result of the literature review on the models of fire physical phenomena that are candidates for sub-modules.

2.2.1. Fire Initiation model:

This step is related to Task 2 (Fire PRA Compartment Selection), Task 3 (Fire PRA Cable Selection), and Task 6 (Fire Ignition Frequencies) in NUREG/CR-6850 [9]. Industrial fires can involve transient or in-situ combustibles. They can be initiated either by human error or, more frequently, from an electrical short. Electrical system design normally incorporates a fire suppression system for the rapid termination of the fire progression by eliminating the energy source (high resistance current flow). Even if the energy source is sustained, there is normally very little combustible material available to sustain the burn. Of course, there are still some systems in power reactors that are designed with a substantial amount of combustible material. Examples are fuel tanks for diesel generators, oil-cooled transformers, hydrogen-cooled generators, water treatment systems with large quantities of acid and base chemicals that could be a high energy source if they were to come into contact with an electrical short. Each of these systems would be amenable to uncertainty quantification in an accident progression represented by linked engineering models of fire spread, suppression, and energy/combustible material sources.

Bayesian updating has been used to estimate the generic fire ignition frequencies for use in Fire PRA (e.g., [9] and [20]). Because the current highly data-driven methodology is simple and conservative (due to assumed prior distributions), the resultant fire frequency data can be too conservative for a realistic modeling of the frequency of fire initiation. As a specific example, consequential events with an assumed prior frequency of 1E-03 or 1E-02 would be significantly affected by the absence of experience in the lifetime of a plant. We anticipate advancing the initiating event modeling beyond its current statistical/experimental state (e.g., Section 17; Appendix A of [21]) by physically modeling the initiation and growth phases of initiating events. This allows physical insights into the assumptions currently made for fire initiation. Research into physical modeling of cabinet fires, effects on solid state equipment, and cable tray propagation modeling (advancing the state as compared to [21], Section 11), will bring the state of Fire PRA closer to a true best-estimate, risk-management-capable framework.

As far as the authors know, the recent efforts for obtaining more accurate fire ignition frequency in the area of nuclear engineering have been mainly directed toward improving the methodology of statistical estimates with some modifications (e.g., trend analysis and choice of prior distributions in [21], while incorporating newer fire event data and considering between-plant variability using the Hierarchical Bayes approach [20]).

2.2.2. Fire Progression model:

The fire progression model in the proposed *integrated* framework is related to Task 8 (Scoping Fire Modeling) and Task 11 (Detailed Fire Modeling) defined in NUREG/CR-6850 [9]. For a more risk-informed (RI)/performance-based (PB) method of fire protection in NPPs, the NRC has verified and validated five mechanistic fire simulation codes, cited in NUREG-1824 [22]: Fire Dynamics Tools (FDT) [23], Fire-Induced Vulnerability Evaluation Revision 1 (FIVE-Rev1) [24], Consolidated Model of Fire Growth and Smoke Transport (CFAST) [16], MAGIC [25], and Fire Dynamics Simulator (FDS) [15]. NUREG-1934 [26] provides guidance on the appropriate selection and application of the models in the RI/PB approach. These simulation codes would be mainly used in our *FSM* to predict the behavior of fire and fire-induced effects (e.g. thermal radiation, high temperature gas, smoke density) on equipment and electrical cables. Table 1 summarizes characteristics of the models that are delineated in NUREG-1934 [26] and the literature that investigated the application of these models. The type of fire scenario to be analyzed and characteristics of the models will determine the type of the fire model. For instance, the FDS code is capable of simulating the fire progression and fire-induced environmental conditions by accounting for the complex geometrical configuration of a fire compartment and complex vent conditions [26]. Recently, the application of the FDS code [15] to a few fire scenarios has been reported by several authors [27-29]. Y. M. Ferng et al. [27] modeled the burning behavior of electrical control cables using the FDS code [15] and compared the outputs of the model with experimental results. They reported that the predicted transient profile of the heat release rate (HRR) was in agreement with experimental data; the maximum value of HRR agreed within 5 %, and the time of maximum HRR agreed within 10 %, while the qualitative shape of the profile (i.e., after a peak, HRR decreased and reached a low steady value) was well reproduced. In addition, S. Qiang et al. [28] simulated a fire event in the fuel tank room for an emergency diesel generator using the FDS code. They were able to simulate the qualitative interaction between the fire source and fire suppression by sprinklers such as the decay of the HRR time-profile and the decrease of 3-D temperature distribution around the fire source after the sprinkler was actuated. Although their work should be validated quantitatively, this example suggests that fire simulation models can be applied in current studies to analyze the effectiveness of fire detection and suppression. These applications of mechanistic fire simulation codes are grouped in Category I as defined at the beginning of this section.

Table 1: Main characteristics of five fire models verified and validated in NUREG-1824 [22].

Model	Category	Advantages	Limitations	Reference
FDT	Algebraic model	Low computational cost; Suitable for a comprehensive sensitivity study;	Not fully considering physical mechanism; Only applicable to steady-state fires or simply defined transient fires; Verified and validated for limited application range	
FIVE-Rev1				
CFAST	Zone model	Low computational cost; Suitable for a comprehensive sensitivity study; Verified and validated for wide range of use;	Larger errors with increasing deviation from a rectangular enclosure; Difficulty in treating horizontal flow paths;	[18] [30] [31]
MAGIC				[32]
FDS	Computational Fluid Dynamics Model	Applicable to complex configuration and vent conditions; Verified and validated for wide range of use;	Large effort to produce input files and post-processing of outputs; Long computational time;	[27] [28] [29] [33]

Several authors have studied the simulation-based modeling of electrical cable failure induced by fire using the THIEF model [34] (Category I), finite-element method [35] (Category I), and the combination of Monte Carlo simulation and CFAST [18] or FDS [19] (Category II). These methods enable us to obtain the time-profile of an electrical cable failure probability during a fire event with the consideration of a time delay caused by the heat transfer process from surrounding hot gas or cable surface to insulator inside the cable. The first two physical models (THIEF model and finite-element method), categorized in Category I, can be used in our *FSM* to simulate the time-dependent temperature distribution inside the electrical cable and to develop their conditional degradation probability. As input data, these models use the outputs from mechanistic fire progression codes such as surrounding environmental conditions (e.g., temperature, heat radiation from fire source, gas composition). Besides, the combination of the sampling method and the fire simulation code (e.g., Monte Carlo sampling and CFAST code [18] or FDS [19], categorized in Category III, is capable of simulating both the fire progression and its effect on targets within one computational framework. The clear advantage of this method is that the time-dependent probability distribution of target damage induced by fire is obtained by random sampling of input variables to the fire simulation code. In other words, this combinational method allows us to quantify and propagate the uncertainties that arise from input parameters directly through failure probability.

However, as mentioned in Table 1, the use of a detailed mechanistic fire model, especially the CFD model, is very resource-intensive in input generation, simulation, and output analysis, even with the current availability of multicore and cluster computing. Typically, the two-zone model (e.g., CFAST and MAGIC) is able to produce the solution in seconds to minutes, while the CFD model produces the corresponding answer in days to weeks [26]. Therefore, algebraic and zone models would be used in our *FSM* where they are adequate in terms of their applicability and accuracy. Also, for the fire scenarios where the algebraic or zone models are not applicable, the other alternative approach for computational cost reduction is to develop a response surface model [36] constructed from simulation output and use it as a part of the input data to *FSM*.

In Phase II of our research project, in order to have a realistic model in the *FSM*, additional "experimental tests", similar to experiments performed in [37-41], may be required to provide the supporting data for the fire simulation codes (e.g., Fire Dynamics Simulator; [15]) and the required analysis (e.g., electric cable degradation analysis). For instance, regarding the fire-induced electric cable damage, although several test programs [42,43] have been reported, we may still need to perform some additional experiments in order to obtain the degradation data under the plant-specific conditions (thermal exposure, cable type and cable arrangement).

2.2.3. Post-fire failure model:

Figure 2 shows a simplified example of the heat from a fire (for example, the pressurizer heater wiring) resulting in a malfunction of the PORV so that it fails and becomes stuck open. At this point, the event is a Small Break Loss of Coolant Accident (SBLOCA). Located near the PORV are the motor-operated block valves that are normally used to terminate this event by closing off the relief path for the respective PORV (usually, two valves are supplied). The same fire could damage either the block valve motor or its wiring to the extent that it would be inoperable. In Figure 2, post-fire failure models correspond to the "Electrical/Mechanical failure model", the "Block valve failure model", and the "PORV failure model". These are related to Task 9 (Detailed Circuit Failure Analysis) of NUREG/CR-6850 [9].

In the current Fire PRA methodology, the likelihood of fire-induced damage to an electric circuit is estimated based on a formulation developed through an expert elicitation process [9,44]. This methodology attempts to account for physical configurations based on limited experimental evidence [37-41], but is too general for a realistic Fire PRA since it cannot take into account plant-specific factors such as the specific shape and layout of electric cables. The inherent uncertainties in knowledge about specific cable placement, condition, configuration, etc. need to be treated in a more detailed manner than is currently possible.

There are several areas where the advancement in mechanistic modeling will benefit by predicting more accurate estimates of the likelihood of post-fire failure. One example of these areas is the calculation of spurious actuation probabilities. In the current methodology [9,45], these probabilities are calculated using either (i) the failure mode probability estimate table derived from expert elicitation [44], or (ii) a reverse-engineered formula from the fire test data [46], with a deterministic assumption (i.e., in cases where the cables of concern are dependent, the likelihood of spurious actuation should be determined by the first cable failure). As pointed out in NUREG/CR-6850 [8], additional consideration of the circuit failure mode likelihood values is needed. Mechanistic modeling will enable us to capture the elements which have not been taken into account in the current methodology, such as the intermediate modes of cable faulting between spurious actuation and fuse blow [44,45] and the effect of multiple cable failures on the spurious actuation [8,45].

2.2.4. Failure state distributions:

This step is related to Task 10 (Circuit Failure Mode & Likelihood Analysis) and Task 15 (Uncertainty & Sensitivity Analysis) in NUREG/CR-6850 [9]. Advanced uncertainty quantification and propagation techniques would be added to the physical models (in the *FSM*) in order to estimate the "probabilities" of basic events of interfaces and then, these probabilities would be incorporated into the Plant-specific PRA. Similar uncertainty propagation has been undertaken in the risk-informed resolution of GSI-191 [13]. Also, recent advances in uncertainty propagation techniques for physical modeling in the computational sciences can provide methodologies in order to circumvent the "curse of dimensionality" in uncertainty quantification. In the models used inside our *FSM*, there are uncertainties associated with the input variables (e.g., mass stoichiometric ratio of air to fuel, heat of combustion) and those associated with the sub-models and correlations (e.g., a sub-model to simulate the flame height) used in those simulation codes [17]. Research in the tailoring of existing uncertainty analysis techniques for application to the proposed *integrated* approach for fire risk analysis would be needed.

2.3. *Input Module*

The elements of the *FSM* would need certain input data. As Figure 2 shows, the *Input Module* includes:

- Plant boundary and partitioning (related to Task 1; Plant Boundary & Partitioning in NUREG/CR-6850 [9]).
- Post-fire HRA (related to Task 12; Post-Fire Screening in NUREG/CR-6850 [9]).
- Fire PRA database containing (i) plant partitioning and fire compartment designation, (ii) plant cable and raceway data (e.g., type and configuration of electrical cables and their relationship with safety equipment), and (iii) fire PRA equipment. It also contains the input parameters to mechanistic models (e.g., physical and chemical properties of electrical cable).
- Input from plant walk downs (e.g., ventilation features, possibly connected compartments).
- Seismic data (related to Task 13; Seismic-Fire Interaction in NUREG/CR-6850 [9])

Plant boundary and partitioning would be inputs to the "fire initiation model". Post-fire HRA would provide input to both fire initiation and fire progression models. HRA data will be also needed for the *Plant-Specific PRA Module*. Having a simulation-based fire module would create the possibility of advancing post-fire HRAs (i.e., using simulation-based HRA models). The Fire PRA database and input from plant walk downs would also be required for fire initiation and progression models. The data from a seismic model would be required to consider the potential seismic-fire interaction in both initiation and progression models.

In addition, as mentioned in the previous section, the generalized models developed based on the output from simulation-based models would be provided in the *Input Module*. The concept is that, instead of directly integrating complex simulation-based models into our *FSM*, we would develop a generalized model such as response surface model or correlation model (e.g., [36]) and provide those generalized models as input data.

3. CONCLUSION

The risk-informed fire protection program, when compared to the traditional deterministic approach, has a potential for more effective fire protection at NPPs. One of the widely recognized drawbacks of current Fire PRA methodology is the limitation in accounting for dynamic aspects of fire phenomena since it uses the classical PRA methodology based on ET/FT. As a solution to this limitation, we propose the integrated framework Fire PRA to model the dynamic phenomena of fire events without moving to a totally simulation-based or dynamic PRA.

In the integrated framework (Figure 2), some of fire-related FTs are replaced with a *FSM* separated from the plant-specific PRA model (i.e., ETs and FTs are extracted from the current PRA model). This FSM contains simulation-based realistic physical models for fire initiation, dynamic progression of fire effects, and post-fire failure. In addition, the uncertainties from the physical model and input parameters would be propagated through the module by sampling of the inputs. The output of the *FSM*, namely the distributions of conditional failure probability for interface basic events, will be imported to the *Plant-Specific PRA Module* and be used to calculate the risk metrics (i.e., core damage frequency).

This research project consists of two phases. In Phase I, we focus on integrating the *existing* physical models of fire events into the *FSM*. The main contributions from Phase I include: (i) change of quantification methods of fire-related risk from ET/FT to simulation-based techniques, (ii) propagation of uncertainties by randomly sampling the input parameters, and (iii) linkage of the *Fire Simulation Module* to the *Plant-specific PRA Module*. In Phase 2, after obtaining the results from Phase I, we would refine some of the physical models to create a more realistic quantification of fire risk.

In future work, for Phase I of the research project, we will continue building the *FSM* by integrating the existing models of fire physical phenomena. The first step in building the module is to identify (and categorize) the dominant fire-induced scenarios and determine the corresponding interface basic events. Then, the *FSM* will be developed for each category of interface basic event. In addition to the models used in the current methodology (NUREG/CR-6850), the models proposed in recent literature, in both the nuclear and non-nuclear arenas, will be considered as candidates for the elements of this module. We plan to complete the construction of the *Fire Simulation Module* and obtain primary outputs by the end of the current year. Then, we will proceed to uncertainty propagation, and verification and validation of the *Fire Simulation Module*, followed by connecting it to the Plant-specific PRA Module and importance measure analysis.

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