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# A PHENOMENA IDENTIFICATION AND RANKING TABLE (PIRT) EXERCISE FOR NUCLEAR POWER PLANT FIRE MODEL APPLICATIONS

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## ABSTRACT

This paper summarizes the results of a Phenomena Identification and Ranking Table (PIRT) exercise performed for nuclear power plant (NPP) fire modeling applications conducted on behalf of the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES). A PIRT exercise is a facilitated expert elicitation process. In this case, the expert panel was comprised of seven international fire science experts and was facilitated by Sandia National Laboratories (SNL). The objective of a PIRT exercise is to identify key phenomena associated with the intended application and to then rank the current state of knowledge relative to each identified phenomenon. The intent is to provide input into the process of identifying and prioritizing future research efforts. In practice, the panel considers a series of specific fire scenarios based on scenarios typically considered in NPP applications. Each scenario includes a defined figure of merit; that is, a specific goal to be achieved in analyzing the scenario through the application of fire modeling tools. The panel identifies any and all phenomena relevant to a fire modeling-based analysis for the figure of merit. Each phenomenon is ranked relative to its importance to the fire model outcome and then further ranked against the existing state of knowledge and adequacy of existing modeling tools to predict that phenomenon. The PIRT panel covered several fire scenarios and identified a number of areas potentially in need of further fire modeling improvements. The paper summarizes the results of the ranking exercise.

*Key Words*: fire modeling, fire PRA, fire PSA

## 1 INTRODUCTION:

This paper summarizes the results of a Phenomena Identification and Ranking Table (PIRT) exercise performed for nuclear power plant (NPP) fire modeling applications. This PIRT exercise was conducted on behalf of the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and facilitated by staff of Sandia National Laboratories (SNL). Full documentation of the PIRT process and results will be available in a NUREG/CR report currently in the publication process.

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## 1.1 Process Overview and Objectives

A PIRT exercise is a structured and facilitated expert elicitation process. In this case, the expert panel was comprised of seven international fire science experts (see acknowledgements section below). The objective of a PIRT exercise is to identify phenomena associated with the intended application and to then rank the current state of knowledge relative to each identified phenomenon. In this particular PIRT exercise the intended application was the use of fire modeling tools in support of NPP regulatory and enforcement analyses, general fire risk analysis, and licensee applications such as exemption requests.

The panel was presented with a series of specific fire scenarios, each based on the types of scenarios typically considered in NPP applications. For each scenario a specific figure of merit was also defined; that is, a specific goal to be achieved in analyzing the scenario through the application of fire modeling tools.

Given each scenario, the panel identifies all those related phenomena that are of potential interest to an assessment of the scenario via fire modeling tools against the figure of merit. The phenomena are then ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge with respect to the ability of existing modeling tools to predict that phenomena, the underlying base of data associated with the phenomena, and the potential for developing new data to support improvements to the existing modeling tools. The phenomena identification and ranking process is conducted in the specific context of the fire scenarios and corresponding figure of merit. Finally, in this particular PIRT exercise, the panelists were also asked to assess the feasibility of performing new tests in order to first develop and then validate fire models capable of addressing important phenomena in cases where the existing state of knowledge was ranked as anything other than high.

In order to ensure consistency among the panelists, specific definitions for the ranking terminology were provided. These definitions are provided in Tables I-IV. Table I presents the ranking definitions used to assess phenomena importance. Tables II and III provide the terms used to define the adequacy of the current state of knowledge relative to both the existing modeling tools and data for model application and validation. Table IV defines the terms used to assess the feasibility of developing data for the development and validation of improved models.

**Table I: Phenomena importance ranking definitions.**

| **Descriptor:** | **Definition:** |
|---|---|
| High (H) | First order importance to figure of merit of interest. |
| Medium (M) | Secondary importance to figure of merit of interest. |
| Low (L) | Negligible importance to figure of merit of interest. Not necessary to model this parameter for this application. |
| Uncertain (U) | Potentially important. Importance should be explored through sensitivity study and/or discovery experiments and the PIRT revised accordingly. |

**Table II: Model adequacy ranking definitions.**

| Descriptor | Definition |
|---|---|
| High (H) | At least one mature physics-based or correlation-based model is available that is believed to adequately represent the phenomenon over the full parameter space of the applications. |
| Medium (M) | Significant discovery activities have been competed. At least one candidate model form or correlation form has emerged that is believed to nominally capture the phenomenon over some portion of the application parameter space. |
| Low (L) | No significant discovery activities have occurred and model form is still unknown or speculative. |
| Uncertain (U) | The panel is unaware of the existing state of fire modeling tools with respect to this phenomenon. |

**Table III: Data adequacy descriptors for existing model input and validation data.**

| Descriptor | Definition |
|---|---|
| High (H) | A high resolution database (e.g., validation grade data set) exists, or a highly reliable assessment can be made based on existing knowledge. Data needed are readily available. |
| Medium (M) | Existing database is of moderate resolution, or not recently updated. Data are available but are not ideal due to age or questions of fidelity. Moderately reliable assessments of models can be made based on existing knowledge. |
| Low (L) | No existing database or low-resolution database in existence. Assessments cannot be made with even moderate reliability based on existing knowledge. |

**Table IV: Data adequacy descriptors for the potential to develop new data to support model development and validation.**

| Descriptor | Definition |
|---|---|
| High (H) | Data needed are readily obtainable based on existing experimental capabilities. |
| Medium (M) | Data would be obtainable but would require moderate, readily attainable extensions to existing capabilities. |
| Low (L) | Data are not readily obtainable and/or would require significant development of new capabilities. |

## 1.2 The Fire Scenarios Considered

The PIRT panel covered four distinct primary fire scenarios. Two of the four primary scenarios had three sub-scenarios each. The sub-scenarios represented, in effect, "variations on a theme." The sub-scenarios shared most aspects of the common primary fire scenario, but introduced variations in one of two aspects; (1) the sub-scenarios introduced variations aspects affecting the nature of the fire or physical configuration, (e.g., alternate types of fire sources such as a liquid pool fire versus a high-pressure spray fire), or (2) the variations involved changes to the figure of merit. The scenarios considered by the panel were:

- Scenario 1 – Fire source: a main control room cabinet fire. Figure of merit: predict if and when fire conditions would force operators to abandon the main control room.
- Scenario 2 – General: switchgear room fires leading to the failure of important safe shutdown cables.
    - Scenario 2a - Fire source: a general thermal fire in a switchgear panel. Figure of merit: predict if and when redundant safe shutdown cables in a crossing cable tray directly above the far end of a bank of cabinets that includes the burning cabinet would be damaged by the fire.
    - Scenario 2b - Fire source: Same as 2a. Figure of merit: predict if and when cables in a more remote location near the rooms upper ceiling would be damaged by the fire.
    - Scenario 2c - Fire source: high energy arc fault fire in a switchgear cabinet. Figure of merit: same as 2a.
- Scenario 3 – General: a large turbine building lube oil leak and fire.
    - Scenario 3a – Fire source: a large (53000 liters or 14000 gallons) but confined lube oil spill and pool fire. Figure of merit: predict if and when heat and/or smoke might spread through an unsealed hole between the turbine building and the adjacent main control room sufficient to cause damage to control components in the control room.
    - Scenario 3b – Fire source: a high pressure leak and spray fire from the lube oil high pressure piping system. Figure of merit: same as 3a.
    - Scenario 3c – Fire source: same as 2b. Figure of merit: predict if and when fire effects might lead to collapse of exposed structural steel supporting the turbine building.
- Scenario 4 – Fire source: a self-ignited cable fire in the containment annulus region. Figure of merit: predict if and when fire effects would cause the failure of redundant cables in an adjacent cable tray.

### 1.3 Approach to the Analysis of Panel Input

As noted above, the objective of the PIRT exercise is to identify and prioritize potential research needs. Nominally, those phenomena that the panel input would identify as potential higher priority items would be those ranked as important to achieving a fire modeling figure of merit (or modeling goal) and at the same time having a poor state of knowledge. Those with a lower priority would be phenomena ranked as unimportant and/or phenomena where the current state of knowledge was already considered high. The analysis of the panel input for the individual scenarios has been analyzed from this perspective.

The analysis and reporting process focused primarily on what are referred to as the “Level 1” phenomena were identified. The Level 1 phenomena are those that were ranked with high importance and low state of knowledge. These would nominally represent potential research priorities from the panel’s perspective.

# 2 SUMMARY OF PANEL FINDINGS

The Level 1 phenomena identified by the panel span various aspects of fire modeling including fire detection, fire suppression, characterization of fire sources, impact of the fire on room environments, response of critical targets, and human performance issues such as manual fire fighting and human detection of fires. The forthcoming report on this project will include documentation of the full panel input for each of the scenarios and sub-scenarios. The input is presented in the form of tables that list all of the phenomena associated with a given scenario, provide all of the panel ranking and state of knowledge assessment results, and provide specific notes and commentary to expand upon the individual rankings. These tables are quite lengthy, and are presented in the full report via four separate appendices.

As with the main report, this paper will focus on the discussion of the Level 1 phenomena as identified by the panel. The full report (pending) discusses the Level 1 phenomena organized by both scenario and topical area. The discussion organized by scenario highlights how phenomena identification and ranking varied based on the nature of the fire scenario as well as the figure of merit. For the purposes of this summary, we will only discuss the phenomena organized by topical area.

## 2.1 Performance of Fixed Fire Detection Systems

Fire detection was debated at some length by the panel for all of the fire scenarios considered. In most scenarios, the panel ranked fire detection as a highly important phenomenon because successful fire detection triggered all of the subsequent behaviors and responses to the fire event (e.g., operator actions and the manual fire brigade). In effect, the act of fire detection defined the subsequent fire timeline. The importance of fire detection was not a particular point of debate or disagreement. The main issue here was the detector itself. The models predict the transport of smoke towards the detector, but the area where the discussion centered around was how the local smoke concentrations could be linked to the detector performance.

However, the panel was sharply divided relative to the state of knowledge in this area. Some panelists felt that the state of knowledge was adequate given that many correlations for predicting the response of fire detectors have been developed and applied. Specific examples were cited as existing in the SFPE and NFPA handbooks [9, 10]. Other panelists felt that the manner in which such correlations worked did not reflect the actual behavior of smoke detectors and could not be considered reliable for a range of fire conditions (e.g. incipient detection systems or incipient fires) including conditions encompassed in a number of the specified fire scenarios (notable exceptions being those fires that began, in effect, fully developed such as the high energy arc fault of Scenario 2c or the oil fires of Scenario 3).

All of the panelists agreed that for a substantial fire occurring under conditions with a simple geometry (e.g., a flat ceiling with minimal obstructions) the existing tools were quite adequate. However, opinions differed relative to the adequacy of such tools given more complex fire conditions. Certain panelists felt that the existing models were not appropriate or adequate for a range of fire conditions and that the state of knowledge was at best medium and arguably low. This was noted to include conditions as specified in the PIRT scenarios 1, 3, and 4, all of which involved complex geometries and obstructions to the normal fire plume development behaviors upon which the common correlations depend.

A specific example cited was the performance of incipient detection systems1 although none of the PIRT scenarios explicitly this system. The panel felt that existing models were clearly unable to deal with a prediction of how an incipient detection system would respond in any of the PIRT fire scenarios. They also acknowledged that such a capability would require a fundamental shift in the way fires are modeled because most fire models begin with a fire that has reached the open flaming stage of combustion.

### 2.2 Performance of Fixed Fire Suppression Systems

Various aspects of fire suppression were identified as relevant phenomena for those fire scenarios where fixed suppression was specified. The rankings of these phenomena tended to be dominated by the panelists' opinions as to effectiveness of the suppression system against the postulated fire. For example, for the high pressure oil spray fire of Scenario 3b, the panel concluded that installed fire sprinklers would be ineffective, and therefore, ranked the importance of phenomena related to sprinkler activation and effectiveness as low. In contrast, when the sprinkler system was thought to be potentially effective, the importance of related phenomena generally ranked as high. Specific aspects of sprinkler performance that were identified with high importance and low state of knowledge were:

- The impact of obstructions on the effectiveness of a fire suppression system (e.g., disruption of the spray patterns and blockage of the fire).
- The effect of obstruction on the response of individual sprinkler heads.
- The ability of a sprinkler system with high rates of water flow to suppress a very large oil pool fire.

All of these factors were considered readily amenable to further experimental research. However, the panel generally felt that the development of fire models that would directly predict such behaviors was highly challenging at best. In particular, one panelist expressed, and others agreed, that the current state of the art relative to the modeling of sprinkler droplet patterns and the interactions of water droplets with a fire was relatively primitive (i.e., a medium model adequacy) and that to extend such models to more complex conditions (e.g., with obstructions) would be a daunting challenge.

### 2.3 Fire Behaviors in the Presence of Obstructions

One theme that has already been touched on in Sections 2.1 and 2.2 was the role of obstructions and their impact on fundamental fire behaviors upon which other subsidiary phenomena depend (e.g., the response of fire detectors and sprinklers). There was considerable discussion among the panel about the obstructions that were seen in the various sample photographs provided as a part of the various fire scenario descriptions. These photographs were intended to illustrate the conditions encountered in a NPP. Certain fire scenario specification included features that held the potential to disrupt the normal development of, for example, a

[1] An incipient detection system is a system designed to detect the precursor products released during the earliest, pre-flaming stages of a fire. Such systems are often based on active air sampling systems. Such systems are a relatively new technological development, but have, over the past decade or so, been installed in some U.S. NPPs.

buoyant fire plume. The phenomena associated with such obstructions were in a number of cases ranked as either of high importance or as unknowns.

Two of the phenomena identified related to the role of the open-grate ceiling specified as a part of Scenario 1 (the MCR fire). This obstruction was made of plastic materials and could have an effect on the plume formation as well as adding combustible material to the fire scenario. However, the identified phenomena were somewhat mirrored by phenomena identified for Scenario 3 (the turbine building oil fires) which was specified as occurring below the operating deck of the turbine building. These obstructions were the open grate steel flooring. Panelists typically questioned how such features would impact fire development and the performance of fire detection and fixed suppression systems.

In the case of Scenario 1 (the MCR fire), one additional identified phenomenon was "the open-grate ceiling's influence on fire phenomena." The further clarification offered with respect to this specific scenario was that the panelists' were concerned with how the open-grate ceiling might impact such fundamental behaviors as plume development (and the implied impact on detector response) and smoke spread (e.g., below the open-grate). If the grate represented a significant barrier to the normal plume flow then a premature development of a smoke layer below the open-grate false ceiling might lead to premature development of adverse environmental conditions and early abandonment. The panelists were uncertain whether this was likely.

## 2.4 Characterizing the Fire Source

A universal theme for all of the fire scenarios was that characterizing the fire source was a critical aspect of the fire modeling problem regardless of what the specific figure of merit was. In particular, characterizing the total fire heat release rate was uniformly ranked as highly important. For some fire sources, the available models were considered marginally adequate (medium for model adequacy) but for others they ranked model adequacy as low. In particular, phenomena ranked as low for model adequacy were as follows:

- Fire spread along cable trays.
- Total HRR for a cable tray fire.
- HRR for the oil spray fire unless the spray pattern and droplet size could be defined.
- HRR for the cabinet fires including the ability to treat the following phenomena:
  - The effects of through-ventilation on fire development and total HRR,
  - Flame extension from the cabinet,
  - Fire spread from a cabinet to overhead cable trays,
  - Fire spread from an overhead cable fire down to an adjacent panel, and
  - The mechanism that initiates the transition from incipient combustion to open flaming.
- The characteristics of the initial fault behavior for the high energy arc fault scenario.
- Characterization of the enduring fire for the arc fault fire scenario.

Another specific area associated with characterizing fire sources that was repeatedly identified as Level 1 phenomena was predicting the generation rates for products of combustion. In particular, particulate, CO, and acid gasses were all cited as important with a low state of knowledge for one or more scenarios. In general the panel expressed the opinion that while basic modeling correlations have been developed and proven for other materials, the knowledge base for cables and electronics was lacking. The general consensus was that the existing models might apply to electrical equipment fires, but would need to be validated and the underlying input with validation data developed.

## 2.5 The Impact of the Fire on the Room Environment

Almost all of the scenarios included the identification of phenomena associated with the development of the general enclosure fire environment. Many aspects of this portion of the fire modeling problem were ranked as being adequately treated by existing fire models (e.g., smoke transport, heat transport, and heat transfer to enclosure surfaces). Further, the panel felt that heat transfer to structural steel was now a well-understood phenomenon with a substantial base of input and validation data available.

However, certain specific aspects of the fire environment problem were ranked among the Level 1 phenomena. This included “window breakage creating new openings” for each of the three turbine building scenarios. The panel was confident that given the nature of the specified fire sources, the windows specified in the scenario as existing near the top of the turbine building walls would, in fact, break. The question that the panel felt was critical but poorly understood was the timing of window breakage relative to the opening of the roof-top smoke vents that were also specified.

Another phenomena specific to Scenario 3a and 3b was smoke transport through the hole from the turbine building to the MCR. The panel felt that dealing with a specified hole (or crack) would be relatively straight-forward, but expressed that dealing with other poorly specified flow paths (e.g., cable and piping penetrations) would be much more difficult.

## 2.6 The Response of Damage Targets

Many of the scenarios included damage targets such as cables or MCR control components. As would be expected, the panel universally ranked damage to the target components with high importance for scenarios involving targets as the figure of merit. In general, the panel ranked the availability of input and validation data as, at best, medium adequacy. Specific factors with a low ranking included the impact of smoke on control components and polymeric breakdown of electrical cables due to heating. In general, the panel felt that models of target heating were at least of medium adequacy. However, the panel did note that given their importance to NPP applications, additional validation of the models would be appropriate.

## 2.7 Human Cognition and Behavior Phenomena

One group of Level 1 phenomena that were repeatedly identified for various fire scenarios were related to human behaviors such as detection of the fire by humans, the cognition processes associated with recognition and notification processes (i.e., realizing that a fire is ongoing and alerting the fire brigade), decision making once a fire has been recognized, and manual fire suppression.

It should be noted that in this particular area, the panel delved into aspects of the fire scenarios that would generally fall outside the scope of the traditional fire modeling tools as applied in NPP applications. That is, fire modeling tools for NPP applications have not traditionally delved into the human cognitive processes or behaviors, but rather, have focused on the mechanistic aspect of the fire (fire growth and spread, response of fixed detection and suppression systems, impact on the environment, target response, etc.). The human cognitive process has traditionally been dealt with via HRA. In the areas of human detection and manual fire suppression, statistical models are commonly applied based on past fire events and experience. The panel did discuss human elements of the scenario at some length, and the presentation and discussion of those results is appropriate. However, given that these aspects of a fire scenario do fall outside the bounds of traditional fire modeling tools, it is not surprising that model adequacy was commonly ranked as low for these phenomena.

One commonly identified human behavior related phenomenon was “the process of humans sensing the fire (i.e., human detection of the fire).” This was only ranked as highly important in the case of Scenario 1, the main control room fire, and then by only half the panel. For the other scenarios human detection was considered of lower importance because (1) the spaces in which the fire scenarios were defined were not continuously manned areas, and (2) most scenarios were specified as including installed fixed detection systems.

Another human behavior related phenomenon commonly identified in one form or another was related to manual fire suppression activities. A typical statement of the phenomenon was “the effectiveness, timing and level of control of the manual fire suppression.” Other closely related phenomena definitions included “actions (detection, notification, and suppression) by the non emergency responders” and “predicting fire suppression (manual fire brigade)”.

For most scenarios the process of manual fire suppression in some form was ranked as highly important with a low to medium state of knowledge. As a basis for comparison, the panel asked how such analyses were handled in a typical NPP application. The meeting facilitator described for the panel the approach documented in the RES/EPRI consensus fire PRA methodology [5] which was also cited as typical of the fire protection SDP and common to various risk analysis methods. This particular method is a statistical approach based on past fire experience that estimates the probability of non-suppression as a function of time. Various “suppression curves” have been generated to reflect a range of fire ignition sources (e.g., electrical cabinets versus welding fires). The panel found this approach to be of questionable merit and ranked its adequacy as low-to-medium depending on the specific fire scenario of interest and the overall impression as to how important manual suppression would be to the scenario. However, the panel also ranked this as a difficult issue to address via fire modeling improvements (low feasibility of developing new input and validation data).

One difference that arose with respect to the state of knowledge rankings was that specific to Scenario 2 (the switchgear room fire scenario) and its sub-scenarios. The feasibility of obtaining new input and validation data for these cases were ranked as uncertain. The panelists felt that this was a human reliability issue which is outside the expertise of the panel. In contrast, for Scenario 1 (the MCR fire scenario) the feasibility of obtaining new input and validation data were both ranked as low. The performance of humans in fire suppression was generally cited by the panel as an important, but especially difficult to predict.

Other aspects of human performance that were debated but ultimately not ranked were those related to human decision making processes.  For example, there was significant discussion as to how operators would respond to a fire alarm. For example, would the fire brigade be called out immediately or would attempts be made to verify that a fire actually existed first? The panel was encouraged to explore such questions to the extent that the answers would impact their importance ranking of other phenomena. However, the discussions ultimately concluded that the human decision making process lies outside the scope of fire modeling and that fire models were unlikely to incorporate human cognition models in the foreseeable future. Hence, such behaviors were generally not included in the fire PIRT phenomena. There are individual exceptions associated with Scenario 1.

# 3 CONCLUSIONS

This paper has summarized the process and findings for a PIRT exercise conducted to assess potential needs associated with improving fire models for use in nuclear power plant fire modeling applications. Based on the PIRT panel results, the phenomena rankings were assessed to identify those phenomena that are of the highest potential importance relative to fire modeling improvement. In particular, those phenomena that were ranked as having high importance and a low state of knowledge adequacy were identified. These phenomena were identified as the "Level 1" phenomena.

The PIRT panel identified a number of Level 1 phenomena. Some were specific to individual fire scenarios, while others were more universal, being identified as Level 1 phenomena for two or more scenarios. The Level 1 phenomena have been discussed here in the context of various topical areas of interest to the NRC. The identified Level 1 phenomena included the following:

- Performance of fire detection systems under complex geometries (e.g., highly congested spaces),
- Performance of incipient detection systems,
- Performance of fire sprinkler systems under highly obstructed conditions,
- Performance of fire sprinkler systems against a large oil pool fire,
- Fire behaviors, such as plume development, in the presence of obstructions such as pipes, drop ceilings, and open grating floors,
- Characterizing/predicting cable fire behaviors including fire spread and total heat release rates,
- Characterizing/predicting electrical cabinet fires including fire spread, total heat release rates, ventilation effects, and HEAF behaviors,
- Modeling the response of damage targets, such as cables, to the fire environment, and
- Human performance issues such as human detection of fires and the performance of fire fighters.

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