U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-6978
SAND2008-3997P

A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402-0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161-0002
   www.ntis.gov
   1-800-553-6847 or, locally, 703-605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer,
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301-415-2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at--

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from--

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
www.ansi.org
212-642-4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG-XXXX) or agency contractors (NUREG/CR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) brochures (NUREG/BR-XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG-0750).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-6978
SAND2008-3997P

A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications

Manuscript Completed: December 2007
Date Published: November 2008

Prepared by
T.J. Olivier, S.P. Nowlen

Sandia National Laboratories
Risk and Reliability Analysis Department 6761
P.O. Box 5800
Albuquerque, NM 87185

J. Dreisbach, D. Stroup, NRC Project Managers

NRC Job Code N6374

Office of Nuclear Regulatory Research

ABSTRACT

This report documents 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 United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES). The PIRT exercise is performed via a facilitated expert elicitation process. In this case, the expert panel was comprised of seven international fire science experts. The panel 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 panel is presented with a series of specific fire scenarios, each of which is based on the types of scenarios typically considered in NPP applications. Each scenario includes a figure of merit; that is, a specific goal to be achieved in analyzing the scenario using fire modeling tools. To illustrate, one scenario involved a main control room fire. For this scenario the figure of merit was predicting the time to operator abandonment. Given each scenario, the panel identifies all those related phenomena that are of potential interest to an assessment based on the figure of merit. The phenomena are ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge and the 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 results are discussed in detail.

FOREWORD

Fire modeling and fire dynamics calculations have been used over the years in a number of nuclear power plant (NPP) fire hazards analyses (FHA), fire risk analyses (FRA), and the Significance Determination Process (SDP) used in the reactor inspection program. More recently, the risk-informed performance-based (RIIPB) voluntary fire protection licensing basis established under 10 CFR 50.48(c) allows licensees to use fire modeling calculations to demonstrate compliance with safety goals. The RI/PB method is based on the National Fire Protection Association (NFPA) Standard 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants.*

The Nuclear Regulatory Commission (NRC) has initiated several research programs to investigate and improve the quality of fire models used in NPP applications. The NRC has sought the advice of several international experts on fire modeling and NPP fire hazard analysis to get insights on the adequacy of fire models to predict NPP fire scenarios. The road map for this project was derived from the NRC-developed Phenomena Identification and Ranking Table (PIRT) process, which has been used to great success in other technically complex areas.

This NUREG-series report documents the results of the PIRT exercise performed for NPP fire modeling applications. This is the first time the NRC has applied the PIRT process for fire modeling. The panel of experts assessed the predictive capabilities of fire models for a number of different postulated NPP scenarios. The experts identified and ranked the important phenomena, and assessed the existing state of knowledge and adequacy of existing modeling tools to predict the phenomena. These results give the NRC valuable technical insights into the predictive capabilities of fire modeling tools. In addition, NRC can use the PIRT results to identify areas where further research and analysis are needed.

The analyses documented in this report represent the efforts of individual experts. The NRC Office of Nuclear Regulatory Research (RES), the Electric Power Research Institute (EPRI), and the National Institute of Standards and Technology (NIST) along with the contractor for this project, Sandia National Laboratories, provided specialists in the use of fire models and other FHA tools to support this project.. The results from this effort do not constitute either a regulatory position or regulatory guidance.

Christiana H. Lui, Director
Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

TABLE OF CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

This report documents 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).

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. 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 (e.g., 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 using 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.

The PIRT panel covered four distinct primary fire scenarios. Two of the four primary scenarios had three sub-scenarios. 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 four primary scenarios considered by the panel involved (1) a main control room fire leading to abandonment, (2) a switchgear room fire leading to the failure of important safe shutdown cables, (3) a turbine building lube oil fire leading either to damage to equipment in the adjacent main control room or failure of the structural steel of the turbine building itself, and (4) a cable fire in the containment annulus region leading to the failure of redundant cables nearby.

As a result of the process “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. 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 report provides both the full PIRT results for each of the scenarios and sub-scenarios via a series of four appendices. The Level 1 phenomena are discussed in the main body of the report as well. The discussions of Level 1 phenomena are organized both by scenario and by topical area.

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 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 high energy arc fault (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.

ACKNOWLEDGMENTS

The authors wish to thank the members of the expert panel, Vyto Babrauskas, Craig Beyler, Doug Carpenter, Dave Evans, Brian Melly, Laurence Rigollet and Jose Torero, for their dedication to the process and for their patience. We also thank the NRC staff for their support in this effort including Jason Dreisbach, David Stroup, and Mark Salley. In addition, we also thank Kevin McGrattan of the National Institute of Standards and Technology (NIST) and Francisco Joglar-Biloch of Science Application International Corporation (SAIC) for their participation as technical area experts during the panel meetings. Finally, the NRC staff would like to express their thanks to Bryan Klein and Anthony Hamins (NIST), Stan Davis and Tom Gorman (PPL Susquehanna Nuclear Power Plant) and Patrick Finney (U.S. NRC Region I) for their help in development of the fire scenarios and supporting materials considered by the panel.

LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
BE	Benchmark Exercise
BOP	Balance of Plant
CAROLFIRE	Cable Response to Live Fire Project
C&F	Combustion and Flame Journal, Official Journal of the Combustion Institute
CFAST	Consolidated Model of Fire and Smoke Transport
CFD	Computational Fluid Dynamics
CSR	Cable Spreading Room
DID	Defense-in-Depth
ECCS	Emergency Core Cooling Systems
EPRI	Electric Power Research Institute
ERFBS	Electrical Raceway Fire Barrier System
FDS	Fire Dynamics Simulator
FDTs	Fire Dynamics Tools
FHA	Fire Hazards Analysis
FIPEC	Fire Performance of Electric Cables
FIVE	Fire-Induced Vulnerability Evaluation
FM	Factory Mutual
FMRC	Factory Mutual Research Corporation (now FM Global)
FPRA	Fire Probabilistic Risk Assessment
GET	General Employee Training
GRS	Gesellschaft fuer Anlagen-und Reaktorsicherheit (Germany)
HEAF	High Energy Arcing Fault
HGL	Hot Gas Layer
HRA	Human Reliability Analysis
HRR	Heat Release Rate
iBMB	Institut für Baustoffe, Massivbau und Brandschutz
ICFMP	International Collaborative Fire Model Project
IN	Information Notice
IRSN	the French Nuclear Radioprotection and Safety Institute
JASMINE	A fire modeling code from the Fire Research Station, United Kingdom (acronym's origin is unknown)
LLNL	Lawrence Livermore National Laboratory
MAGIC	A fire model from Éléctricité de France (acronym's origin unknown)
MCR	Main Control Room
MOU	Memorandum of Understanding
NBS	National Bureau of Standards (now NIST)
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
POC	Product of Combustion
PRA	Probabilistic Risk Assessment
RES	the NRC Office of Nuclear Regulatory Research
SAIC	Science Applications International Corporation

SCBA	Self-Contained Breathing Apparatus
SDP	Significance Determination Process
SFPE	Society of Fire Protection Engineers
SNL	Sandia National Laboratories
SSD	Safe Shut Down
SWGR	Switchgear Room
V&V	Verification and Validation
VTT	Technical Research Center of Finland

1. INTRODUCTION

1.1. Overview

This report documents 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 Sandia National Laboratories (SNL).

A PIRT exercise is a structured and facilitated expert elicitation process. In this case, the expert panel was comprised of seven internationally recognized fire science experts. Technical area experts, available for consultation with the expert panel, were provided by the National Institute of Standards and Technology (NIST), the NRC, and Science Applications International Corporation (SAIC) courtesy of the Memorandum of Understanding (MOU) between NRC-RES and the Electric Power Research Institute (EPRI).

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 various NPP fire scenarios. Potential applications of interest included, but were not limited to, fire probabilistic risk assessment (PRA). Other potential applications that the panel was asked to consider included general fire safety assessments by licensees and regulatory applications such as the significance determination process (SDP) [1] and risk-informed performance-based fire protection strategies such as those outlined in the National Fire Protection Association Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants" (NFPA-805) [2].

The panel was presented with a series of specific fire scenarios, each based on the types 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 using fire modeling tools. For example, one of the PIRT fire scenarios involved a main control room (MCR) fire and the figure of merit specified was predicting the time to operator abandonment. The panel was asked to identify phenomena relevant to the fire modeling analysis of each fire scenario. When identifying phenomena of interest, and in particular when ranking phenomena importance and the adequacy of existing fire modeling tools and data, the panel was asked to specifically weigh these factors in the context of the specified figure of merit.

Given each scenario, the panel identifies all those related phenomena that are of potential interest to an assessment of the scenario using fire modeling tools to evaluate the figure of merit. Each phenomenon is then ranked relative to its 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 PIRT panel evaluated four distinct primary fire scenarios. Two of the four primary scenarios included three sub-scenarios. The sub-scenarios represented, in effect, “variations on a theme.” The sub-scenarios share most aspects of a common primary fire scenario, but introduced certain variations. The variations introduced changes that were related to one of two aspects of the fire scenario. In some cases the changes related to a key aspect of the fire source scenario. For example, two sub-scenarios might deal with different types of fire sources such as a liquid pool fire versus a high-pressure spray fire. In other cases the changes involved redefining the scenario figure of merit. For example, the figure of merit in one sub-scenario might be smoke spread to adjacent areas and in a second sub-scenario it might be collapse of exposed structural steel.

1.2. Report Organization

Section 2 provides a more complete description of the PIRT process and goals focusing in particular on how the PIRT process was defined and exercised for this project. Section 2 also identifies the panel members and introduces the scenarios considered by the panel. Section 3 provides an overview of the results of the PIRT exercise focusing on the results obtained for each individual scenario. Section 4 provides similar summary discussions focusing on a comparison of results across the fire scenarios. The individual fire scenarios considered and the associated panel findings are covered in detail in the accompanying Appendices A-D. Resumes for the members of the PIRT panel and the panel facilitator are provided in Appendix E. Appendix F provides the background and introductory materials presented to the panel during the first panel meeting.

A video DVD of the opening meeting is also included to provide the reader an introduction to the Fire Modeling PIRT’s goals and objectives.

2. OVERVIEW OF THE PHENOMENA IDENTIFICATION RANKING TABLE PROCESS APPLIED

2.1. Background

A PIRT exercise is a formal expert elicitation process with the final output being the ranking tables. The U.S. NRC has utilized the PIRT approach for a range of applications. However, this project represents the NRC's first attempt to apply the process to fire modeling applications. RES has been engaged in a fire model verification and validation (V&V) effort designed to benchmark fire modeling tools. This effort has been conducted by RES in collaboration with EPRI and NIST. A report has recently been published on this subject [3]. The V&V efforts had previously indicated that fire modeling improvements would be desirable.

The goal of the PIRT exercise is to develop input to the NRC staff for consideration in their efforts to prioritize future fire model improvement efforts. In particular, this PIRT process provides insights into those areas of fire modeling that fire science experts consider to be (1) important, (2) poorly understood or poorly dealt with given the current state of the art, and (3) amenable to additional research.

2.2. Selection of Panelists

Members of the PIRT panel were identified jointly by staff at SNL and NRC/RES. The selected panelists represent a range of specific expertise areas and backgrounds. They also span the range that includes researchers, academics, and those working with practical field applications.

Fire modeling is a highly specialized field of expertise, and the number of individuals in the world with suitable expertise, experience and recognition is limited. The field of NPP fire protection is also a highly specialized field of expertise. Only a very small number of experts in the world provide expertise specific to fire modeling for NPP applications. Four of the seven members of the PIRT panel explicitly possessed prior experience in the application of fire modeling tools to NPPs. The other three members of the PIRT panel are widely recognized fire science experts, but were not specifically associated with NPP applications prior to this PIRT exercise.

The individuals who made up the expert panel included five U.S. experts and two experts drawn from the international fire science community. The panel members were:

- Dr. Vyto Babrauskas, Fire Science and Technology, Inc.,
- Dr. Craig Beyler, PE, Hughes Associates Inc.,
- Mr. Douglas Carpenter, PE, Combustion Science & Engineering, Inc.,
- Dr. David Evans, PE, Society of Fire Protection Engineers,
- Mr. Brian Melly, PE, TRIAD Corporation,
- Prof. Jose Torero, CEng, University of Edinburgh, Edinburgh, Scotland, and
- Mrs. Laurence Rigollet, Fire Research and Development of Uncertainty and Simulation Methods Laboratory, Nuclear Radioprotection and Safety Institute (IRSN), Cadarache, France.

All of the selected panelists are widely recognized and well published. Appendix E presents the resumes supplied by each of the seven panelists and for the meeting facilitator, Mr. Steven Nowlen, Distinguished Member of the Technical Staff, Sandia National Laboratories. In the presentation of panel results, the identities of the individual panelists have been obscured. The panelists are identified using a randomly assigned letter code rather than by name. The letter code is P1 through P7 for panelists 1 through 7.

2.3. The PIRT Process Applied

This section describes the PIRT process as exercised for this project. Once the expert panel members had been identified and all had agreed to participate, three separate three-day meetings were scheduled. It was during these meetings that panel deliberations took place and the panel's primary input was solicited.

As a part of the first panel meeting, the panel members were provided with a series of introductory presentations intended to establish the PIRT goals, describe the PIRT process, and define the role that the panelists were being asked to fulfill. All of the presentation materials shown at this meeting are reproduced in Appendix F. The introductory meeting began with opening remarks from Dr. Jennifer Uhle, who at that time was the Deputy Director of the Division of Fuel, Engineering and Radiological Research at the RES. Mr. Nowlen, the PIRT facilitator, presented additional introductory material to the panelists focusing on the PIRT process. Mr. Nowlen's presentation included the objectives, processes, products, and terminology definitions for the PIRT. The panelists were then introduced to NPP fire safety applications by Mr. Mark Henry Salley, M.S, P.E., and currently Chief of the Fire Research Branch at RES. His presentation was titled "A Brief Introduction to Fire Hazard Analysis (FHA) & Fire Modeling in Commercial Nuclear Power Plant (NPP)." The final introductory presentations were given by two of the technical areas' experts who provided support to the process. These were Dr. Kevin McGrattan from NIST and Dr. Francisco Joglar-Biloch from SAIC. Both of these individuals were principal investigators in the fire modeling V&V effort noted above. Their presentation was titled "Validating Fire Models for Nuclear Power Plant Applications" and focused in particular on the fire model verification and validations efforts being conducted by RES in collaboration with NIST and EPRI (i.e., [3]). These opening presentations were video taped for the benefit of panel members who could not attend the first meeting. A DVD containing the video has been included as part of this report to assist the reader in understanding this report.

Following the opening remarks and introductions, the panelists were presented with the first PIRT fire modeling scenario. Each of the four primary scenarios, and their associated sub-scenarios, were then considered over the course of the balance of the three planned meetings. Additional input was solicited from the panel between meetings in the form of review of the materials generated during the previous meeting, recommended readings, and preparation for the next planned meeting. PIRT panelists also reviewed and commented on this final report.

Each scenario was evaluated independently. For each given fire scenario, the panelists were asked to complete the following stages of assessment:

1. Understand the given fire scenario and figure of merit, and ask clarifying questions as needed.
2. Identify phenomena of interest and, as appropriate, key parameters associated with any identified phenomena.
3. Rank the importance of each phenomenon in the context of the figure of merit.
4. Rank the state of knowledge of phenomenon relative to the adequacy of existing fire modeling tools, the availability of supporting experimental data, and the prospects for gathering data if existing data were not ranked as "high".
5. Rank the importance and state of knowledge for any key parameters identified for any given phenomenon.

To complete the first stage of analysis, the given fire scenario was presented to the panelists. Scenario definitions included descriptive text, illustrative figures, photographs of similar configurations taken from actual NPPs, relevant physical dimensions, compartment physical characteristics, the assumed ventilation configuration, fire protection features, and general geometric descriptions (e.g., distances from a fire source to a target component). Also included were a general description of the fire source (e.g., type of fire source and location) and a defined figure of merit. Often the figure of merit would be associated with damage to key targets (e.g., cables or other equipment) and in such cases the targets of interest would also be defined. Panelists were given an opportunity to ask any clarifying questions, and the technical area experts supporting the process often played a key role in answering such questions.

Given these specifics, the panelists then identified relevant phenomena and parameters that might play a role in fire modeling predictions as applied to the defined scenario and figure of merit. An example of a phenomenon was heat transfer to the wall surface. Examples of corresponding key parameters were thermal conductivity of the wall, wall density, and the surface heat transfer coefficient.

During this stage, the main focus was identifying phenomena. However, when necessary the panel would identify key parameters for various phenomena. This particular approach developed over the course of the PIRT process to some extent as there was some considerable debate as to what constituted a phenomenon as apposed to a parameter. Definitions were offered by the facilitator and debated by the panel. These definitions can be found in Appendix F in the PIRT introduction presentation. Ultimately, allowing for the identification of both phenomena and key parameters led the panel to a more consistent treatment of what constituted a phenomenon. This practice also helped to narrow the focus to specific aspects of an identified phenomenon that were considered the "lynchpins" to weaknesses in the existing state of knowledge.

Once a list of phenomena had been developed, the next stage of the analysis was to rank each phenomenon for importance relative to the figure of merit. The panel was asked to rank phenomena importance according to the descriptors provided in Table 2.1. Note that these descriptors and definitions were included in the introductory presentation given by Mr. Nowlen, and were frequently referred back to during the panel meetings.

Using these descriptors, each panelist was asked to offer an individual opinion regarding the ranking of a given phenomenon. The process then involved moderated discussions to clarify and define the reasoning behind the offered rankings. If the panelists disagreed, the moderator attempts to seek panel consensus via these discussions. Ultimately, the panel did not always agree, and no attempts were made to force a consensus opinion. Rather, the moderator sought to clarify and document the reasons for the differences in opinion, and the process moved forward to the next phenomenon. For some phenomena there were strong differences of opinion expressed among the panel. These cases and the basis for the panelist's differing opinions are noted in the tables provided in the scenario appendices (Appendices A-D).

Table 2.1: 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.

Note that for any identified key parameters, the panel was asked to rank their importance using the same descriptors, but as a group (a consensus position only). The importance of the key parameters rarely led to significant disagreements among the panelists.

The next stage of the assessment was to rank the state of knowledge with respect to the general adequacy of existing fire modeling tools to meet the needs for modeling of each identified phenomenon. For this stage of the PIRT the panel ranks the state of knowledge as a group (rather than as individuals). The panel aimed for consensus but in some cases one or more panelist's disagreed with the final state of knowledge ranking. Such cases are noted via a "notes" field in the associated ranking tables.

The panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters were intended to solicit panel opinions in two main areas. First was the general adequacy of the existing and generally available[1] fire models to deal with the identified phenomenon. The descriptors used by the panel for this ranking activity are defined in Table 2.2. Second was the adequacy of existing data needed to support model development and model validation. The descriptors used for ranking the adequacy of existing input and validation data are defined in Table 2.3.

[1] The panel was asked to consider the adequacy of existing models based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee (e.g., commercial software packages) was not considered a barrier to ready availability. However, fire models of a proprietary nature that are not readily available to general users were to be excluded from consideration.

Table 2.2: 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 2.3: 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.

The final aspect of the model and data adequacy assessment was to rank the feasibility of getting new model input and validation data if the existing data were ranked as anything other than "high" adequacy. The descriptors used for this aspect of the assessment are defined in Table 2.4.

Table 2.4: 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.

This last aspect of the PIRT process, the feasibility of getting new input and validation data, was intended to provide an added level of input to the NRC staff. In particular, the feasibility question was intended to identify the "low hanging fruit" as compared to those aspects of fire model improvement that, while potentially important, might be quite difficult and/or quite expensive to pursue. The rankings relative to feasibility also reflect the technical risk associated with pursuing various aspects of fire model improvement in the future. That is, those items rank high in terms of feasibility should represent low risk undertakings with a high probability of success. In contrast, items ranked with low feasibility will be higher risk undertakings with a significant chance of failure.

As noted previously, the phenomena identification and ranking tables themselves are the output of the PIRT process. However, as a part of the reporting process, the raw tables have been analyzed and the identified phenomena have been summarized based on four levels of overall importance. The overall importance is judged based on two factors; namely, the importance ranking assigned by the panelists (considering the majority opinion if split rankings are assigned) and the state of knowledge ranking. The overall importance levels are defined as follows:

- Level 1: The highest level of overall importance is assigned to those phenomena that were ranked with a *high* level of importance and a *low* state of knowledge.
- Level 2: The second level of overall importance was assigned to those phenomena that were ranked with either a *high* importance and *medium* state of knowledge or *medium* importance and *low* state of knowledge.
- Level 3: The third level of overall importance was assigned to those phenomena that were ranked as uncertain by the panelists for importance ranking and/or state of knowledge rankings. This level represents areas that might require further exploration before a true assessment of importance and state of knowledge is possible.
- Level 4: The fourth level was assigned to those phenomena that were given one of the following rankings: high importance with a high state of knowledge; medium importance with either a medium or high state of knowledge; or low importance given with having a low, medium, or high state of knowledge. These rankings reflect a panel opinion that the phenomena are either important but well understood, or are relatively unimportant.

The results for each of the four primary scenarios considered are presented in the appendices as follows:

- Appendix A: Scenario 1
- Appendix B: Scenario 2a, 2b, and 2c
- Appendix C: Scenario 3a, 3b, and 3c
- Appendix D: Scenario 4

Note that in addition to the consideration of the ranking for each scenario individually, the consideration of phenomena rankings across the scenarios provides added insight. Such a cross-comparison is presented in Section 3.

2.4. Summary Scenario Descriptions

This section briefly discusses the four fire scenarios and any related sub-scenarios that were considered by the panel. Complete descriptions of the scenarios are provided in the accompanying appendices (A-D). These appendices include the full text descriptions as provided to the panel including any clarifications offered in response to panelist questions. All of the associated graphics (e.g., layout drawings, example photographs, etc.) that were presented to the panel are also included.

2.4.1. Fire Scenario 1

PIRT fire Scenario 1 was a postulated electrical cabinet fire occurring in a shared two-unit NPP MCR. The cabinet was specified as a low voltage (<600V) control cabinet in the MCR but outside the main control horseshoe (i.e. a "back panel"). The fire was assumed to initiate due to an electrical failure that led to a self-sustaining and growing fire in the cabinet. The figure of merit for this scenario was predicting the time of forced abandonment of the MCR and the transfer of plant operations to an alternate shutdown (operational control of the plant can be transferred to an alternate and redundant control room specifically designed to handle the abandonment of the primary control room). That is, the figure of merit was the impact of the fire on the operators working in the MCR with the potential that the effects of the fire on room conditions would eventually force them to leave the area. The exact conditions that might cause abandonment were not specified, but rather, were left to the panel to define and explore.

It was also explained to the panel that all plants in the U.S. provide an alternate shutdown capability that is independent of the MCR. In general such facilities provide a minimum set of equipment to achieve hot shutdown conditions. Further, when asked as to where the alternate shutdown was located, the panelists were told to assume a typical location such as an area within the overall control structure but in a separate fire area two floors below the MCR. Discussions also led to questions as to how willing/reluctant operators would be to abandon the MCR and rely on alternate shutdown. In effect, the panel wanted to know if the operators would abandon at the first sign of a fire, or if they would stay with the main control room until they literally could no longer inhabit the space. The explanation given was that operators would strongly prefer to stay in the MCR as long as they can since this is their "home base," they are comfortable being there, and abandonment would be a last resort action. However, upon indications that a significant fire was developing, operators would likely begin preparing for the possibility of abandonment. The operators do have self-contained breathing apparatus (SCBA) and are trained to use them. A more in-depth scenario description and the full results for Scenario 1 are provided in Appendix A.

2.4.2. Fire Scenario 2

PIRT fire Scenario 2 involved a postulated cabinet fire in a switchgear room and included three sub-scenarios (2a, 2b, and 2c). All sub-scenarios occurred in the same fire area (same geometry etc.) and involved the same electrical cabinet as the fire source. In all cases, the figure of merit was damage to a critical electrical cable located in the fire area. The variations between sub-scenarios involved the location of the target cable and the nature of the fire.

This switchgear room contained electrical cabinets on the west, south, and east walls and a stepped ceiling (one part taller than the other). All of the cabinets, including the fire source cabinet, were located in that portion with a lower ceiling. The ceiling height in this area was specified as 3.0 m (about 10 ft). The balance of the room was given a ceiling height of 9.1 m (about 30 ft). The specific cabinet in which the fire was assumed to occur was roughly in the middle of a long bank of electrical cabinets. An in-depth scenario description and the results for scenarios 2a, 2b, and 2c are given in Appendix B.

Scenario 2a: For this scenario the fire originated from an electrical component failure which led to a self-sustaining and slowly growing electrical cabinet fire. The figure of merit for this case was to predict if and when the target cable would fail given the cabinet fire. The target cable was located in a cable tray above the end of the cabinet bank in which the source fire was located. A cable tray was specified as running directly above and parallel to the bank of cabinets 0.6 m (2 ft) above the top of the cabinets. The target cable was not directly above the cabinet of fire origin. Rather the target cable was in a crossing tray above one end of the bank of cabinets, but still under that part of the room with a lower-level ceiling.

Scenario 2b: All aspects of PIRT fire Scenario 2b are identical to Scenario 2a except that the location of the target cable was changed. The target cable was moved to a cable tray just beneath the higher-level ceiling. Further, the cable tray was specified as being protected by a one-hour rated electrical raceway fire barrier system (ERFBS). The figure of merit remains the same, failure to the target cable.

Scenario 2c: As compared to 2a, Scenario 2c changed only the characteristics of the fire source. For Scenario 2c, the fire was specified as occurring in a medium voltage cabinet (a 4kV switchgear cabinet) as the result of a high energy arcing fault. The panel was provided with additional information on such fires based on a 2001 event that occurred at the San Onofre Nuclear Generating Station [4]. The figure of merit was again predicting if and when fire-induced failure would occur for a target cable located in a cable tray 0.6 m (2 ft) above the bank of cabinets where the fire originated at the end of the cabinet bank (i.e., the same as the target for Scenario 2a).

2.4.3. Fire Scenario 3

PIRT fire Scenario 3 also had three sub- scenarios associated with it. The base scenario involved a large oil leak and fire occurring in the turbine building below the main turbine lube oil storage tanks. The variations between sub-scenarios were again related to both the figure of merit and the nature of the fire source. An in-depth scenario description and the results for scenarios 3a, 3b, and 3c is provided in Appendix C

Scenario 3a: For Scenario 3a, a pool fire was specified. This is caused by a leak in the main turbine's lube oil storage tank. The entire inventory of oil spills into a dike-enclosed spill containment pool below the tank and is ignited. The fire for this scenario involved a large pool (53000 liters or 14000 gallons) of hot lube oil. The fire was located one level below the turbine operating deck. The figure of merit for this case involved the impact of the fire on the MCR. The MCR was located at the same elevation as the operating deck of the turbine building, the two fire areas being separated by a 0.9 m (3 ft) thick concrete wall. There was presumed to be a large hole, 0.1 m^2 or about 1 ft^2 total area, identified in the wall that separates the MRC from the turbine building (e.g., an inspection finding case). The figure of merit for Scenario 3a was fire-induced failure of equipment in the MCR just inside the separating wall.

Scenario 3b: PIRT fire Scenario 3b was quite similar to Scenario 3a except that, rather than a pool fire, the fire was specified as a high-pressure spray fire. This is characterized by lube oil leaking from a high pressure portion of the lube oil system creating an oil spray that is ignited. The rest of the scenario specifics, target, and figure of merit are the same as those in Scenario 3a.

Scenario 3c: PIRT fire Scenario 3c used the same fire source as Scenario 3a (pool fire), but changed the figure of merit. For 3c the figure of merit is structural failure of the unprotected steel supporting the turbine building. The modeling objective is to predict if and when fire-induced damage to the structural steel would occur, leading to collapse of the building.

2.4.4. Fire Scenario 4

The final PIRT fire was Scenario 4. This scenario involved a fire in the containment annulus region which is protected by fixed automatic sprinklers. The sprinkler heads were installed on a loop header around the annulus space and were located 17 meters (55 feet) above grade but well below the top of the containment structure (several meters, although the exact distance was not specified). Each sprinkler head was equipped with a heat collector plate in an attempt to improve the responsiveness of the sprinklers [5]. In this case the fire began as a self-ignited cable fire in one vertical raceway. The figure of merit involved damage to the cables of the redundant train located in a parallel vertical raceway. Cabling for the safe-shutdown (SSD) equipment is routed to equipment inside containment through the annulus from adjacent buildings (e.g., the auxiliary building or reactor building). The fire begins in cable tray A, which is located 1.8 m (6 ft) to the left and 1.5 m (5 ft) higher than the target cables in tray B. The figure of merit is if and when damage would occur to the SSD cables in cable tray B. An in-depth scenario description and the results for Scenario 4 are provided in Appendix D.

3. SUMMARY OF LEVEL 1 PHENOMENA ORGANIZED BY INDIVIDUAL FIRE SCENARIOS

This section provides a brief summary of the phenomena identified by the PIRT panel with the highest level of importance (Level 1). This includes those phenomena ranked with a high importance and low state of knowledge. In this section, the discussions are organized by fire scenario. Section 4 provides companion discussions of the PIRT results organized by high level topical areas. For more complete details of the individual scenario results, refer to Appendices A-D.

3.1. Scenario 1

Scenario 1 involved an electrical cabinet fire occurring in the MCR. The figure of merit was predicting if and when fire effects would force operators to abandon the MCR.

This was the first scenario considered by the panel. In reviewing the results, the reader will note that for this case the panel defined phenomena at a rather high level of detail compared to subsequent scenarios. In later scenarios, the panel tended to identify phenomena at a higher level and ended up with shorter phenomena lists with each phenomenon being somewhat more broadly defined. The panel also tended to rank more of the phenomena as of high importance than was the case in later scenarios. In particular, this panel identified a number of phenomena related to human performance issues and these were generally ranked as highly important. As discussed in Section 4.7, these aspects of a fire scenario lie outside the traditional bounds of fire modeling tools. For example, in fire PRA, such factors are dealt with either via a human reliability analysis (HRA) or based on statistical models derived from past experience. The results for this scenario should be viewed accordingly.

There were several phenomena that the PIRT panel identified as of high importance and low state of knowledge for Scenario 1. These are summarized as follows.

- *"The effectiveness, timing and level of control of the manual fire suppression"* was ranked with an overall high level of importance (note that one panelist ranked this as uncertain importance). All of the states of knowledge rankings were low for this phenomenon. The candidate model considered by the panel was that documented in NUREG/CR-6850 [6] which is based on statistical analysis of past fire events. Given the potential importance of manual fire fighting to the scenario, the panel did not consider this model to be adequate to the need

- One phenomenon directly related to manual suppression that some panelists ranked as highly important was "*the process of humans sensing the fire (i.e., human detection of the fire)."* The importance rankings for this phenomenon were split among panel members with three panelists ranking it medium and three ranking it high (the seventh Panelist did not participate in the discussion of this scenario). While a human's ability to detect the fire was identified as a phenomenon for various scenarios, the relatively high ranking was unique to

Scenario 1. In other scenarios it was identified as relevant but was not ranked as highly important. The panel ascribed the higher level of importance for Scenario 1 to the fact that the fire was specified in a continuously manned area and prompt detection and suppression would be critical to the probability that the fire might never grow to threatening levels. The phenomenon was ranked as having a low state of knowledge because the panel was unaware of any candidate models of the human fire detection process. The panel also ranked the availability of input and validation data as low. Finally the panel ranked the feasibility of gaining input and validation data as low due in part to the difficulties associated with human experimentation.

- Another factor that was unique to Scenario 1 was the specification of an "open-grate" false ceiling in the MCR space. This open-grate ceiling was specified as being made of a thermoplastic material. Such open grate ceilings are used to give the MCR space a more human-friendly appearance and feel. The panel identified the role that this open-grate might play in the fire as important but with a low state of knowledge. In particular, the panel identified the following specific phenomena: "the open-grate ceiling influence on fire phenomena" and the "potential burning behavior of the open-grate ceiling material and its role as a fuel". Both were raked as high importance (with individual panelists dissenting from this ranking) with a low state of knowledge. The feasibility of getting new input and validation data was ranked high because the data are readily attainable with existing capabilities. The justification for the high importance rankings are that the role of the open-grate ceiling in the fire phenomenon is related to fire propagation, fire spread, and mixing. The panelists also mentioned that the removal of the open-grate would eliminate the problem.

- One phenomenon that was grouped under the higher level category "characterizing the fire source" and was identified as Level 1 phenomenon was *"transition of the fire from the incipient (pre-open-flaming) stage to open flaming*". There was some disagreement among the panel as to the importance of this phenomenon. One panelist in particular felt this was a high importance phenomenon because this transition will establish "time zero" for the fire development phase. Another panelist ranked the importance as medium because the fire characteristics after the transition to open flaming are more important than establishing time zero. The state of knowledge was ranked low for the model adequacy and available input and validation data because the panelists were unaware of any model that currently treats this transitional stage of a fire. The development of such models would require a very precise and small scale evaluation. Hence, the feasibility of getting the data was ranked as medium because the capability does exits but a very large number of experiments would need to be performed given that there is a very large range of possible cabinet configurations and fire ignition scenarios possible. The general consensus of the panel was that incorporating such transitional models into fire modeling tools would be an exceedingly complex and difficult undertaking, but that it was feasible given enough time and money.

- Another phenomenon related to fire behavior identified as a Level 1 phenomenon was *"fire behavior/characteristics during open flaming period".* The panel was unanimous in their ranking of this as a critical phenomenon for the given scenario as this would drive the rest of the problem. The low state of knowledge ranking was based on the fact that given today's commercially available fire models the physics of flame structure and movement are not implemented. That is, while data exist that provide a global measure of cabinet fire characteristics for at least some portion of the parameter space, existing fire models are unable to treat fire behaviors within the cabinet that ultimately drive the global behaviors. Again, the panel consensus was that treating fire behaviors at this level was an exceedingly challenging problem.

- Another Level 1 fire characterization phenomenon identified by the panel was *"fire spread beyond the cabinet of fire origin."* This phenomenon was considered important because fire spread, if it were to occur, would be critical to the figure of merit; that is, if and when control room abandonment might occur. The state of knowledge was ranked low because none of the cabinet fire tests performed to date have explored the question of fire spread to combustibles outside the originating cabinet.

- Another Level 1 fire characterization phenomenon identified by the panel was *"the potential behaviors that might be associated with oxygen starvation/re-flash of the fire."* The high importance ranking was assigned because this phenomenon can be fundamental to how the scenario progresses, in particular, if operators open the burning cabinet and a significant re-flash occurs. The low state of knowledge ranking was based on the fact that there has not been any significant work in this area that has developed into a model. The feasibility of getting both the input and validation data was ranked as high.

- Another phenomenon considered by some members of the panel as a Level 1 phenomenon was *"the plume/flame behavior for the cabinet fire."* There was strong disagreement among the panel as to the importance ranking for this phenomenon with importance rankings ranging from low to high. The Panelist assigning a low importance ranking cited that this phenomenon was not going to have a large impact on the model and that variation in behavior would have a minimal impact on the overall model predictions. One Panelist assigning a high importance ranking argued that this phenomenon was a fundamental characteristic of the overall fire behavior, the entrainment, and the spread of fire outside the cabinet. Panelists did agree to low model adequacy and low rankings for available input and validation data. The panelists felt that the feasibility of getting both the input and validation information is high.

- "Ventilation flow within and through the source cabinet" was also ranked as a Level 1 phenomenon. This phenomenon specifically refers to the gross ventilation rates (air change rates) through the burning cabinet. This was considered of high importance because the ventilation would directly influence the overall fire heat release rate (HRR). Prior testing was cited and discussed including tests by Keski-Rahkonen of Finland [6] and by IRSN in France [7]. However, the panel did not consider the existing data adequate to the need. The Keski-Rahkonen ventilation model was cited as not working well due to its inability to deal with ventilation changes caused by thermal deformation of the cabinet side panels. Hence, state of knowledge was ranked as low.

- The last of the Level 1 phenomena identified for Scenario 1 was *“acid gases during the open flaming stage of the fire”* referring primarily to the production of acid gases by the cabinet fire. The majority of the panelists ranked this phenomenon as high because it could have an affect on the electrical equipment, and equipment failures were considered a factor in forced abandonment. The adequacy of the model for this phenomenon was ranked low as were the availability of input and validation data. The feasibility of obtaining new input and validation data was ranked medium based on the variety of materials involved and the variability of potential fire conditions.

3.2. Scenario 2

Recall that Scenario 2 dealt with fires in a switchgear area. This particular scenario had three variations involving the location of the cable target and the nature of the fire source.

3.2.1. Scenario 2a

Scenario 2a involved a slowly developing cabinet fire leading to the ignition of cables in cable tray above and to the side of the initiating cabinet. In this case a slowly growing cabinet fire was specified. Those phenomena that the PIRT panel identified as of high importance and low state of knowledge are summarized as follows.

- *“The flame spread rate along the cable tray located above the cabinet fire”* is one of the Level 1 phenomena identified for Scenario 2a. The panel all agreed the phenomena was important given that fire spread was assumed necessary to damaging the specified target cables. This was considered a fire modeling problem for which models were currently nonexistent to, at best, inadequate. This was also an area ranked as medium for the feasibility of getting new input and validation data (some readily attainable extensions to existing methods might be needed).

- *“Fire spread from burning cable tray to cabinet below*” (e.g., dripping of melted plastic cable insulation or downward spread on the vertical cable risers) was also ranked as a Level 1 phenomena. In this case the panel felt that the potential to involve additional cabinets could significantly impact the overall fire development and intensity.

- Also ranked as a Level 1 phenomenon was *“fire growth on cable tray (i.e. HRR).”* The overall HRR was considered critical to modeling the fire scenario with both the adequacy of available models and availability of input and validation data ranked low. The feasibility of getting new data was ranked as medium.

- As with other scenarios, the panel also ranked “generation of particulates” as a Level 1 phenomenon. The panel felt that this would be especially important in the assessment of manual fire fighting conditions. All agreed that the current state of knowledge was low, although gaining the required support data was considered relatively straight-forward (medium feasibility).

- With respect to fire suppression, there was only one Level 1 phenomenon identified; namely, *"actions (detection, notification, suppression) by the non emergency responders."* This phenomenon was ranked with a high importance by all but one panelist who ranked this as medium importance. In general, the majority of the panel felt that rapid intervention by early responders (i.e. non-fire brigade) would be a key to preventing damage. It should be noted that activities such as manual suppression lie outside the purview of most fire models and is typically handled via statistical treatments and/or HRA.

- The final Level 1 phenomenon for Scenario 2a was related to damage to SSD cables, the figure of merit for this scenario. The phenomenon *"thermal (polymeric) decomposition of SSD cable (melting, charring, electrical)"* was ranked by a majority of the panel with high importance. Two panelists dissented in this view, assigning low and medium importance rankings. The differences in ranking were based on the panelists' opinions regarding what would dominate the cable failure mechanisms and to what extent a detailed understanding of polymer degradation would have as compared to gross pass/fail sorts of assessments. The state of knowledge rankings were low across all categories.

3.2.2. Scenario 2b

Recall that Scenario 2b was similar to 2a except that the target cable was moved to a location high in the room well away from the fire source. The phenomena identification and ranking results parallel those for Scenario 2a in most regards. While some additional phenomena were identified, and some of these were given high importance ranking, no unique Level 1 phenomena were identified for this scenario beyond those already discussed for Scenario 2a.

3.2.3. Scenario 2c

Recall that Scenario 2c was similar to Scenario 2a except that the fire source was changed to a high energy arc fault. Many of the phenomena already identified and ranked for Scenario 2a were retained with identical or similar rankings for Scenario 2c. This included all of the previously identified Level 1 phenomena. However, a number of additional phenomena specific to the fire source were identified and some were ranked as Level 1 phenomena. Those unique phenomena that the PIRT panel identified as of high importance and low state of knowledge are summarized below.

Several of the newly identified Level 1 phenomena were associated with characterizing the fire source and were specifically tied to the higher level phenomena grouping "characterizing the initiating event (initial high energy arc fault)." Level 1 phenomena identified under this high level grouping included pressure effects, temperature effect, and the initial energy release.

- The first Level 1 phenomenon was *"blast dynamics."* This was ranked as high importance by all but one of the panelists. The dissenting panelist ranked this as medium importance arguing that the thermal effects from the ensuing fire were going to be more severe and damaging to the cable of interest than the early pressure/blast effects. Others argued that the initial blast effects would establish the starting point of the fire and were therefore highly important. The panel did agree that current fire models cannot treat such effects, and the input and validation data were generally unavailable (low). The feasibility of obtaining new input and validation data was ranked as medium.

- The next Level 1 phenomenon was *"the ignition of any secondary materials due to arc"* which was ranked as high importance with a low model adequacy rating. The panel consensus ranked the feasibility of obtaining new input and validation data as medium in general on the basis that these would be challenging experiments to conduct, but did not require extensive development of new experimental methods.

- The next Level 1 phenomenon associated with the arcing behavior was *"cascading faults"* (i.e., propagation of the arc fault to additional cabinet sections). The state of knowledge rankings were "low to medium" for model adequacy. The panelists considered that cascading faults would be expected, but that predicting such behaviors would be quite difficult.

- One phenomenon retained from scenarios 2a and 2b whose ranking changed for 2c was *"the development of the fire in the cabinet as characterized by its overall burning rate (i.e.. total HRR)."* For both scenarios this was ranked with high importance, but for 2a and 2b the panel considered the existing models and data to be of "medium" adequacy. For the specific case of the high energy arc fault, these adequacy ranking were reduced to "low." The panel attributed the lower ranking to the uncertainties associated with the initial arc event.

- The last Level 1 phenomenon that was unique to Scenario 2c was "survival of the detector given the initial event." The panel felt that the survival of smoke detectors might be threatened by the initial blast event. The panel felt that predicting detectors survival would directly effect the prediction of the overall time line of the event.

3.3. Scenario 3

Scenario 3 involved a set of fire scenarios occurring in the turbine building. The figure of merit and the nature of the fire source were varied among three sub-scenarios. The subsections that follow summarize the results of the PIRT process for each of the three sub-scenarios.

3.3.1. Scenario 3a

Scenario 3a involved a turbine lube oil pool fire leading to damage to components in the MCR with communication between the turbine building and the MCR via a hole in the separated concrete wall. The figure of merit for this case involved the impact of the fire on the MCR. Those phenomena that the PIRT panel identified as of high importance and low state of knowledge are summarized as follows.

- The phenomenon "*fire suppression by under deck sprinklers"* was identified as relevant to all three scenarios, but was only ranked as a Level 1 phenomenon for Scenario 3a. Scenario 3 had specified that automatic sprinklers were installed below the operating deck of the turbine building in close proximity to the oil containment pool. Note that for scenarios 3b and 3c, the spray fire cases, the under-deck sprinklers were uniformly assumed to be ineffective and this phenomenon was assigned a lower importance ranking as a result. However, with the large pool fire of Scenario 3a, the panel felt that the sprinklers might well have a substantive impact on the fire behavior. However, they also concluded that our understanding of how such sprinklers would impact such a large and obstructed pool fire was poor; hence, they assigned a low state of knowledge. The feasibility of obtaining new input and validation data was ranked as high for this case. The tests that might be needed were considered to be difficult to perform, but relatively straight-forward from a technology standpoint.

- The next Level 1 phenomenon was *"particulate production."* The panel considered this to be an important factor because damage to components in the main control room by smoke deposition would be driven in large part by how much smoke was actually produced by the fire. The available input and validation data for this phenomenon were also ranked low. The feasibility of obtaining new input data was ranked medium and the feasibility of getting new validation data was ranked low to medium.

- The panel was sharply divided in the ranking of a third related phenomenon, *"CO (carbon monoxide) production."* This was ranked as of high importance by four of the seven panelists on the basis that CO production from such a large fire could hamper early fire fighting efforts. The other three panelists ranked this as of low importance arguing that fire fighters would be protected from CO exposure, and CO production was not relevant to potential equipment damage in the adjoining MCR spaces. The panel did agree that model adequacy was low and the availability of input and validation data were low. The feasibility of obtaining new input data was ranked medium and the feasibility of getting new validation data was ranked low to medium.

- One Level 1 phenomenon associated with characterizing the environment in the turbine building was *"window breakage creating new openings."* This phenomenon was ranked with a high importance by the panel with a low to medium model adequacy ranking. The general consensus of the panel was that breakage of the window, and in particular the timing of window breakage, could substantially impact both fire development and the performance of the roof smoke vents specified as a part of the scenario. There was little doubt in the minds of the panel that the windows would break, but the question of when was considered more difficult, and important, to answer.

- Another Level 1 phenomenon for this scenario was related to the smoke flow through the specified hole and the impact of that smoke on equipment in the MCR. The panel in general did not consider it plausible that enough heat would get into the MCR to cause equipment damage. However, smoke was considered a potentially plausible damage source. The ability to predict the onset of equipment damage due to smoke was therefore ranked with high importance by a majority of the panel members and all agreed that model adequacy was low.

- Finally, the panel also ranked two behaviors associated with the flow through the MCR wall as Level 1 phenomena. These were "leakage through cable penetrations" and "leakage through pipe penetrations." The panel considered the treatment of a specified hole as a more straight-forward challenge than was the treatment of the unspecified openings that might be associated with the cable and piping penetrations.

3.3.2. Scenario 3b

Scenario 3b was identical to Scenario 3a except in that the fire was specified as a spray fire rather than a pool fire. Most of the phenomena identification and ranking exercise paralleled that for Scenario 3a. The differences were associated with characterization of the fire source. The spray fire was unique in comparison to the pool fire. The spray fires scenario lead to some unique phenomena specific to the characterization of the spray. The only other significant change was a lower importance ranking for phenomena associated with the sprinkler system. For the spray fire, the panel simply did not expect the sprinklers to be as effective for fire suppression and assigned lower importance rankings to those phenomena. The unique phenomenon that the PIRT panel identified as of high importance and low state of knowledge is summarized as follows.

- The panel identified one Level 1 phenomenon associated with characterization of the fire source that is unique to the oil spray fire; namely, *"heat release rate of the spray fire."* This was ranked as highly important by all panelists. Model adequacy was ranked from "low to high" by panelists. This ranking was a bit unique and reflected the panel's opinion that the ability to model the spray fire would depend on the geometry and size of the spray droplets which were not specified for this scenario. The feasibility of getting new input and validation data, as well as the available validation data were all ranked low. This is a difficult type of fire source to deal with that has many variable parameters. Exploration of the parameter space sufficient to develop and validate fire models was considered a very challenging task that would require development of new experimental methods. On the other hand, doing tests to measure HRR for specific spray fires would be relatively straight-forward. These measurements were not, however, considered the primary need with respect to the development of fire models.

3.3.3. Scenario 3c

Scenario 3c was similar to Scenario 3a (a pool fire) but the figure of merit involved damage to the structural steel leading to collapse of the turbine building. Most of the identified phenomena and rankings exactly paralleled those for Scenario 3a. The exceptions involved the addition of phenomena associated with characterizing the response of the structural steel and the deletion of phenomena associated with transport of heat and smoke into the MCR space.

For this case, a number of the phenomena identified for the prior scenarios were not relevant. Those retained were assigned somewhat lower importance rankings for this scenario. The panel felt this scenario was a more sharply focused problem, resulting in fewer important phenomena (e.g., items like smoke generation and transport were not considered important to the figure of merit). The only phenomenon that retained high importance and low state of knowledge was the window breakage issue which has already been discussed above in Section 3.3.1.

There is one specific outcome for Scenario 3c that should be noted here. The focus of this scenario was placed on the response and potential collapse of the structural steel. The panel was unanimous in the opinion that modeling the response of the structural steel to the fire, while highly important, was also relatively straight-forward (high model adequacy). In particular, significant work in the area of fire and structural steel has occurred since September 11, 2001 and the panel felt that adequate models and data for this situation have been developed.

3.4. Scenario 4

Scenario 4 involved a self-ignited cable fire in the containment annulus region and the potential fire-induced failure of redundant train cables nearby. The phenomenon that the PIRT panel identified with high importance and low state of knowledge is summarized below.

- One Level 1 phenomenon associated with Scenario 4 was identified, and it relates to suppression. This phenomenon was “*suppression of fire by water spray.”* This phenomenon was specifically associated with the higher level phenomena grouping *“plume flow/sprinkler.”* The majority of the panelists ranked this as a highly important phenomenon, and all agreed that the state of knowledge was poor (low ranking). The dissent relative to the “highly important” ranking was expressed by those panelists who were of the opinion that the system as specified would simply not work and was therefore unimportant. All of the panelists agreed that the use of the “heat collector plates” was unlikely to enhance the sprinkler performance substantially. However, the majority of the panelists felt that the sprinklers might still play an important role in the overall development of the fire scenario. The feasibility of obtaining new input and validation data for this case was ranked as low due to the unique aspects of the configuration and the difficulty one would encounter in exploring the range of potential fire conditions that would need to be considered in formulating a new model.

4. SUMMARY OF HIGHEST RESEARCH PRIORITY PHENOMENA (LEVEL 1) ORGANIZED BY TOPICAL AREAS

This section will discuss the results of a cross-scenario analysis of the PIRT results. Those phenomena categorized as Level 1 from all scenarios are organized by topical areas relevant to the fire modeling problems with the PIRT results compared and contrasted across the scenarios. Recall that the Level 1 phenomena are defined here as those phenomena that were ranked with a high importance and a low state of knowledge. Section 3 provides a similar discussion focusing on the PIRT results for each individual scenario.

4.1. 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 systems[2] although none of the PIRT scenarios explicitly considered 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.

4.2. 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.

4.3. Fire Behaviors in the Presence of Obstructions

One theme that has already been touched on in Sections 4.1 and 4.2 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 buoyant fire plume. The phenomena

[2] 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.

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.

4.4. 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.

4.5. 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.

4.6. 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.

4.7. 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 (see Section 3.1), 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. For further discussion of this particular phenomena, refer to Section 3.1.

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.

5. SUMMARY

This report documents 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. The PIRT panel was comprised of seven internationally recognized experts in the fields of fire protection, fire safety and fire modeling. The panel's input was gathered during three separate three-day meetings.

A PIRT is a general expert elicitation process that focuses on identifying phenomena relevant to a given analysis application and then ranking the identified phenomena for both importance and current state of knowledge. The process involves the consideration of a series of specific scenarios by a panel of knowledgeable experts (the PIRT panel). In this case, the application was NPP fire modeling so the panel considered four typical NPP fire scenarios. The scenarios included a MCR electrical cabinet fire, a switchgear fire, a turbine building lubricating oil fire, and a cable fire in the annulus region inside containment. For each scenario, a figure of merit was defined which represents, in effect, the goal or objective that the fire modeling tools are intended to achieve or support. For example, in the case of the MCR fire scenario, the figure of merit was predicting if and when fire conditions might force operators to abandon the MCR and assume operations at the alternate shutdown station.

For each scenario the PIRT panel first identifies any and all relevant phenomena associated with the application of fire models as necessary to achieve the figure of merit. The panel then ranked each phenomenon for importance relative to the figure of merit. The panel then assessed the adequacy of current fire models to predict or assess each phenomenon. In this PIRT, a final step was incorporated in which panelists were asked to assess the feasibility of improving the state of fire modeling for any phenomenon where the current state of knowledge adequacy was ranked as anything other than "high."

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. In this report, these 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. Chapter 3 has discussed the Level 1 phenomena organized by fire scenarios, and Chapter 4 has discussed the Level 1 phenomena 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.

6. REFERENCES

1. Fire Protection Significance Determination Process, U.S. NRC, Inspection Manual Chapter 06.09, Attachment F, Feb. 28, 2005 (http://www.nrc.gov/reading-rm/doc-collections/insp-manual/manual-chapter/index.html).
2. Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plant, NFPA, Quincy MA, NFPA 805, 2001.
3. U.S. NRC and EPRI, Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, NUREG-1824, EPRI Preliminary Report 1011999, Vols. 1-7, January 2006.
4. NRC Information Notice 2002-27, “Recent Fires At Commercial Nuclear Power Plants in the United States,” September 20, 2002.
5. *Information Notice (IN) 02-24, “Potential Problems with Heat Collectors on Fire Protection Sprinklers”*, U.S. NRC, July 19, 2002 (*http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/2002/).*
6. Fire PRA Methodology for Nuclear Power Facilities, NUREG/CR-6850 and TR 1011989 (a report in two volumes), U.S. NRC, Washington, D.C, and EPRI, Palo Alto, CA, September 2005.
7. Keski-Rahkonen, Olavi and Mangs, J., Full scale fire experiments on electronic cabinets, VTT Technical Research Centre of Finland, Espoo, Finland, 1994.
8. Rigollet, Laurence and Melis, Stéphane, Fires of Electrical Cabinets, IRSN Institut de Radioprotection et de Sûreté Nucléaire, The 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, 2005.
9. Fire Protection Handbook, NFPA, Quincy, MA.
10. The SFPE Handbook of Fire Protection Engineering, Third Edition, SFPE, Quincy, MA, 2002.
11. Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations, NFPA, Quincy MA, NFPA 850, 2005.

APPENDIX A: PIRT FIRE SCENARIO 1

A.1 Scenario 1 Description

PIRT Fire Scenario 1 is a postulated main control room (MCR) control cabinet fire for a two-unit NPP. This control room complex is a defined fire area per the plant fire protection program and is shared by the two units shown in Figure A.1. The dimensions of the overall fire area are 37.8 m (124 ft) by 17 m (57 ft) with a ceiling height of 5.2 m (17 ft). The operational portion of the main control room (MCR) has dimensions of 24 m (80 ft) by 16 m (53 ft). The balance of the fire area is comprised of other general support areas (described further below). The room is poured reinforced concrete from slab to slab. There is a dropped ceiling that is 3 m (10 ft) above the floor. The purpose of the dropped open-grated ceiling (shown in Figure A.4) is to give the operators an office-like setting. There is lighting above and below the dropped ceiling. The floor is covered with carpet with a flame rating of less than 25 as measured by ASTM E-84[1]. The fire area boundaries (walls, floor and ceiling) are 1 m (3 ft) thick reinforced poured concrete with a three hour fire endurance rating. The inside west wall is 0.3 m (1 ft) thick concrete and the other interior partition walls are 0.02 m (5/8 in) gypsum covering the steel studs. These interior partition walls are not specifically fire rated.

Typically there are many electrical cabinets in the MCR. These electrical cabinets serve a range of instrumentation, indication, and control functions required for operation of the plant. These cabinets are arranged in a two-unit double horseshoe, a set of “back panels” generally associated with balance of plant (BOP) equipment, and typical office equipment like computers and desks. A computer generated example is shown in Figure A.2. The cabinet depicted in red in Figure A.1, is where the fire is postulated. An example of the type of cabinet where the fire is postulated is shown in Figure A.3. The cabinet is a low voltage (<600V) control cabinet behind the main control panels on the west side of the room (a back panel). The fire is assumed to be initiated by an electrical failure in the cabinet.

The plant controls are analog (rather than digital) since the plant is assumed to be based on technology from the 1960s and ‘70s as used by the existing U.S. nuclear power plants (NPP). An example of an analog control board is shown in Figure A.5.

There are other gypsum partition assemblies within the control room complex. The control room is occupied by operators on a continuous basis. The control room is manned 24 hours a day, 7 days a week, 365 days a year by shift workers. Because of this, the other partitioned areas consist of an office space, a small kitchenette, a locker room and a restroom. The kitchenette typically has a small stove, coffee pot, microwave oven among other conventional items.

There are smoke detectors above and below the open-grate ceiling. For this postulated scenario, the control room does not have any fixed suppression (i.e. no fixed sprinklers, CO_2, halon systems, etc.). Fire suppression would involve the use of portable hand-held fire extinguishers and, if necessary, use of manual hose streams provided by the plant fire brigade. At least one operator on each shift is typically a member of the fire brigade. The ventilation is 57

[1] ASTM Standard E 84, 2007a, “Test Methods for Surface Burning Characteristics of Building Materials,” ASTM International, West Conshohocken, PA, www.astm.org.

cubic meters per minute (2,000 cfm) which is provided by a 0.6 m (2 ft) by 0.6 m (2 ft) diffuser 3 m (10 ft) above the floor through the drop ceiling; 120 Pa (0.02 psi) over-pressure is maintained in the MCR for the purposes of general environmental protection. The over-pressure ensures that leakage goes outward away from the MCR instead of inwards. A smoke purge system can be manually actuated if necessary and will provide ventilation of 283 cubic meters per minute (10,000 cubic feet per minute or about 12 air changes a minute).

The figure of merit for this scenario is the operators and forced abandonment of the MCR. That is, what phenomena are necessary to model this abandonment scenario? How important are the phenomena in the context of fire model predictions of MCR habitability to the humans during the fire scenario? On abandonment, operators would transfer control to an alternate shutdown panel containing a minimum set of equipment that is typically located a few floors below or in a separate area from the MCR. The operators do have self-contained breathing apparatuses (SCBA) and are trained to use them.

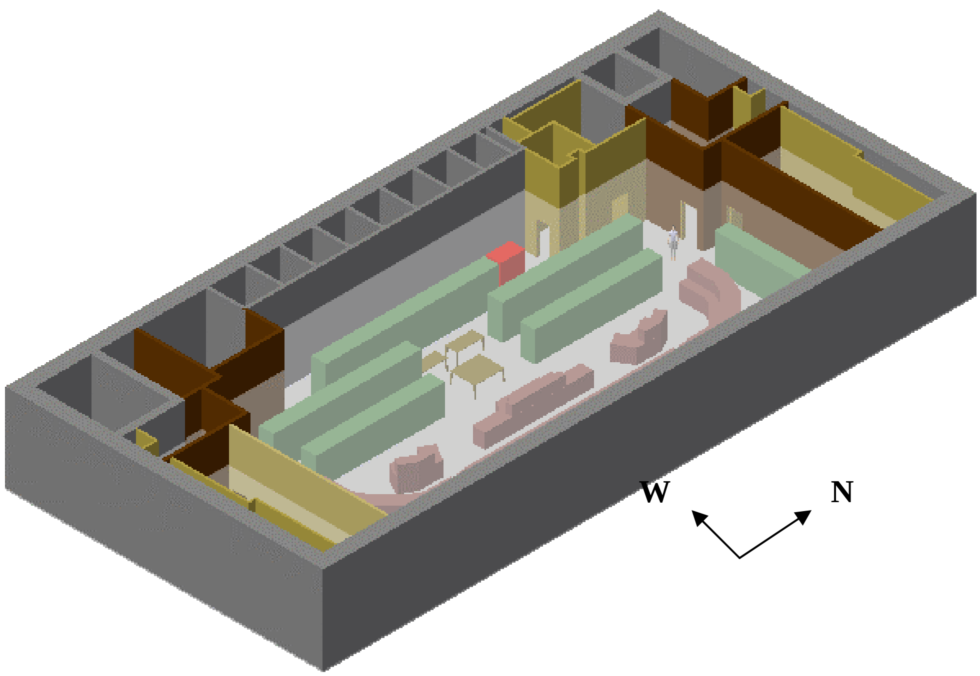


Figure A.1: Generic Main Control Room Layout

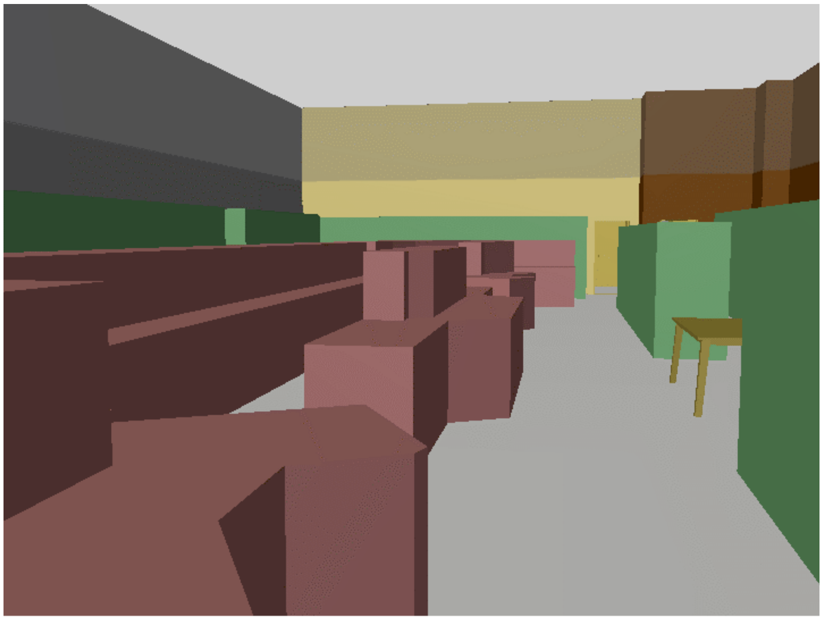


Figure A.2: Generic Main Control Room Office Equipment Layout

Figure A.3: Example of a Cabinet inside the Main Control Room

Figure A.4: Example of a Grated Ceiling Found in Main Control Room

Figure A.5: Example of an Analog Control Panel in a Main Control Room

A.2 Scenario 1 Phenomena Identification

The list of phenomena identified for this scenario will be discussed. The Panelists identified groupings of phenomena which included sub phenomena. The order of the groups of phenomena does not indicate the level of importance. Below the phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *predicting detection response for detectors below the open-grate ceiling*.

A. The general process of fire detection; specifically, how the characteristics of the fixed fire detection system would influence this phenomenon.

B. The actual response of smoke detectors to the fire (i.e., as related to modeling detector response).
C. Buoyant flow induced by the fire given the ceiling configuration (e.g., the open-grate ceiling and other potential obstructions such as beam pockets).

Phenomenon 2: *predicting detection response for detectors on the hard upper ceiling*. (The hard ceiling is the upper concrete ceiling.)

A. The general process of fire detection; specifically, how the characteristics of the fixed fire detection system would influence that phenomenon.
B. The actual response of smoke detectors to the fire (i.e., as related to modeling detector response).
C. Buoyant flow induced by the fire given the ceiling configuration (e.g., the open-grate ceiling and other potential obstructions such as beam pockets).

Phenomenon 3: *Predicting room conditions/response* is the next group of phenomena.

A. The effects of communication (i.e., through open doorways) between spaces within the 3 hour boundary.
B. The forced air flow configuration for the general control room and its effect on the development of the fire environment.
C. The buildup of combustion products within the room leading to reduction in visibility.
D. The development of an adverse temperature environment within the room.
E. The process of radiant heat from the fire source that might impact the operators (i.e., radiant heat from the fire source impinging on people nearby).
F. The process of smoke filling for the MCR; specifically, in light of the ventilation configuration.
G. The process of manual fire suppression, specifically, as related to the effectiveness, timing, and level of control of the fire.
H. The ceiling jet behavior as it relates to the fire source plume.

Phenomenon 4: *heat transfer to the surfaces* within the MCR

A. Heat transfer to the room walls.
B. Heat transfer to the floor, specifically near the fire source.
C. Heat flux to the floor, specifically away from the fire source.
D. Heating of surfaces in the room other than the walls and floor, specifically as it might impact re-radiation to the operators.
E. Heat transfer to the panels that bound the source fire electrical cabinet.
F. The open-grate ceiling's influence on fire phenomena; specifically, including both the open-grate material as a potential fuel and the potential effects on the plume, hot gas layer, and/or smoke mixing behaviors.

Phenomenon 5: *characterizing fire spread* as it relates to this specific scenario.

A. Fire spread among the content of the source cabinet.
B. Fire Spread on the floor (near the fire source).
C. The potential burning behavior of the open-grate ceiling material and its role as a fuel.

Phenomenon 6. *Characterizing the Fire Source*

A. The development of the fire in the cabinet as characterized by its overall burning rate (i.e., total heat release rate (HRR)).

B. Air flow within and through the burning electrical cabinet; specifically, the effects of the ventilation openings, open versus closed doors, ventilation opening size, etc., on this behavior.
C. The transition of the fire from the incipient (pre-open-flaming) stage to open burning.
D. The transition of the fire from the opening flaming stage to the smolders (natural burnout).
E. Fire behavior during that stage of the fire that precedes the open flaming behavior (i.e., the non-flaming or incipient stages of combustion).
F. The fire behavior during the smoldering (post-open-flaming or natural burnout) stages of the fire.
G. The fire behavior/characteristics during the open flaming period.
H. Fire spread beyond the cabinet of fire origin.
I. The potential behaviors that might be associated with oxygen starvation/re-flash of the fire (i.e., oxygen limited burning or apparent burnout followed by re-flash, if the panel doors are opened).
J. The release of heat by the fire radiatively (as opposed to convectively).
K. The plume/flame behavior for the cabinet fire; specifically, as compared to the plume/flame behavior observed from an open fire.
L. The ventilation flow within and through the source cabinet; specifically, inlight of the potential for gross changes that might result from structural effects or deformation of the cabinet boundary panels.

Phenomenon 7: *generation of fire/combustion products*

A. The generation of smoke particulate during the open flaming stages of the fire.
B. The generation of acid gases during the open flaming stage of the fire.
C. The generation of hydrogen cyanide, (HCN) during the open flaming stages of the fire.
D. The generation of carbon monoxide, (CO) during the open flaming stages of the fire.
E. The generation of smoke particulate during the pre-combustion (incipient or pre-open flaming) stages of the fire.
F. The generation of acid gases during the pre-combustion (incipient or pre-open flaming) stages of the fire.

Phenomenon 8: *predicting operator behaviors*.

A. Radiant heating; specifically, the delivery of radiant heat flux to the operators.
B. The process of humans sensing the fire (i.e., human detecting the fire).
C. Operators' response to the fire and the impact of the fire on the decision making process.

A.3 Scenario 1 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table A.1. The listed phenomena with their importance rankings are shown in Table A.1 through Table A.16.[2] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to

[2] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using a randomly assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table A.1: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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 A.2: Importance Ranking for Scenario 1, Predicting Detection Response for Detectors below the Open-Grate Ceiling

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Predicting Detection Response for Detectors below the Open-Grate Ceiling								The panel assumed that the smoke detectors were the common photoelectrical type detectors.
A. The General Process of Fire Detection	L	X	M	M	M	L	L	The panel based their ranking on assuming that the operators will detect a fire before a smoke detector since the MCR is continuously manned. The order of detection and the time interval between was the issue.
B. The Actual Response of Smoke Detectors to the Fire	L	X	M	M	M	L	L	
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	L	X	M	M	M	L	L	

Table A.3: Importance Ranking for Scenario 1, Predicting Detection Response for Detectors on the Hard Upper Ceiling

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling								
A. The General Process of Fire Detection	L	X	M	M	M	L	L	Panelist 4's medium ranking is based on that the time period between nose detection versus automatic detection is so small relative to the overall time. Also because of the uncertainty of human reliability; a person will wait for assurance from the detector going off. Panelist 7, Panelist 6, and Panelist 1's low rankings are based on the scenario specifics of the MCR being continuously manned with at least 5 operators. From this they are assuming an operator will detects the fire.
B. The Actual Response of Smoke Detectors to the Fire	L	X	M	M	M	L	L	Same as above
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	L	L	M	M	M	L	L	The panel wanted to be clear that these importance rankings are based on the scenario specification of the fire located in a cabinet and not in the overhead.

Table A.4: Importance Ranking for Scenario 1, Predicting Room Conditions/Response (1 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Room Conditions/Response								This group of phenomena is specific to predicting the overall control room environment.
A. Communication Between Spaces within the 3-hour Rated Boundary	M	X	L	M	M	L	L	This phenomenon is more specific to the airflows between these opening in the control room. Panelists 7's justification for their low importance ranking is that the added space is a relatively small volume compared to the entire control compartment for this scenario.
B. Forced Air Flow Configuration for the General Control Room	H	X	H	H	H	M	H	The panel's reasoning for the high importance ranking is that this phenomenon will govern the temperature rise in the room and with strongly define the smoke layer.
C. Predicting the Buildup of Combustion Products within the Room	H	X	H	H	H	H	H	The panel's high importance raking is justified as being directly related to one of the abandonment criteria specific to this scenario. Panelist 3 adds assuming that the control room operators are highly motivated for a successful outcome; they will put on SCBA during the fire event. Therefore, the operators will remain in the control room as long as they can effectively perform their duties even in reduced visibility. Assuming that a cabinet fire could produce a significant reduction in visibility that would impair the ability to control the reactor, a suitable ranking is high. The operators may also have to leave the MCR if they can not perform their duties because the SCBA mask has soot depositing on the surface faster than they can keep it clean.

Table A.5: Importance Ranking for Scenario 1, Predicting Room Conditions/Response (2 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Room Conditions/Response (Cont.)								This group of phenomena is specific to predicting the overall control room environment.
D. The development of an adverse temperature environment within the room	M	X	M	M	M	H	M	Panelist 6's justification for a high importance rating is that this phenomenon is directly related to one of the abandonment conditions for this scenario. Panelist 1 does not think temperature will be the limiting condition but smoke concentration will, justifying their medium importance ranking.
E. The process of radiant heat from the fire source that might impact the operators (i.e., radiant heat from the fire source impinging on people nearby)	L	X	L	L	M	L	L	The panel mentioned that predicting the heat flux from the fire source to human (skin) depends on how close the cabinet (fire location) is to where the operator works.

Table A.6: Importance Ranking for Scenario 1, Predicting Room Conditions/Response (3 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Room Conditions/Response (Cont.)								
F. Smoke Filling	H	X	H	H	H	H	H	The panel does not feel like the two-layer model (hot gas layer model) will apply to the smoke filling phenomenon for this scenario. They agree that the mixing behavior of the ventilation is the key factor that is unique to this scenario. The effects of forced ventilation, such as that defined for the panel, on smoke mixing behavior was expected to be significant especially once the smoke layer reaches the level of the ventilation inlet diffusers (which were specified as facing downward).
G. Effectiveness, Timing and Level of Control of the Manual Fire Suppression.	H	X	H	H	U	H	H	
H. Ceiling Jet Behavior	M	X	L	L	L	L	M	Panelist 7's basis for the medium importance ranking is that the ceiling jet behavior influences the smoke filling. Panelist 1's basis for the medium importance ranking is that if the prediction of the ceiling jet behavior is wrong then it will affect the thermodynamics. Panelist 4's basis for a low importance ranking is the ceiling jet behavior is a minor effect compared to all the other larger effects.

Table A.7: Importance Ranking for Scenario 1, Heat Transfer to Surfaces (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Heat Transfer to Surfaces								
A. Heat Transfer to the Room Walls	L	X	L	L	L	L	L	The panel agrees on the low importance ranking due to the fact that the heat transfer to the room walls is not going to drive the humans out of the control room. The panel mentions that, by the time the heat transfer to the walls becomes a dominant factor, environmental conditions will be much worse.
B. Heat Transfer to the Floor (near the fire source)	L	X	L	H	H	H	H	Panelist 1's basis for the low importance ranking is that the operators will have evacuated before this phenomenon has a significant impact. Panelist 6's basis for a high importance ranking is that the carpet will produce a lot of smoke when it ignites. Panelist 7's high ranking basis is that the carpet is fuel. The difference in rankings here is based on the threshold of when this phenomenon will be important.
C. Heat Flux to the Floor, Specifically, away from the Fire Source	L	X	L	L	L	L	L	The panel agrees on the low importance ranking because the control room will have been evacuated before this phenomenon is an issue.

Table A.8: Importance Ranking for Scenario 1, Heat Transfer to Surfaces (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Heat Transfer to Surfaces (cont.)								
D. Heating of Surfaces in the Room other than the Walls and Floor	L	X	L	L	L	L	L	Specifically the heating of all the contents in the room besides the walls, floor, and ceiling.
E. Heat Transfer to the Panels that Bound the Source Fire Electrical Cabinet	M	X	M	M	M	M	M	This phenomenon is specific to the panels housing the source cabinet. Panelist 1's basis for the medium importance ranking is that the heat transfer to the panels that bound the cabinet will affect the thermal environment of the early fire which will affect everything down stream. The rest of the panel members agree.
F. The Open-Grate Ceilings Influence on Fire Phenomena	H	X	H	H	U	H	U	The justification for the high importance ranking is that the role of the open-grate ceiling in fire phenomenon is related to fire propagation, fire spread, and mixing.

Table A.9: Importance Ranking for Scenario 1, Characterizing Fire Spread

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Characterizing Fire Spread								
A. Fire Spread Among the Contents of the Source Cabinet	L	X	L	L	L	L	L	The panel's basis for the low importance ranking is assuming that the overall HRR has already been characterized. This makes the details of the spread of fire in the cabinet a low importance. Panelist 5 adds that this phenomenon is low because it is hard to characterize and it is ventilation controlled. Panelist 4 mentions that the burning rate is more important than knowing how the flame spreads in the cabinet.
B. Fire Spread on the Floor (near the fire source)	L	L	L	H	H	M	H	The panel members who ranked the importance high is based on the flame spread along the carpeted floor being strongly correlated to the heat flux to the floor.
C. The Potential Burning Behavior of the Open-Grate Ceiling Material and its Role as a Fuel	H	X	L	H	H	H	H	The panel's basis for the high importance ranking is that the open-grate ceiling is plastic and thermally thin. Panelist 3's low ranking is based on ignition and fire spread specific to the scenario; like the carpet, the ignition of new deposits of solidified or liquid plastic on the floor and on equipment would be under conditions that would be untenable for control room operators.

Table A.10: Importance Ranking for Scenario 1, Characterizing the Fire Source (1 of 4)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Characterizing the Fire Source								
A. Overall Burning Rate of the Cabinet (i.e. total HRR)	H	X	H	H	H	H	H	The panel's basis for the high importance ranking is that the burning rate of the cabinet is the driving factor in the fire model.
B. Air Flow within and through the Burning Cabinet	H	X	H	H	H	H	H	Specifically, the effects of the ventilation openings, open versus closed doors, ventilation opening size, etc., on this behavior The panel's high importance ranking is based on that the ventilation of the cabinet is the driving factor for the burning rate. As mentioned above the panel states that the burning rate is the driving factor for the fire model. This phenomenon was specific to the effects of the ventilation openings, open versus closed doors, ventilation opening size, etc.
C. The Transition of the Fire from the Incipient (Pre-Open-Flaming) Stage to Open Flaming	H	X	H	H	H	H	M	The basis for the high importance rankings are that this transition will establish time zero. Panelist 7's basis for the medium importance ranking is that the open flame characteristics are more important that establishing time zero.

Table A.11: Importance Ranking for Scenario 1, Characterizing the Fire Source (2 of 4)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Characterizing the Fire Source (Cont.)								
D. The Transition of the Fire from the Open Flaming Stage to Smolders (Natural Burnout)	L	X	L	L	L	L	L	
E. Fire Behavior During that Stage of the Fire that Precedes the Open Flaming Behavior (i.e., the Non-Flaming or Incipient Stages of Combustion)	U	X	L	L	H	L	L	Panelist 5's basis for a high importance ranking is that this stage is longer so it is important for risk assessment. The panel's ranking here was impacted by the way the Scenario and merit were defined. The panel agrees that this is important to the overall time line but it is not what is going to drive the operator out of the room.
F. The Fire Behavior during the Smoldering (Post-Open-Flaming or Natural Burnout) Stages of the Fire	L	X	L	L	L	L	L	Panelist 7's basis for a low importance ranking is that if there is no trouble up to this point, then the tail end of the scenario is not as important. Panelist 4 also includes that the environmental effect will be low.

Table A.12: Importance Ranking for Scenario 1, Characterizing the Fire Source (3 of 4)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Characterizing the Fire Source (Cont.)								
G. The Fire Behavior/Characteristics during the Open Flaming Period	H	X	H	H	H	H	H	The high importance rankings based on that this phenomenon is fundamental to the burning rate.
H. Fire Spread Beyond the Cabinet of Fire Origin	H	X	H	H	H	H	H	The panel agrees on a high importance ranking because if this phenomenon comes into play it will be of very high importance. Understanding whether or not it happens is really important.
I. The Potential Behaviors that might be Associated with Oxygen Starvation/Re-Flash of the Fire	H	X	H	H	H	H	H	The panel agrees on a high importance ranking for this phenomenon. Panelist 7 mentions that this is a real hazard that needs to be understood.
J. The Release of Heat by the Fire Radiatively (as Opposed to Convectively)	H	X	H	H	H	H	H	The panel agrees on a high importance ranking. Panelist 4 mentions that the radiative HRR of the fire is robust enough to use values in the literature. Panelist 1 mentions that the radiative fraction will vary only in extreme cases, and that this scenario will not have these extreme cases.

Table A.13: Importance Ranking for Scenario 1, Characterizing the Fire Source (4 of 4)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Characterizing the Fire Source (Cont.)								
K. The Plume/Flame Behavior for the Cabinet Fire	L	X	H	H	M	H	M	Panelist 1's basis for a low importance ranking is that there is a low ability to influence the model outcome by varying this phenomenon. Panelist 1 assumed this phenomenon does not include the HRR but instead it includes more of the structure and fire dynamic effects that affect the shape. This has very little influence on the model if the user has correctly input the HRR. Panelists 7's basis for the high importance ranking is that this phenomenon characterizes the fire behavior, the entrainment, and the spill fire outside the cabinet. Panelist 7 also mentions that this phenomenon is important to fire spread and it might have an effect on the open-grated ceiling.
L. The Ventilation Flow within and through the Source Cabinet	H	X	H	H	H	H	H	The panel defined this phenomenon to clarify that a specific intent was specified, "gross change" that might result from structural effects or deformation of the cabinet boundary panels.

Table A.14: Importance Ranking for Scenario 1, The Generation of Fire/Combustion Products (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
7. The Generation of Fire/Combustion Products								
A. Smoke Particulate during the Open Flaming Stages of the Fire	H	H	H	H	H	H	H	
B. Acid Gases During the Open Flaming Stages of the Fire	H	L	L	H	H	H	H	Panelist 1's ranking is high because this phenomenon can have a large impact on the electronics.
C. HCN during the Open Flaming Stages of the Fire	M	L	L	H	H	H	M	Panelist 1's basis for the medium importance ranking is that this scenario may not have materials that produce HCN. If this phenomenon is an issue then it is going to have a major impact. Some materials that produce HCN can be those with nitrogen either in the base resin itself or as a major additive to the resin, such as nylon and Kapton.

Table A.15: Importance Ranking for Scenario 1, The Generation of Fire/Combustion Products (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
7. The Generation of Fire/Combustion Products (Cont.)								
D. Production of CO during the Open Flaming Stages of the Fire	H	L	L	H	H	H	H	Panelist 7 ranked this higher than the HCN because CO production is more common. The panel would like it to be known that all these products are important; these importance rankings are based on the specified scenario. The difference between the low and high rankings is that the low's were based on that the SCBA is effective. Panelists 1's ranking is high because they do not give credit to the procedure on SCBA. Panelist 4's agrees with Panelists 1; if the SCBA fails they want to know how much CO is present in the room. Panelist 6 does not credit the SCBA and is interested to know what the environment is like before the SCBA is put on.
E. Production of Smoke Particulate during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	H	H	H	H	H	H	H	
F. Production of Acid Gases during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	L	L	L	L	L	L	L	Panelist 1 questions the assertion that the operators would put on their SCBA gear.

Table A.16: Importance Ranking for Scenario 1, Predicting Operator Behaviors

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
8. Predicting Operator Behaviors								
A. Delivery of Radiant Heat Flux to Operators	M	X	L	M	M	M	M	This phenomenon is specific to the radiant heating from the fire to the operators. The basis for the medium importance rankings are based on that this phenomenon is a secondary effect and the operator is able to move.
B. The Process of Humans Sensing the Fire (i.e., human detecting the fire)	H	X	M	M	M	H	H	Panelist 1's basis for a high importance ranking is that this phenomenon will start the chain of events. Panelists 6's basis for a high importance ranking is the relevance this phenomenon has to time. Panelist 4's basis for a medium importance ranking is their bias as an engineer who tries to weed out human behavior. Panelist 4 thinks more effort should be put towards the mechanical sensors.
C. Operators' Response to the Fire and the Impact of the Fire on the Decision Making Process	H	X	H	H	H	H	H	The panel identified this phenomenon as a critical factor in the overall fire development/timeline/scenario that lies outside the current traditional fire modeling tools as applied to NPP applications. For NPP applications this is deferred to human reliability analysis (HRA).

A.4 Scenario 1 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge for the phenomena is assessed. For this stage of the PIRT, the panel ranks the state of knowledge as a group (rather than as individuals). The panel aimed for consensus but in some cases one or more Panelists disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table A.20 through Table A.31 are the state of knowledge rankings for the identified phenomena for Scenario 1.

The Panelists were asked to evaluate five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First is the general adequacy of the existing and generally available[3] fire models with predicting the identified phenomena. The second are the adequacy of data needed to support model development and model validation in addition to the feasibility of obtaining new data. The issue of feasibility was not pursued for phenomena where the existing data availability was ranked "high."

The list below is the five state of knowledge parameters and cites the table that shows the definitions of each ranking.

1. Model Adequacy (Table A.17)
2. Available Input Data (Table A.18)
3. Feasibility of Getting New Input Data (Table A.19)
4. Available Data for Validation (Table A.18)
5. Feasibility of Getting New Validation Data (Table A.19)

This section also identifies key parameters associated with the scenario phenomena and may be illustrated in Table A.32 through A.40. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., the importance of key parameters in the context of the associated phenomenon and the corresponding state of knowledge).

[3] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table A.17 Model Adequacy Ranking Definitions

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 completed. 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 A.18 Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., validation grade data set) exists, or a highly reliable assessment can be made based on existing knowledge. The 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 A.19 Data Adequacy for Potential to Develop New Data Rankings Definitions

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.

Table A.20: State of Knowledge Ranking for Scenario 1, Predicting Detection Response for Detectors below the Open-Grate Ceiling

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
1. Predicting Detection Response for Detectors below the Open-Grate Ceiling						
A. The General Process of Fire Detection	NA[4]	H	NA	NA	NA	The importance rankings for this phenomenon were low, so these rankings were not analyzed due to the large disparity between the Panelists.
B. The Actual Response of Smoke Detectors to the Fire	L-M	L	L	L	H	Panelist 7's model adequacy ranking is medium. The rest of the panel's low rankings are due to the unavailability of models that can deal with the early development of fires that start small. The physical variables associated to fires and detection can be tracked, but it is the hardware response that is not well characterized.
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	H	H	NA	L-M	H	The L-M ranking for available validation data was a consensus for all panelists.

[4] The Non-Applicable (NA) ranking is either explained in the notes column or if the ranking for the available input or available validation data is high then the feasibility of obtaining new data was not necessary to rank.

Table A.21: State of Knowledge Ranking for Scenario 1, Predicting Detection Response for Detectors on the Hard Upper Ceiling

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling						
A. The General Process of Fire Detection	NA	H	NA	NA	NA	
B. The Actual Response of Smoke Detectors to the Fire	L-M	L	L	L	H	Panelist 7's model adequacy ranking is medium. The rest of the panel's low model adequacy ranking is due to the unavailability of models that can deal with the early development of fires that start small.
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	H	H	NA	L-M	H	For the available data for validation of models, the L to M ranking was a consensus among the panel.

Table A.22: State of Knowledge Ranking for Scenario 1, Predicting Room Conditions/Response (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
3. Predicting Room Conditions/Response						
A. Communication Between Spaces within the 3-hour Rated Boundary	H	H	NA	H	NA	
B. Forced Air Flow Configuration for the General Control Room	M	H	NA	M	M	Panelist 4 mentions that a growing fire with the interaction of opposed flow is not handled well. Panelist 5 agrees there is nothing in FDS and CFAST that can model the interaction between the fire and ventilation. At minimum FDS can handle ventilation without diffusers.
C. Predicting the Buildup of Combustion Products within the Room	H	H (L)	H	M	H	The panel agrees on a high model adequacy ranking with the exception of the understanding of smoke yield. The understanding of smoke yield is reflected in the table under the available input data, this would be ranked low.

Table A.23: State of Knowledge Ranking for Scenario 1, Predicting Room Conditions/Response (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
3. Predicting Room Conditions/Response (Cont.)						
D. The development of an adverse temperature environment within the room.	H	H	NA	H	NA	
E. The process of radiant heat from the fire source that might impact operators (i.e. radiant heat from the fire source impinging on people nearby)	H	H	NA	H	NA	
F. Smoke Filling	H	H	NA	M	M	
G. Effectiveness, Timing and Level of Control of the Manual Fire Suppression.	L	L	L	L	L	
H. Ceiling Jet Behavior	H	H	NA	H	NA	

Table A. 24: State of Knowledge Ranking for Scenario 1, Heat Transfer to Surfaces (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
4. Heat Transfer to Surfaces						
A. Heat Transfer to the Room Walls	H	H	NA	L	H	
B. Heat Transfer to the Floor (near the fire source)	H	H	NA	H	NA	
C. Heat Flux to the Floor, Specifically, away from the Fire Source	H	H	NA	H	NA	
D. Heating of Surfaces in the Room other than the Walls and Floor	H	H	NA	H	NA	
E. Heat Transfer to the Panels that Bound the Source Fire Electrical Cabinet	M	H	NA	H	NA	The boundary conditions put into the model will bound this phenomenon.
F. The Open-Grate Ceilings Influence on Fire Phenomena	L	L	H	L	H	

Table A.25: State of Knowledge Ranking for Scenario 1, Characterizing Fire Spread

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
5. Characterizing Fire Spread						
A. Fire Spread Among the Contents of the Source Cabinet	L	L	L	L	L	
B. Fire Spread on the Floor (near the fire source)	M	M	H	M	H	
C. The Potential Burning Behavior of the Open-Grate Ceiling Material and its Role as a Fuel	L	L	M	L	L	The melting of the open-grate ceiling is very difficult to model. Getting rid of the problem (open-grate) might be more feasible than doing research to address the concern.

Table A.26: State of Knowledge Ranking for Scenario 1, Characterizing the Fire Source (1 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
6. Characterizing the Fire Source						
A. Overall Burning Rate of the Cabinet (i.e.., total HRR)	M	M	H	L	H	There was mention of some cabinet fire tests done in France[5].
B. Air Flow within and through the Burning Cabinet	M	H	NA	L	H	
C. The Transition of the Fire from the Incipient (pre-open-flaming) Stage to Open Flaming	L	L	M	L	M	The feasibility of getting new input data was ranked medium because multiple experiments can be performed; however, due to the large amount of uncertainty the experimental work could be costly. The medium ranking for the feasibility of getting new validation data was ranked medium because of the large variation with the components within the cabinet. Because of this multiple experiments will be needed for validation purposes.

[5] Rigollet, Laurence and Melis, Stéphane, Fires of Electrical Cabinets, IRSN Institut de Radioprotection et de Sûreté Nucléaire, The 11th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, 2005.

Table A.27: State of Knowledge Ranking for Scenario 1, Characterizing the Fire Source (2 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
6. Characterizing the Fire Source (Cont.)						
D. The Transition of the Fire from the Opening Flaming Stage to Smolders (natural burnout)	M	M	H	L	H	There is a large uncertainty with the burnout time. The probabilistic model has used all the available data.
E. Fire Behavior during that Stage of the Fire that Precedes the Open Flaming Behavior (i.e., the non-flaming or incipient stages of combustion)	L	L	H	L	H	
F. The Fire Behavior during the Smoldering (post-open-flaming or natural burnout) Stages of the Fire	L	L	H	L	H	
G. The Fire Behavior/Characteristics during the Open Flaming Period	L	L	L	L	L	

Table A.28: State of Knowledge Ranking for Scenario 1, Characterizing the Fire Source (3 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
6. Characterizing the Fire Source (Cont.)						
H. Fire Spread Beyond the Cabinet of Fire Origin	L	L	M	L	M	The feasibility of getting new input data is medium if it is outside the structure versus cabinet to cabinet spreading. In the latter case it would be ranked as low. For new validation data, some are easier to than others.
I. The Potential Behaviors that might be Associated with Oxygen Starvation/Re-Flash of the Fire	L	L	H	L	H	
J. The Release of Heat by the Fire Radiatively (as opposed to convectively)	H	H	NA	H	NA	The rankings assume that the total HRR is known.
K. The Plume/Flame Behavior for the Cabinet Fire;	L	L	H	L	H	The low state of knowledge rankings are based on that the boundary conditions are unknown for this phenomenon.
L. The Ventilation Flow within and through the Source Cabinet	L	L	L	L	H	

Table A.29: State of Knowledge Ranking for Scenario 1, The Generation of Fire/Combustion Products (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
7. The Generation of Fire/Combustion Products						The panel has assumed the HRR has already been characterized for all phenomena under "The Generation of Fire/Combustion Products".
A. Smoke Particulate During the Open Flaming Stages of the Fire	M	L	M	L	L	Assuming the HRR has already been characterized, availability of input data is low because of the materials that are being analyzed in this scenario.
B. Acid Gases during the Open Flaming Stages of the Fire	L	L	M	L	M	
C. HCN during the Open Flaming Stages of the Fire	L	L	M	L	M	
D. CO during the Open Flaming Stages of the Fire	M	M	M	M	M	

Table A.30: State of Knowledge Ranking for Scenario 1, The Generation of Fire/Combustion Products (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
7. The Generation of Fire/Combustion Products (Cont.)						The panel has assumed the HRR has already been characterized for all phenomena under "The Generation of Fire/Combustion Products".
E. Smoke Particulate during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	L	L	M	L	L	
F. Acid Gases during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	L	L	H	L	H	

Table A.31: State of Knowledge Ranking for Scenario 1, Predicting Operator Behaviors

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data	
8. Predicting Operator Behaviors						
A. The Delivery of Radiant Heat Flux to Operators	H	H	NA	H	NA	
B. The Process of Humans Sensing the Fire (i.e., human detecting the fire)	L	L	L	L	L	
C. Operators' Response to the Fire and the Impact of the Fire on the Decision Making Process	U	U	U	U	U	

Table A.32: Key Parameters and Their Rankings for Scenario 1, Predicting Detection Response for Detectors below the Open-Grate Ceiling

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Predicting Detection Response for Detectors Below the Open-Grate Ceiling				
A. The General Process of Fire Detection	grid spacing of detectors	H	H	
	location relative to ventilation ducts	H	H	
	location of detector (s) relative to fire	H	H	
	detector type	M	H	For this scenario smoke detectors were specified.
B. The Actual Response of Smoke Detectors to the Fire	sensitivity of detectors	L	L	The panel's basis for a low state of knowledge was because of a very narrow range of sensitivity available. Within that range, one will not know the sensitivity of a particular detector.

Table A.33: Key Parameters and Their Rankings for Scenario 1, Predicting Detection Response for Detectors on the Hard Upper Ceiling (1 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling				
A. The General Process of Fire Detection	grid spacing of detectors	H	H	
	location relative to ventilation ducts	H	H	
	location of detector (s) relative to fire	H	H	
	detector type	M	H	For this scenario smoke detectors were specified.
B. The Actual Response of Smoke Detectors to the Fire	sensitivity of detectors	L	L	The panel's basis for a low state of knowledge was because of a very narrow range of sensitivity available. Within that range, one will not know the sensitivity of a particular detector.

Table A.34: Key Parameters and Their Rankings for Scenario 1, Predicting Detection Response for Detectors on the Hard Upper Ceiling (2 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling (Cont.)				
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	ceiling characteristics-flat vs. beam pockets	H	M	
	other ceiling obstructions	L-H	L	The panel's importance ranking L to H is dependant on the density of the obstructions. This would cover the types of obstructions that are not typically resolved in modeling, specifically cable trays, pipes etc. The low to high importance ranking is based the amount of obstructions (i.e. if you have one cable (low) versus a ton of cables (high)).

Table A.35: Key Parameters and Their Rankings for Scenario 1, Predicting Room Conditions/Response

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
3. Predicting Room Conditions/Response				
C. Predicting the Buildup of Combustion Products within the Room	specific extinction coefficient	H	M	
F. Smoke Filling	ventilation conditions for room	H	H	

Table A.36: Key Parameters and Their Rankings for Scenario 1, Heat Transfer to Surfaces

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
4. Heat Transfer to Surfaces				
B. Heat Transfer to the Floor (near the fire source)	type of carpet	H	H	
E. Heat Transfer to the Panels that Bound the Source Fire Electrical Cabinet	characterizing the cabinet boundaries	H	H	
F. The Open-Grate Ceilings Influence on Fire Phenomena	define plastic ceiling	H	L	

Table A.37: Key Parameters and Their Rankings for Scenario 1, Characterizing the Fire Source (1 of 3)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
6. Characterizing the Fire Source				
A. Overall Burning Rate of the Cabinet (i.e., total HRR)	characterizing cabinet contents relative to combustibility	H	H-L	The panel's ranking for state of knowledge is high for cables and low for anything else.
	fire growth correlation choice	H	M	
	location of where the fire starts in the cabinet	H	L	The panel's high importance ranking is when the cabinet is open or well ventilated.
B. Air Flow within and through the Burning Cabinet	characterizing the cabinet boundaries	H	H	

Table A.38: Key Parameters and Their Rankings for Scenario 1, Characterizing the Fire Source (2 of 3)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
6. Characterizing the Fire Source (Cont.)				
H. Fire Spread Beyond the Cabinet of Fire Origin	characterizing the cabinet boundaries	H	H	
	pathway of cables as a mechanism for fire spread	H	H	
	fire spread to the carpet	L	M	
	fire spread horizontally to other cabinets	H	M	
	fire spread down cables	M	L	The importance ranking of medium by the panel is based on that the importance is higher for thermo-plastic cables and lower for thermo-set cables.
	fire spread overhead	H	L	The panel's basis for a low state of knowledge for this parameter based on that there is a wide variety of "things" overhead.

Table A.39: Key Parameters and Their Rankings for Scenario 1, Characterizing the Fire Source (3 of 3)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
6. Characterizing the Fire Source (Cont.)				
J. The Release of Heat by the Fire Radiatively (as opposed to convectively)	radiative fraction	H	H	
K. The Plume/Flame Behavior for the Cabinet Fire	plume correlations	H	H	
	placement of fire for modeling purposes	H	L	

Table A.40: Key Parameters and Their Rankings for Scenario 1, The Generation of Fire/Combustion Products

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
7. The Generation of Fire/Combustion Products				
A. Smoke Particulate during the Open Flaming Stages of the Fire	species yield	H	M	
B. Acid Gases during the Open Flaming Stages of the Fire	species yield	H	M	
C. HCN during the Open Flaming Stages of the Fire	species yield	H	M	
D. CO during the Open Flaming Stages of the Fire	species yield	H	M	
E. Smoke Particulate during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	species yield	H	L	
F. Acid Gases during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	species yield	H	L	

A.5 Scenario 1 PIRT Analysis and Summary

This section includes the analysis and summary of the PIRT findings for Scenario 1. The phenomena and their rankings were analyzed using four criteria that will be presented here. The Level 1 phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table A.41 through Table A.43. The Level 2 phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table A.44 through Table A.45. The Level 3 phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. There is one sub-phenomenon for this level and it is shown in Table A.46. The Level 4 phenomena are those that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking, or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table A.47 through A.51.

The Level 1 phenomena are going to be discussed further in this section. In Table A.41, phenomenon 3.G, *the effectiveness, timing and level of control of the manual fire suppression*, was ranked with an overall high level of importance; however, one Panelist was uncertain. All the states of knowledge rankings were low. This phenomenon is a human reliability (i.e. predicting how people respond to a fire) issue and is outside the area of expertise of this panel.

The summary of heat transfer to the interior surfaces is also presented in Table A.4. The phenomenon 4.F, *the open-grate ceilings' influence on fire phenomena*, was ranked as high and uncertain in importance with a low state of knowledge. For four of the six Panelists, the importance was ranked high because the open-grated ceiling will add to the fuel load if it burns. The grated ceiling is a thin plastic and will heat rapidly so the heat transfer is an important phenomenon. Second, the feasibility of getting new input and validation data is ranked high because the data is readily attainable with existing capabilities.

The next phenomenon is 5.C, *the potential burning behavior of the open-grate ceiling material and its role as a fuel*, was ranked with high importance overall, mostly because this will add to the fuel load upon melting and burning. One Panelist ranked the phenomena as low which opposed the other's opinion. There are many things that make the open-grate ceiling complex in terms of the knowledge base. The issues of the complexity of the material are parameters related to burning, melting, and dripping. Panelists 3's low ranking is based on the ignition of new deposits of solidified or liquid plastic on the floor and on equipment would be under conditions that would be untenable for control room operators. The model adequacy was ranked low; however, the feasibility of getting new input and validation data are high since the Panelists state that the experiments are achievable and the capability exists. The panel agreed that the problem here are the grates and if they were designed differently, substituted or made of non-flammable materials, this discussion would not exist.

Table A.42 also identifies Level 1 phenomena in group 6, *characterizing the fire source.* The sub-phenomenon 6.C, *the transition of the fire from the incipient (pre-open-flaming) stage to open flaming*, was ranked high overall for importance. The Panelist 2 felt this was a high importance phenomenon because this transition will establish time zero. One Panelist ranked this importance as medium. Panelists 7's basis for a medium importance ranking is that the open flame characteristics are more important than establishing time zero. The state of knowledge was ranked low for the model adequacy and available input and validation data. This stage of a fire requires very precise and small scale evaluation. The feasibility of getting the data was ranked as medium because the capability does exits but numerous experiments would have to be performed since there is a large range of possible cabinet configurations.

In Table A.42, the next phenomenon, 6.G, *the fire behavior/characteristics during open flaming period,* was ranked with a high importance by the panel and a low state of knowledge for the individual aspects. Since this phenomenon is fundamental to the burning rate, the Panelists decided on the high importance ranking. The low state of knowledge ranking is due to the fact that with, the full predictive capabilities of the physics of flame structure and movement are not implemented.

In Table A.42, the phenomenon 6.H, *fire spread beyond the cabinet of fire origin*, was ranked with a high importance and a low state of knowledge. This phenomenon is important because the panel states that if this phenomenon could become significant to the figure of merit. Thus understanding whether or not it happens is important in this scenario. The feasibility of getting new input data was ranked assuming the fire was outside the cabinet structure. If it were inside the structure (cabinet to cabinet spreading) then the ranking would be low. The feasibility of getting new validation data was also ranked assuming the flames were outside the cabinet structure.

In Table A.42, the phenomenon 6.I, *the potential behaviors that might be associated with oxygen starvation/re-flash of the fire,* was ranked with a high importance and a low model adequacy. The high importance ranking was because this phenomenon can be fundamental to how the scenario progresses. The low state of knowledge ranking is based on the simple fact that there has not been any significant work in this area that has developed into a model. The feasibility of getting both the input and validation data was ranked as high.

In Table A.42, the phenomenon, 6.K *the plume/flame behavior for the cabinet fire*, produced disagreement amongst the panel for the importance rankings. The rankings ranged from low to high. The low importance ranking was because this phenomenon is not going to have a large impact on the model specifically with variation of the phenomenon. Panelist 1 assumed that this phenomenon was related to the structure and fire dynamic affects of the plume. One of the presumptions for the high importance ranking is that this phenomenon characterizes the fire behavior, the entrainment, and the spill fire outside the cabinet. This phenomenon was ranked as having a low model adequacy, available input data, and available validation data. On the other hand, the Panelists felt that the feasibility of getting both the input and validation information is high.

In Table A.42, the phenomenon 6.L, *the ventilation flow within and through the source cabinet*, was ranked with a high importance and an overall low state of knowledge. This specifically refers to the gross ventilation change and was ranked with a high level of importance because this may directly influence the overall HRR. For state of knowledge, all the components were ranked low besides the feasibility of getting new validation data. The Panelists ranked the feasibility of getting new validation data assuming that the capability of the input data would exist.

Shown in Table A.43 are the remaining Level 1 phenomena. The first sub-phenomenon is 7.B, *acid gases during the open flaming stage of the fire.* The majority of the Panelists ranked this phenomenon as high because it could have an affect on the electrical equipment. The adequacy of the model for this phenomenon was ranked low for adequacy and availability of data. The feasibility of obtaining new input and validation data were given a medium ranking for this scenario. Phenomenon 7.E, *smoke particulate during the pre-combustion (incipient or pre-open flaming) stages of the fire* was ranked with a high importance by all panel members. The state of knowledge rankings for this phenomenon were the same as the previous phenomenon. The adequacy of the model for this phenomenon was ranked low for adequacy and availability of data. The feasibility of obtaining new input and validation data were ranked medium for this scenario

The final sub-phenomenon in Table A.43, 8.B, is *the process of humans sensing the fire (i.e., human detecting the fire)*. The overall importance ranking was in the middle of medium to high. Three Panelists ranked this medium and three ranked this as high importance. The state of knowledge rankings were low for all categories.

Table A.41: Level I PIRT Results and Summary for Scenario 1 (1 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
3. Predicting Room Conditions/Response													
G. Effectiveness, Timing and Level of Control of the Manual Fire Suppression.	H	X	H	H	U	H	H		L	L	L	L	L
4. Heat Transfer to Surfaces													
F. The Open-Grate Ceilings Influence on Fire Phenomena	H	X	H	H	U	H	U		L	L	H	L	H
5. Characterizing Fire Spread													
C. The Potential Burning Behavior of the Open-Grate Ceiling Material and its Role as a Fuel	H	X	L	H	H	H	H		L	L	M	L	L

Table A.42: Level I PIRT Results and Summary for Scenario 1 (2of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
6. Characterizing the Fire Source													
C. The Transition of the Fire from the Incipient (pre-open flaming) Stage to Open Flaming	H	X	H	H	H	H	M		L	L	M	L	M
G. The Fire Behavior/Characteristics during the Open Flaming Period	H	X	H	H	H	H	H		L	L	L	L	L
H. Fire Spread Beyond the Cabinet of Fire Origin	H	X	H	H	H	H	H		L	L	M	L	M
I. The Potential Behaviors that might be Associated with Oxygen Starvation/Re-Flash of the Fire	H	X	H	H	H	H	H		L	L	H	L	H
K. The Plume/Flame Behavior for the Cabinet Fire	L	X	H	H	M	H	M		L	L	H	L	H
L. The Ventilation Flow within and through the Source Cabinet	H	X	H	H	H	H	H		L	L	L	L	H

Table A.43: Level I PIRT Results and Summary for Scenario 1 (3 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
7. The Generation of Fire/Combustion Products													
B. Acid Gases During the Open Flaming Stages of the Fire	H	L	L	H	H	H	H		L	L	M	L	M
E. Smoke Particulate during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	H	H	H	H	H	H	H		L	L	M	L	L
8. Predicting Operator Behavior													
B. The Process of Humans Sensing the Fire (i.e., human detecting the fire)	H	X	M	M	M	H	H		L	L	L	L	L

Table A.44: Level 2 PIRT Results and Summary for Scenario 1 (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
1. Predicting Detection Response for Detectors below the Open-Grate Ceiling													
B. The Actual Response of Smoke Detectors to the Fire	L	X	M	M	M	L	L		L-M	L	L	L	H
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling													
B. The Actual Response of Smoke Detectors to the Fire	L	X	M	M	M	L	L		L-M	L	L	L	H
3. Predicting Room Conditions/Response													
B. Mechanical Ventilation	H	X	H	H	H	M	H		M	H	NA	M	M

Table A.45: Level 2 PIRT Results and Summary for Scenario 1 (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
6. Characterizing the Fire Source													
A. Overall Burning Rate of the Cabinet (i.e., total HRR)	H	X	H	H	H	H	H		M	M	H	L	H
B. Air Flow within and through the Burning Cabinet	H	X	H	H	H	H	H		M	H	NA	L	H
5. Characterizing Fire Spread													
B. Fire Spread on the Floor (near the fire source)	L	L	L	H	H	M	H		M	M	H	M	H
7. The Generation of Fire/Combustion Products													
A. Smoke Particulate during the Open Flaming Stages of the Fire	H	H	H	H	H	H	H		M	L	M	L	L
D. CO during the Open Flaming Stages of the Fire	H	L	L	H	H	H	H		M	M	M	M	M

Table A.46: Level 3 PIRT Results and Summary for Scenario 1

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
8. Predicting Operator Behaviors													
C. Operators' Response to the Fire and the Impact of the Fire on the Decision Making Process	H	X	H	H	H	H	H		U	U	U	U	U

Table A.47: Level 4 PIRT Results and Summary for Scenario 1 (1 of 5)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
1. Predicting Detection Response for Detectors below the Open-Grate Ceiling													
A. The General Process of Fire Detection	L	X	M	M	M	L	L		NA	H	NA	NA	NA
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	L	X	M	M	M	L	L		H	H	NA	L-M	H
2. Predicting Detection Response for Detectors on the Hard Upper Ceiling													
A. The General Process of Fire Detection	L	X	M	M	M	L	L		NA	H	NA	NA	NA
C. Buoyant Flows Induced by the Fire given the Ceiling Configuration	L	L	M	M	M	L	L		H	H	NA	L-M	H

Table A.48: Level 4 PIRT Results and Summary for Scenario 1 (2 of 5)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
3. Predicting Room Conditions/Response													
A. Communication Between Spaces within the 3-hour Rated Boundary	M	X	L	M	M	L	L		H	H	NA	H	NA
C. Predicting the Buildup of Combustion Products within the Room	H	X	H	H	H	H	H		H	H(L)	H	M	H
D. Room Temperatures	M	X	M	M	M	H	M		H	H	NA	H	NA
E. Radiant Heat from the Fire Source Impinging on People Nearby	L	X	L	L	M	L	L		H	H	NA	H	NA
F. Smoke Filling	H	X	H	H	H	H	H		H	H	NA	M	M
H. Ceiling Jet Behavior	M	X	L	L	L	L	M		H	H	NA	H	NA

Table A.49: Level 4 PIRT Results and Summary for Scenario 1 (3 of 5)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
4. Heat Transfer to Surfaces													
A. Heat Transfer to the Room Walls	L	X	L	L	L	L	L		H	H	NA	L	H
B. Heat Transfer to the Floor (near the fire source)	L	X	L	H	H	H	H		H	H	NA	H	NA
C. Heat Flux to the Floor, Specifically, away from the Fire Source	L	X	L	L	L	L	L		H	H	NA	H	NA
D. Heating of Surfaces in the Room other than the Walls and Floor	L	X	L	L	L	L	L		H	H	NA	H	NA
E. Heat Transfer to the Panels that Bound the Source Fire Electrical Cabinet	M	X	M	M	M	M	M		M	H	NA	H	NA

Table A.50: Level 4 PIRT Results and Summary for Scenario 1 (4 of 5)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
5. Characterizing Fire Spread													
A. Fire Spread Among the Contents of the Source Cabinet	L	X	L	L	L	L	L		L	L	L	L	L
6. Characterizing the Fire Source													
D. The Transition of the Fire from the Open Flaming Stage to Smolders (natural burnout)	L	X	L	L	L	L	L		M	M	H	L	H
E. Fire Behavior During that Stage of the Fire that Precedes the Open Flaming Behavior (i.e., the non-flaming or incipient stages of combustion)	U	X	L	L	H	L	L		L	L	H	L	H
F. The Fire Behavior during the Smoldering (post-open-flaming or natural burnout) Stages of the Fire	L	X	L	L	L	L	L		L	L	H	L	H
J. The Release of Heat by the Fire Radiatively (as opposed to convectively)	H	X	H	H	H	H	H		H	H	NA	H	NA

Table A.51: Level 4 PIRT Results and Summary for Scenario 1 (5 of 5)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available input data	Feasibility of getting new input data	Available data for validation of models	Feasibility of getting new validation data
7. The Generation of Fire/Combustion Products													
C. HCN during the Open Flaming Stages of the Fire	M	L	L	H	H	H	M		L	L	M	L	M
F. Acid Gases during the Pre-Combustion (incipient or pre-open flaming) Stages of the Fire	L	L	L	L	L	L	L		L	L	H	L	H
8. Predicting Operator Behaviors													
A. Delivery of Radiant Heat Flux to Operators	M	X	L	M	M	M	M		H	H	NA	H	NA

APPENDIX B: PIRT FIRE SCENARIO 2

PIRT Fire Scenario 2 is a postulated cabinet fire in a switchgear room (SWGR) in a nuclear power plant (NPP). There are three scenarios in the SWGR that will be discussed; 2a, 2b, and 2c. Scenario 2a and 2b are both an electrical cabinet fire with the figure of merit being the safe shut down (SSD) cable. The difference between these two scenarios is the location of the SSD cable. Scenario 2c is a medium energy arc fault is an electrical cabinet with the same figure of merit as Scenario 2a.

B.1 Fire Scenario 2a Description

PIRT Fire Scenario 2a is a postulated cabinet fire in a SWGR with a high bay. The dimensions of the room are 8.5 m (28 ft) by 17 m (56 ft) by 3.7 m (12 ft) high and the high bay is 8.5 m (28 ft) by 17 m (56 ft) by 15 m (50 ft) high. The walls are 0.9 m (3 ft) thick concrete and the ceiling and floors are 0.6 m (2 ft) thick concrete. The smoke detectors are on both the lower (3.7 m) and upper (15 m) ceilings. The ventilation is 28.3 cubic meters per minute (1000 cubic feet per minute). This space contains electrical cabinets on the west, south, and east walls, only under the 3.7 m (12 ft) ceiling.

The fire is located in the red electrical cabinet shown in Figure B.1. The target is the safe shutdown (SSD) cable which is located in a cable tray 0.6 m (2 ft) above the cabinet of fire origin. The blue arrow in Figure B.1 is pointing to the SSD cables. The figure of merit is damage to the SSD cables, (how important are the identified phenomena to determining whether the cable will be damaged during the fire, rendering SSD equipment non-functional?).

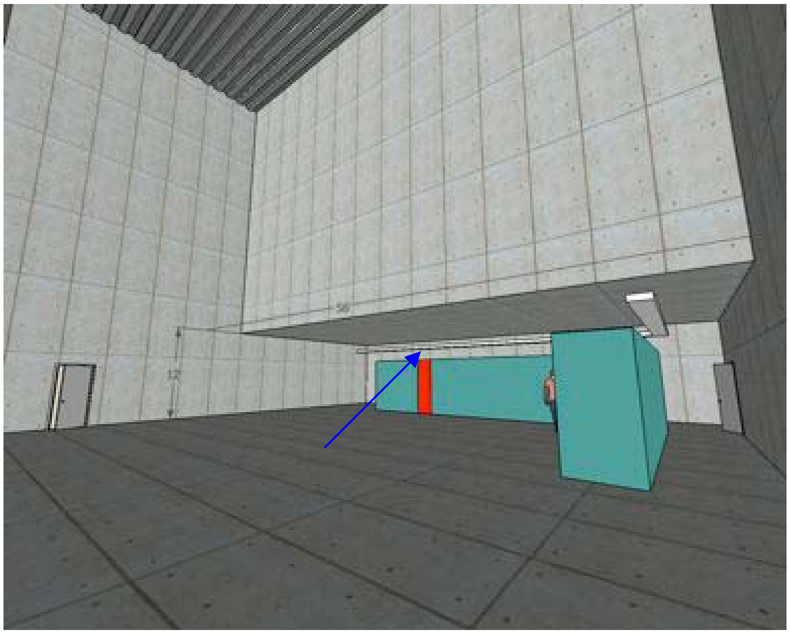


Figure B.1: Generic Switchgear Room Layout

Figure B.2: Example of a Switchgear Room

B.1.1 Phenomena Identification

The list of phenomena identified for this scenario will be discussed in this section. The Panelists identified groups of phenomena which include sub-phenomena. The order of the groups of phenomena does not indicate the level of importance. The Panelists kept the phenomena at a higher level for this scenario compared to Scenario 1. This is because after gaining the experience of the PIRT process with the first scenario, the panelists felt keeping the phenomena at a higher level would serve the same purpose. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *characterizing the fire*

A. Characterizing the initiating event, more specifically the ignition of the electrical fire start point.
B. Characterizing the incipient stage and transition to open flaming.
C. The development of the fire in the cabinet as characterized by its overall burning rate (i.e., total HRR).
D. Cabinet enclosure effects, the effects of ventilation on combustion dynamics.

E. Fire propagation to adjacent cabinets (including subsequent contribution to fire heat release rate, (HRR) and products of combustion (POCs).
F. Flame extension from cabinet specifically predicting the flame structure and spread outside the cabinet.
G. Ignition of the overhead cable tray.
H. Vertical fire propagation along cable riser from cabinet to tray.
I. The flame spread rate along the cable tray located above the cabinet fire.
J. Fire growth on cable tray (i.e. HRR) located above the cabinet fire.
K. Fire spread from burning cable tray to cabinet below (dripping, downward spread on the riser).

Phenomenon 2: *predicting detection response time*.
A. Smoke transport from source to detector.
B. Response of the detector.

Phenomenon 3: *predicting products of combustion*.
A. The production of smoke particulate.
B. The production of carbon monoxide, (CO).
C. The production of hydrogen cyanide, (HCN).
D. The production of acid gases.

Phenomenon 4: *predicting fire suppression specifically to the manual fire brigade*.
A. Predicting emergency response time.
B. Predicting the brigade performance based on fire size.
C. Predicting the actions (detection, notification, and suppression) by non emergency responders.

Phenomenon 5: *damage to SSD cables*.
A. Thermal response of the cable.
B. Electrical degradation of SSD cable.
C. Thermal (polymeric) decomposition of SSD cable (melting, charring, electrical).
D. Ignition of non-SSD cable(s) in same tray.
E. Mechanical failure of the cable tray

Phenomenon 6: p*redicting enclosure environment*.
A. Heat and smoke transport (including other POCs).
B. Heat transfer to enclosure surfaces and contents.
C. Performance of ventilation system (airflow, operation of dampers, effects of POC on vent-flow).

Phenomenon 7: *predicting structural response*.
A. Spalling concrete fragments impacting cables.

B.1.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table B.1. The listed phenomena with the importance rankings are shown in Table B.2 through Table B.10.[1] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to reach consensus among the panel, but sometimes they

[1] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using a randomly assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table B.1: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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 B.2: Importance Ranking for Scenario 2a, Characterizing the Fire (1 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Fire								
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	H	L	L	H	H	L	L	Panelist 4's basis for a high importance ranking is that the process of modeling the ignition is important to the effects of the outcome of the scenario. Panelist 4's example of how this affects the HRR is; a fire's peak HRR will tend to be higher when a smoldering fire transitions to open flaming along warm cables versus fire growth along cold cables. Panelist 5's perspective is based on experiments where the incipient stage is very important to predicting the HRR curve. The low rankings are based on the figure of merit. Panelist 2's low ranking is based on a difference of judgment; they do not think the phenomenon will later impact the scenario.
B. Characterizing the Incipient Stage and Transition to Open Flaming	U	L	L	H	H	L	L	Panelist 2's low ranking is based on the technology for smoke detection; a detector will not detect the fire at this stage. Panelist 4's high ranking is based on the importance of knowing the prehistory of the fire scenario which defines the history of the scenario.

Table B.3: Importance Ranking for Scenario 2a, Characterizing the Fire (2 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Fire (Cont.)								
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	H	H	H	H	H	H	H	
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	H	H	H	H	H	H	H	
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	H	H	H	H	H	H	H	
F. Flame Extension from Cabinet	H	H	H	H	H	H	H	
G. Ignition of the Overhead Cable Tray	H	H	H	H	H	H	H	
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	H	H	H	H	
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	H	H	H	H	

Table B.4: Importance Ranking for Scenario 2a, Characterizing the Fire (3 of 3)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Fire (Cont.)								
J. Fire Growth on Cable Tray (i.e., HRR)	H	H	H	X	H	H	H	
K. Fire Spread from Burning Cable Tray to Cabinet Below (Dripping, Downward Spread on the Riser)	H	H	H	X	H	H	H	These high importance rankings were based the uncertainty with the cable characteristics in the tray. There could be a variety of different configurations for the type and quantity of cables in the tray.

Table B.5: Importance Ranking for Scenario 2a, Predicting Detection Response Time

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Predicting Detection Response Time								This top level phenomenon is specific to the smoke detectors in this scenario.
A. Smoke Transport from Source to Detector	H	H	H	H	H	H	H	
B. Response of the Detector	H	H	H	H	H	H	H	

Table B.6: Importance Ranking for Scenario 2a, Predicting Products of Combustion

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Products of Combustion								The Panelists were briefed with information about the GET (general employee training), which includes fire protection. The employees at a NPP are instructed, if the fire is small enough, to extinguish it and call the main control room.
A. Particulate	H	H	H	H	H	H	H	Panelist 2's high ranking for just "particulate" with respect to all POCs is due to its larger impact on the responders in terms of manual suppression and detection. Panelist 3's basis for three high rankings (particulate, CO, and HCN) is that they felt that knowing the environment for the first responders is important to this scenario.
B. CO	L	M	H	M	M	M	L	Panelist 7's high for "particulate" versus low for the others (CO, HCN, and acid gases) reflects the importance for manual detection. The two Panelists with low rankings mention that this phenomenon is unimportant to the target, detection, and the emergency responders.
C. HCN	L	M	H	M	M	M	L	
D. Acid Gases	L	M	M	M	M	M	L	

Table B.7: Importance Ranking for Scenario 2a, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Predicting Fire Suppression (Manual Fire Brigade)								
A. Emergency Response Time	H	H	H	H	H	H	H	It was clarified that this phenomenon included all the people that are part of the emergency response procedure.
B. Brigade Performance Based on Fire Size	H	H	H	H	H	H	H	
C. Actions (Detection, Notification, Suppression) by Non-Emergency Responders	H	M	H	H	H	H	H	Panelist 2's medium ranking is based on how this phenomenon is not as important as the emergency response time phenomenon.

Table B.8: Importance Ranking for Scenario 2a, Damage to SSD Cables

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Damage to SSD Cables								
A. Thermal Response of Cable	L	H	H	H	H	L	H	Panelist 1 and 6's low ranking is based on that it is more important to know when the cable is going to fail.
B. Electrical Degradation of SSD Cable	H	H	H	H	H	H	H	The high importance rankings are based on the thermal response of cables and thermal decomposition of the SSD cable being steps to achieve electrical degradation of the SSD cable.
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	H	H	H	H	L	M	
D. Ignition of Non-SSD Cable(s) in Same Tray	H	H	H	H	H	H	H	
E. Mechanical Failure of Cable Tray	H	L	L	H	L	L	L	Panelist 2 and 6's low rankings are based on the presumption that the cable tray will withstand the fire longer than the cable. Panelist 1 assigned a high ranking to the phenomena because knowing if there is early buckling of the cable tray is important because this will lead to failure of the SSD cable.

Table B.9: Importance Ranking for Scenario 2a, Predicting Enclosure Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Predicting Enclosure Environment								
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	H	H	H	M	
B. Heat Transfer to Enclosure Surfaces and Contents	M	M	M	M	M	M	X	
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	M	H	H	H	H	X	Panelist 2's basis for a medium ranking is that there is enough space in this scenario that the impact on the ventilation system will not be as important.

Table B.10: Importance Ranking for Scenario 2a, Predicting Structural Response

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
7. Predicting Structural Response								
A. Spalling Concrete Fragments Impacting Cables	U	L	U	U	U	L	X	Panelist 6's low ranking is based on if the fire scenario is to the point where spalling will be a factor, then the SSD cable is already going to have failed. Panelist 4's uncertain ranking is based on not knowing whether this phenomenon is going to happen. Therefore, knowing if spalling happens is important to the scenario.

B.1.3 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge must be identified. The panel ranks the state of knowledge as a group (rather than as individuals) during this phase of the PIRT. The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Tables 14 through Table 23 are the state of knowledge rankings for the identified phenomena for Scenario 2a.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First is the general adequacy of the existing and generally available[2] fire models to deal with the identified phenomena. The second is the adequacy of data needed to support model development and model validation. Included with this second area is an assessment of the feasibility of getting new development and validation data. The feasibility question was not pursued for phenomena where the existing data availability was ranked “high.”

The list below presents the five state of knowledge parameters and cites the table that include the definitions for each ranking parameter.

1. Model Adequacy (Table B.11)
2. Available Input Data (Table B.12)
3. Feasibility of Getting New Input Data (Table B.13)
4. Available Data for Validation (Table B.12)
5. Feasibility of Getting New Validation Data (Table B.13)

This section identifies key parameters associated with the scenario phenomena. These key parameters associated with their phenomena are shown in Table 24 through Table 28. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed for each key parameter. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., how important is the key parameter in the context of the associated phenomenon and what is the corresponding state of knowledge?).

[2] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table B.11: Model Adequacy Ranking Definitions

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 B.12: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., validation grade data set) exists, or a highly reliable assessment may 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 may 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 B.13: Data Adequacy for Potential to Develop New Data Ranking Definitions

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.

Table B.14: State of Knowledge Rankings for Scenario 2a, Characterizing the Fire (1 of 4)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire						
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	L	L	L	L	L	
B. Characterizing the Incipient Stage and Transition to Open Flaming.	L	L	L	L	L	The low state of knowledge rankings are based on the complexities associated with modeling this transition. This phenomenon is not something typically in a fire model.
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	L-M	L	M	M	H	For model adequacy there were 4 low rankings and 3 medium rankings. For available input data Panelist 1's ranking is medium. For feasibility of getting new input data Panelist 2's ranking is low.

Table B.15: State of Knowledge Rankings for Scenario 2a, Characterizing the Fire (2 of 4)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire (Cont.)						
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	M	M	H	M	H	The ranking of medium for the available date for validation of models is based on that the models for ventilation have certain parameters that are not well developed. For the available data for validation of models, Panelist 1's ranking is High.
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	M	M	H	L	H	The Panelists' rankings are based on assuming a well characterized source, i.e. the first cabinet.

Table B.16: State of Knowledge Rankings for Scenario 2a, Characterizing the Fire (3 of 4)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire (Cont.)						
F. Flame Extension from Cabinet	H	L	H	L	H	The Panelists' rankings are assuming a well characterized source, i.e. the first cabinet and the excess pyrolysis is known. The available input data is low because the enclosure environment is needed. The panel looked at the Bullen and Thomas paper from C&F and the combustion symposium from the late 1970's and confirmed, only three tests were done on ethanol, change availability of validation data from M to L.
G. Ignition of the Overhead Cable Tray	M	M	H	M	H	The Panelists ranked this phenomenon assuming a well characterized source with known flame extension.

Table B.17: State of Knowledge Rankings for Scenario 2a, Characterizing the Fire (4 of 4)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire (Cont.)						
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	M	M	H	M	H	There was discussion of FIPEC, LLNL, and FMRC work on cable fire flammability.
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	L	L	M	L	M	The rankings reflect that there are numerous complications with topics such as geometry, materials, and porosity.
J. Fire Growth on Cable Tray (i.e., HRR)	L	L	M	L	M	For this phenomenon, factor the burnout phenomenon on the back side of the fire was considered when ranking the state of knowledge.
K. Fire Spread from Burning Cable Tray to Cabinet Below (Dripping, Downward Spread on the Riser)	L	L	M	L	M	

Table B.18: State of Knowledge Rankings for Scenario 2a, Predicting Detection Response Time

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Predicting Detection Response Time						
A. Smoke Transport from Source to Detector	H	H	NA	M	H	
B. Response of the Detector	M	M	H	M	H	If there was a detector within the cabinet to detect an incipient fire, the rankings would be different. For Scenario 2, the Panelists presume the detectors are outside of the cabinet are not expected to detect an incipient fire.

Table B.19: State of Knowledge Rankings for Scenario 2a, Predicting Product of Combustion

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Predicting Products of Combustion						This is specific to predicting the production of the products of combustion.
A. Particulate	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 rank the phenomena as low, Panelist 3 is L to M, the rest are M.
B. CO	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 rank the phenomena as low, Panelist 3 is L to M, the rest are M.
C. HCN	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L to M, the rest are M.
D. Acid Gases	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L to M, the rest are M.

Table B.20: State of Knowledge Rankings for Scenario 2a, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Predicting Fire Suppression (Manual Fire Brigade)						
A. Emergency Response Time	M-H	M	H	M	H	It was mentioned by a Panelists that the emergency response team is ready to fight the fire with water, which includes decision making. The range in rankings for model adequacy is based on the phenomenon which is outside the expertise of the fire physics experts.
B. Brigade Performance Based on Fire Size	M	L-M	H	L	H	The PIRT panel is a group of experts in fire physics and not human factors. The available input data ranking has a range because the available input data is from incident events and drills.
C. Actions (Detection, Notification, Suppression) by Non Emergency Responders	L	L	U	L	U	This is outside the fire physics area.

Table B.21: State of Knowledge Rankings for Scenario 2a, Damage to SSD Cables

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
5. Damage to SSD Cables						
A. Thermal Response of Cable	M	M	H	M	H	
B. Electrical Degradation of SSD Cable	M	M	H	L	H	
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	L	L	L	L	
D. Ignition of Non-SSD Cable(s) in Same Tray	M	M	H	M	H	This phenomenon was ranked assuming the fire environment is well known.
E. Mechanical Failure of Tray	L	H	NA	L	H	This phenomenon includes the mechanical failure of the tray causing damage to the SSD cable.

Table B.22: State of Knowledge Rankings for Scenario 2a, Predicting Enclosure Environment

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
6. Predicting Enclosure Environment						
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	H	H	
B. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	H	H	
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	M	M	H	M	H	For available input data, the areas of weakness are fusible links on dampers and filter clogging.

Table B-23: State of Knowledge Rankings for Scenario 2a, Predicting Structural Response

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
7. Predicting Structural Response						
A. Spalling Concrete Fragments Impacting Cables	L	L	L	L	L	

Table B.24: Key Parameters and Their Rankings for Scenario 2a, Characterizing the Fire (1 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire				
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	Internal Partitions	H	H	Panelist 5's basis for the high ranking is that this parameter is not important if it is ventilation controlled. The panelist is referring to the situation where the fire is contained in one cabinet. The panel agreed with this thought. They concluded that if the external electrical panels create a ventilation controlled condition then this parameter would not be important.
	Type, Location, and Configuration of Fuel (Bundling)	H	M	
	Characterizing the Proportion of Thermal Radiation Versus Convective HRR	L-M	H	Panelist 1 ranks this low for importance based on that this parameter is a constant that is well known and varies little over time with respect to the fire scenario.
	Flame Structure and Plume Behavior Within the Cabinet.	H	L	High importance ranking is based on that this parameter influences the spread of fire within the cabinet.

Table B.25: Key Parameters and Their Rankings for Scenario 2a, Characterizing the Fire (2 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
Characterizing the Fire (Cont.)				
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	Air Flow Within and Through the Burning Electrical Cabinet	H	M	This parameter was specific to things such as the effects of the ventilation openings, open versus closed doors, ventilation opening size, among other conditions with this phenomenon.
	Flame Structure and Plume Behavior Within Cabinet.	H	L	The state of knowledge ranking is low because the Panelists are concerned with how vitiation and high temperature environment would affect the flame structure.
	Deformation of the Cabinet Boundary Panels	H	L	
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	Deformation of the Cabinet Boundary Panels	H	L	

Table B.26: Key Parameters and Their Rankings for Scenario 2a, Characterizing the Fire (2 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
G. Ignition of the Overhead Cable Tray	Pilot/Un-Pilot	M	M	
	Ignition Criteria (eg, Critical Temperature, Mass Loss Rate)	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	This parameter includes both the conduction into cables and the conduction down the length of the cables.
	Physical Response (Melting, Dripping, Charring)	H	L	
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	Heat Conduction along Cables	M	M	
	Flame Length	H	M	
	HRR of Burning Section of Cable	H	M	
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	This parameter depends on the ignition criteria of the unburned cable.

Table B. 27: Key Parameters and Their Rankings for Scenario 2a, Characterizing the Fire (3 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	Flame Radiation Ahead of the Flame Foot	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	
	Physical Response (Melting, Dripping, Charring)	H	L	
	HRR of Burning Section of Cable	H	M	Panelist 2's medium ranking for state of knowledge that the modeling ability is low but the state of knowledge is better.
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Fire Retardant Coatings	H	M	
	Porosity (% Fill of Tray, Air Spaces Between Cables)	H	L	
	Fire Retardant Materials (i.e. Cable Jackets)	H	M	

Table B.28: Key Parameters and Their Rankings for Scenario 2a, Characterizing the Fire (4 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
J. Fire Growth on Cable Tray (i.e., HRR)	Pilot/Un-Pilot	M	M	
	Ignition Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	This parameter includes both the conduction into cables and the conduction down the length of the cables.
	Physical Response (Melting, Dripping, Charring)	H	L	

B.1.4 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 2a. The phenomena and their rankings were analyzed using four criteria that will be presented here. The first level phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table B.29 and Table B.30. Level two phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table B.31 through Table B.34. The third level phenomena are those that were deemed uncertain in their importance and/or state of knowledge rankings by the Panelists. This level is deemed necessary to explore the phenomenon further. There is one sub-phenomenon for this level and it is shown in Table B.35. The fourth level are those phenomena that were given one of the following overall rankings: high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking , or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table B.36. The Level 1 phenomena are going to be discussed further below.

Table B.29 is the first table with the Level 1 phenomena listed. *The flame spread rate along the cable tray located above the cabinet fire* (1.I), is the first sub-phenomenon under the *characterizing the fire*. The importance ranking was high for all the Panelists. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data. Phenomenon 1.J, f*ire growth on cable tray (i.e. HRR)*, is the next sub-phenomenon which was also ranked with a high importance. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data. Phenomenon 1.K, *fire spread from burning cable tray to cabinet below (dripping, downward spread on the riser)* was ranked with a high importance. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data.

The next group of phenomena in Table B.29 is *predicting products of combustion*. The sub-phenomenon, 3.A, associated with this top level phenomenon is *particulate*. It was ranked with a high importance and a low to medium state of knowledge. The available input and validation data was ranked as low while the feasibility of obtaining new input and validation data was ranked as medium.

The next table with PIRT results for Level 1 phenomena is Table B.30Table . The first group of phenomena is (4) *predicting fire suppression (manual fire brigade).* There is only one sub-phenomenon that was analyzed with a Level 1 result; phenomenon 4.C, *actions (detection, notification, suppression) by the non emergency responders*. This phenomenon was ranked with a high importance for all but one Panelist who ranked this as medium importance. The state of knowledge was ranked as low for both adequacy and available input and validation data. The feasibility of obtaining new input and validation data was ranked as uncertain. The uncertain ranking based on that the Panelists feel that this phenomenon deals with human reliability which outside their areas of expertise. The next top level phenomenon (5) is *damage to SSD cables* which is directly related to the figure of merit for this scenario. The sub-phenomenon 5.C, *thermal (polymeric) decomposition of SSD cable (melting, charring, electrical)* was ranked with a majority of high importance with two low and one medium importance rankings. The differences are based on what the Panelists feel will be the dominate failure mechanisms for the cable. The state of knowledge rankings were low across all categories.

Table B.29: Level 1 PIRT Results and Summary for Scenario 2a (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	H	H	H	H		L	L	M	L	M
J. Fire Growth on Cable Tray (i.e., HRR)	H	H	H	X	H	H	H		L	L	M	L	M
K. Fire Spread from Burning Cable Tray to Cabinet Below (Dripping, Downward Spread on the Riser)	H	H	H	X	H	H	H		L	L	M	L	M
3. Predicting Products of Combustion													
A. Particulate	H	H	H	H	H	H	H		L-M	L	M	L	M

Table B.30: Level 1 PIRT Results and Summary for Scenario 2a (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
4. Predicting Fire Suppression (Manual Fire Brigade)													
C. Actions (Detection, Notification, Suppression) by Non Emergency Responders	H	M	H	H	H	H	H		L	L	U	L	U
5. Damage to SSD Cables													
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	H	H	H	H	L	M		L	L	L	L	L

Table B.31: Level 2 PIRT Results and Summary for Scenario 2a (1 of 4)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	H	L	L	H	H	L	L		L	L	L	L	L
B. Characterizing the Incipient Stage and Transition to Open Flaming.	U	L	L	H	H	L	L		L	L	L	L	L
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	H	H	H	H	H	H	H		L-M	L	M	M	H
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	H	H	H	H	H	H	H		M	M	H	M	H

Table B.32: Level 2 PIRT Results and Summary for Scenario 2a (2 of 4)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire (Cont.)													
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	H	H	H	H	H	H	H		M	M	H	L	H
F. Flame Extension from Cabinet	H	H	H	H	H	H	H		H	L	H	L	H
G. Ignition of the Overhead Cable Tray	H	H	H	H	H	H	H		M	M	H	M	H
2. Predicting Detection Response Time													
B. Response of the Detector	H	H	H	H	H	H	H		M	M	H	M	H

Table B.33: Level 2 PIRT Results and Summary for Scenario 2a (3 of 4)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Predicting Products of Combustion													
B. CO	L	M	H	M	M	M	L		L-M	L	M	L	M
C. HCN	L	M	H	M	M	M	L		L-M	L	M	L	M
D. Acid Gases	L	M	M	M	M	M	L		L-M	L	M	L	M
4. Predicting Fire Suppression (Manual Fire Brigade)													
A. Emergency Response Time	H	H	H	H	H	H	H		M-H	M	H	M	H
B. Brigade Performance Based on Fire Size	H	H	H	H	H	H	H		M	L-M	H	L	H

Table B.34: Level 2 PIRT Results and Summary for Scenario 2a (4 of 4)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
5. Damage to SSD Cables													
A. Thermal Response of Cable	L	H	H	H	H	L	H		M	M	H	M	H
B. Electrical Degradation of SSD Cable	H	H	H	H	H	H	H		M	M	H	L	H
D. Ignition of Non-SSD Cable(s) in Same Tray	H	H	H	H	H	H	H		M	M	H	M	H
E. Mechanical Failure of Tray	H	L	L	H	L	L	L		L	H	NA	L	H
6. Predicting Enclosure Environment													
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	M	H	H	H	H	X		M	M	H	M	H

Table B.35: Level 3 PIRT Results and Summary for Scenario 2a

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
7. Predicting Structural Response													
A. Spalling Fragments Impacting Cables	U	L	U	U	U	L	X		L	L	L	L	L

Table B.36: Level 4 PIRT Results and Summary for Scenario 2a

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	H	H	H	H		M	M	H	M	H
2. Predicting Detection Response Time													
A. Smoke Transport from Source to Detector	H	H	H	H	H	H	H		H	H	NA	M	H
6. Predicting Enclosure Environment													
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	H	H	H	M		H	H	H	H	H
B. Heat Transfer to Enclosure Surfaces and Contents	M	M	M	M	M	M	X		H	H	H	L	H

B.2 Fire Scenario 2b Description

PIRT Fire Scenario 2b is similar to Fire Scenario 2a; however, the target (figure of merit) changed from the initial scenario description. The target is the SSD cables that are located in a cable tray just beneath the 9.1m (30 ft) ceiling; a generic view of the ceiling configuration is shown in Figure A.2. The cable tray is protected by a one hour rated fire barrier system. The other considerations remained the same in this second scenario. The purpose of this alteration was to analyze the varying PIRT results.

B.2.1 Phenomena Identification

The list of identified phenomena for Scenario 2b will be discussed in this section. The Panelists identified groups of phenomena that include sub-phenomena. The order of the phenomena groups does not indict the level of importance. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *characterizing the fire*.

A. Characterizing the initiating event, more specifically the ignition of the electrical fire starting point.
B. Characterizing the incipient stage and transition to open flaming.
C. The development of the fire in the cabinet as characterized by its overall burning rate (i.e., total heat release rate (HRR)).
D. Cabinet enclosure effects, the effects of ventilation on combustion dynamics.
E. Fire propagation to adjacent cabinets (including subsequent contribution to fire HRR and products of combustion (POCs)).
F. Flame extension from cabinet.
G. Ignition of the overhead cable tray.
H. Fire propagation along cable riser from cabinet to tray (vertically).
I. The flame spread rate along the cable tray located above the cabinet fire.
J. Fire growth on cable tray (i.e., HRR).
K. Fire spread from burning cable tray to cabinet below (dripping, downward spread on the riser).

Phenomenon 2: *predicting detection response time*.

A. Smoke transport from the source to the detector.
B. Response of the detector.

Phenomenon 3: *predicting products of combustion*.

A. Production of smoke particulate.
B. Production of carbon monoxide (CO).
C. Production of hydrogen cyanide (HCN).
D. Production of Acid Gases.

Phenomenon 4: *predicting fire suppression specifically to the manual fire brigade*.

A. Predicting the emergency response time.
B. Predicting the brigade performance based on fire size.

C. Predicting the actions (detection, notification, and suppression) by non emergency responders.

Phenomenon 5: *damage to SSD cables*.

A. Thermal response of the cable.
B. Electrical degradation of SSD cable.
C. Thermal (polymeric) decomposition of SSD cable (melting, charring, electrical).
D. Ignition of non-SSD cable(s) in same tray.
E. Mechanical failure of SSD target tray (only new phenomenon added from Scenario 2a to 2b).
F. Mechanical failure of tray above cabinet.

Phenomenon 6: *Predicting enclosure environment*

A. Heat and smoke transport (including other POCs).
B. Heat transfer to enclosure surfaces and contents.
C. Performance of ventilation system (airflow, operation of dampers, effects of POC on vent-flow).

B.2.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table B.37. The listed phenomena with the importance rankings are listed Table B.38 through Table B.44.[3] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using a randomly assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table B.37: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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.

[3] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

Table B.38: Importance Ranking for Scenario 2b, Characterizing the Fire (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Fire								
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	H	L	L	X	H	L	L	
B. Characterizing the Incipient Stage and Transition to Open Flaming.	U	L	L	X	H	L	L	Panelist 2's low ranking is based on the technology for detection; a smoke detector will not detect the fire in this stage.
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	H	H	H	X	H	H	H	
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	H	H	H	X	H	H	H	
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	H	H	H	X	H	H	H	
F. Flame Extension from Cabinet	H	H	H	X	H	H	H	
G. Ignition of the Overhead Cable Tray	H	H	H	X	H	H	H	
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	X	H	H	H	

Table B.39: Importance Ranking for Scenario 2b, Characterizing the Fire (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Fire (Cont.)								
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	X	H	H	H	
J. Fire Growth on Cable Tray (i.e., HRR)	H	H	H	X	H	H	H	
K. Fire Spread from Burning Cable Tray to Cabinet Below (Dripping, Downward Spread on the Riser)	H	H	H	X	H	H	H	These high importance rankings were based the uncertainty with the cable characteristics in the tray. There could be a variety of different configurations for the type and quantity of cables in the tray.

Table B.40: Importance Ranking for Scenario 2b, Predicting Detection Response Time

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Predicting Detection Response Time								This phenomenon was specific to the smoke detectors.
A. Smoke Transport from Source to Detector	H	H	H	X	H	H	H	
B. Response of the Detector	H	H	H	X	H	H	H	

Table B.41: Importance Ranking for Scenario 2b, Predicting Products of Combustion

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Products of Combustion								
A. Particulate	H	H	H	X	H	H	H	Panelist 2's high for just "particulate" is based on its larger impact on the responders who will be suppressing the fire. Panelist 3's high ranking for particulate, CO, and HCN emphasizes that having knowledge of the environment is important for the first responders.
B. CO	L	M	H	X	M	M	L	Panelist 7's high importance ranking for "particulate" versus low importance rankings for the other POCs (CO, HCN, and acid gases) reflects the importance for manual detection. Panelist 7 mentions that predicting the amount of smoke particulate is important to how fast a human can sense that there is a fire. Panelist 7 also states that the low important rankings for certain POC (CO, HCN, and acid gases) phenomena are because they are unimportant to the target, detection, and the emergency responders.
C. HCN	L	M	H	X	M	M	L	
D. Acid Gases	L	M	M	X	M	M	L	

Table B.42: Importance Ranking for Scenario 2b, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Predicting Fire Suppression (Manual Fire Brigade)								
A. Emergency Response Time	H	H	H	X	H	H	H	It was clarified that this phenomenon included all people who are a part of the emergency response procedure.
B. Brigade Performance Based on Fire Size	H	H	H	X	H	H	H	
C. Actions (Detection, Notification, Suppression) by Non-Emergency Responders	H	M	H	X	H	H	H	Panelist 2's medium ranking is based on how this phenomenon is not as important as the emergency response time phenomenon.

Table B.43: Importance Ranking for Scenario 2b, Damage to SSD Cables

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Damage to SSD Cables								
A. Thermal Response of Cable	L	H	H	X	H	H	H	Panelist 6's low ranking is based on that knowing when the cable is going to fail is more significant than the thermal response of the cable.
B. Electrical Degradation of SSD Cable	H	H	H	X	H	H	H	The thermal response of cables and thermal decomposition of SSD cable are steps to achieve electrical degradation of SSD cable.
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	H	H	X	H	L	M	Panelist 6's low ranking is based on that knowing when the cable is going to fail is more significant than the thermal response of the cable.
D. Ignition of Non-SSD Cable(s) in Same Tray	L	L	L	X	L	L	L	Panelist 2's low importance ranking is based on this scenario, this cable is unlikely to ignite.
E. Mechanical Failure of SSD Target Tray	M	L	L	X	L	L	L	Panelist 2's low is based on that cable tray will withstand the fire longer than the cable. Panelist 1 reduced their ranking to medium compared to 2a based on distance from fire source.
F. Mechanical Failure of the Tray Above the Cabinets	H	L	L	X	L	L	L	Panelist 1's high is based on if the cable tray fails, then the fire will propagate faster to the cables.

Table B.44: Importance Ranking for Scenario 2b, Predicting Enclosure Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Predicting Enclosure Environment								
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	X	H	H	H	For Scenario 2b, the importance of the spill plume is becomes more significant since the Panelists feel this will impact the scenario specific target.
B. Heat Transfer to Room Enclosure Surfaces and Contents	M	M	M	X	M	M	H	Panelist 7's ranking is high because for this scenario the importance of heat transfer to the room enclosure could directly impact the target.
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	H	H	X	H	H	H	

B.2.3 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge must be identified. The panel ranks the state of knowledge as a group (rather than as individuals) during this phase of the PIRT. The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table B.48 through Table B.54 are the state of knowledge rankings for the identified phenomena for Scenario 2b.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First, is the general adequacy of the existing and generally available[4] fire models to deal with the identified phenomena. The second are, is the adequacy of data needed to support model development and model validation. Included with this second area is an assessment of the feasibility of getting new development and validation data. The feasibility question was not pursued for phenomena where the existing data availability was ranked "high."

The list below presents the five state of knowledge parameters and cites the table that include the definitions of rankings for each.

1. Model Adequacy (Table B.45)
2. Available Input Data (Table B.46)
3. Feasibility of Getting New Input Data (Table B.47)
4. Available Data for Validation (Table B.48)
5. Feasibility of Getting New Validation Data (Table B.49)

This section identifies key parameters associated with the scenario phenomena. These key parameters associated with their phenomena are shown in Table B.55 through Table B.56. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed for each key parameter. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., how important is the key parameter in the context of the associated phenomenon and what is the corresponding state of knowledge?).

[4] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table B.45: Model Adequacy Ranking Definitions

Model Adequacy Ranking Definitions	
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 B.46: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

Data Adequacy for Existing Input Data and Validation Data Ranking Definitions	
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 B.47: Data Adequacy for Potential to Develop New Data Ranking Definitions

Data Adequacy for Potential to Develop New Data Rankings Definitions	
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.

Table B.48: State of Knowledge Rankings for Scenario 2b, Characterizing the Fire (1 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire						
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	L	L	L	L	L	
B. Characterizing the Incipient Stage and Transition to Open Flaming.	L	L	L	L	L	
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	L-M	L	M	M	H	For model adequacy there are 4 low rankings and 3 medium rankings. For available input data, Panelist 1 is medium. For feasibility of new input data, Panelist 2 ranking is low.
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	M	M	H	M	H	The available data for validation of models is a medium because some of the models for things like ventilation are good but other parameters are not as well developed. For available data for validation of models, Panelist 1's ranking is high.

Table B.49: State of Knowledge Rankings for Scenario 2b, Characterizing the Fire (2 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire (Cont.)						
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	M	M	H	L	H	Assuming a well characterized source, i.e. the first cabinet.
F. Flame Extension from Cabinet	H	L	H	L	H	Assuming a well characterized source, i.e. the first cabinet. The excess pyrolysis also needs to be known. The available input data is low here because the enclosure environment is needed.
G. Ignition of the Overhead Cable Tray	M	M	H	M	H	For these rankings the Panelists are assuming a well characterized source with known flame extension.

Table B.50: State of Knowledge Rankings for Scenario 2b, Characterizing the Fire (3 of 3)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Fire (Cont.)						
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	M	M	H	M	H	There was discussion of FIPEC, LLNL, FMRC work on cable fire flammability
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	L	L	M	L	M	The rankings are based on lot of complications with things like geometry, materials, and porosity.
J. Fire Growth on Cable Tray (i.e. HRR)	L	L	M	L	M	One factor that is different from the above is the burnout phenomenon on the back side of the fire.
K. Fire Spread from Burning Cable tray to Cabinet Below (Dripping, Downward Spread on the Riser)	L	L	M	L	M	

Table B.51: State of Knowledge Rankings for Scenario 2b, Predicting Detection Response Time

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Predicting Detection Response Time						
A. Smoke Transport from Source to Detector	H	H	NA	M	H	
B. Response of the Detector	M	M	H	M	H	If there was a smoke detector inside the cabinet to detect an incipient fire the rankings would be different. For this scenario the detectors are outside the cabinet are not expected to detect an incipient fire.

Table B.52: State of Knowledge Rankings for Scenario 2b, Predicting Product of Combustion

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Predicting Products of Combustion						
A. Particulate	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
B. CO	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
C. HCN	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
D. Acid Gases	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L-M, the rest are M.

Table B.53: State of Knowledge Rankings for Scenario 2b, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Predicting Fire Suppression (Manual Fire Brigade)						
A. Emergency Response Time	M-H	M	H	M	H	It was mentioned that the emergency response team is there ready to fight the fire (ready to apply water), which includes decision making. This is outside the fire physics area which reflects the range of model adequacy rankings.
B. Brigade Performance Based on Fire Size	M	L-M	H	L	H	Put a caution in that this is a fire physics group and not a human factors group. The range in available input data ranking based on the available input data from incident events and drills which is why the available input data has a low to medium range for a ranking.
C. Actions (Detection, Notification, Suppression) by Non Emergency Responders	L	L	U	L	U	This is outside the fire physics area.

Table B.54: State of Knowledge Rankings for Scenario 2b, Damage to SSD Cables

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
5. Damage to SSD Cables						
A. Thermal Response of Cable	M	M	H	M	H	
B. Electrical Degradation of SSD Cable	M	M	H	L	H	
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	L	L	L	L	
D. Ignition of Non-SSD Cable(s) in Same Tray	M	M	H	M	H	The Panelists ranked this phenomenon assuming the environment is well known.
E. Mechanical Failure of SSD Target Tray	L	H	NA	L	H	This phenomenon includes the mechanical failure of the tray causing damage to the SSD cable.
F. Mechanical Failure of the Tray Above the Cabinets	L	H	NA	L	H	

Table B.55: State of Knowledge Rankings for Scenario 2b, Predicting Enclosure Environment

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
6. Predicting Enclosure Environment						
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	H	H	
B. Heat Transfer to Room Enclosure Surfaces and Contents	H	H	H	L	H	
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	M	M	H	M	H	For available input data, the areas of weakness were identified as the fusible links on dampers and filter clogging.

Table B.55: Key Parameters and Their Rankings for Scenario 2b, Characterizing the Fire (1 of 5)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire				
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	Internal Partitions	H	H	Panelist 5 said that this parameter is not important if the fire scenario is ventilation controlled. The experts agree that if the external panels create the ventilation controlled condition, it is not important.
	Type, Location, and Configuration of Fuel (Bundling)	H	M	
	Characterizing the Proportion of Thermal Radiation versus Convective HRR.	L-M	H	Panelist 1's ranking is low for importance because they think it is a constant that is well known and varies little.
	Flame Structure and Plume Behavior within the Cabinet	H	L	The Panelists' high importance ranking based on that this phenomenon influences the spread of fire within the cabinet.

Table B.56: Key Parameters and Their Rankings for Scenario 2b, Characterizing the Fire (2 of 5)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire (Cont.)				
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	Air Flow within and through the Burning Electrical Cabinet; Specifically, the Effects of the Ventilation Openings, Open versus Closed Doors, Ventilation Opening Size, etc., on this Behavior	H	M	
	Flame Structure and Plume Behavior within Cabinet	H	L	
	Deformation of the Cabinet Boundary Panels	H	L	
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	Deformation of the Cabinet Boundary Panels	H	L	

Table B.57: Key Parameters and Their Rankings for Scenario 2b, Characterizing the Fire (3 of 5)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire (Cont.)				
G. Ignition of the Overhead Cable Tray	Pilot/Un-Pilot	M	M	
	Ignition Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	This parameter includes both the conduction into cables and the conduction down the length of the cables.
	Physical Response (Melting, Dripping, Charring)	H	L	
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	Heat Conduction along Cables	M	M	
	Flame Length	H	M	
	HRR of Burning Section of Cable	H	M	
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	This parameter depends on the ignition criteria of the unburned cable.

Table B.58: Key Parameters and Their Rankings for Scenario 2b, Characterizing the Fire (4 of 5)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire (Cont.)				
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	Flame Radiation ahead of the Flame Foot	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	
	Physical Response (Melting, Dripping, Charring)	H	L	
	HRR of Burning Section of Cable	H	M	The medium ranking for state of knowledge based on that the modeling ability is low but the state of knowledge is better.
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Fire Retardant Coatings	H	M	
	Porosity (% Fill of Tray, Air Spaces between Cables)	H	L	
	Fire Retardant Materials (i.e. Cable Jackets)	H	M	

Table B.59: Key Parameters and Their Rankings for Scenario 2b, Characterizing the Fire (5 of 5)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Fire (Cont.)				
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire (continued)	Thermo-Physical Properties of the Cables	H	M	There are thermo-physical properties of cables that are global/generic. Panelist 1 mentions that it is almost impossible to get k, rho, and c values for thermo-plastic materials as a function of time. It is feasible to develop a program but it is a high risk to implement. Cabinets also bring in other materials (e.g. circuit cards), where state of knowledge is low.
J. Fire Growth on Cable Tray (i.e. HRR)	Pilot/Un-Pilot	M	M	
	Ignition Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	This parameter includes both the conduction into cables and the conduction down the length of the cables.

B.2.4 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 2b. The phenomena and their rankings were analyzed using four criteria that will be presented here. The first level phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table B.61 through Table B.62. Level two phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table B.63-B.65. The third level phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. There are no Level 3 phenomena for this scenario. The fourth level are those phenomena that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking , or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table B.66 through Table B.67. The Level 1 phenomena are going to be discussed further in this section.

Table B.61 is the first table that summarizes the Level 1 PIRT results for Scenario 2b's top phenomenon (1), *characterizing the fire*. The sub-phenomenon 1.C, *the development of the fire in the cabinet as characterized by its overall burning rate (i.e., total HRR)* was ranked with a high importance with a low to medium model adequacy ranking. The availability of input data was ranked as low with one Panelist ranking of medium. The availability of the validation data was ranked as medium. The feasibility of obtaining new input data was ranked as medium with one Panelist ranking of low. This Panelist felt as though obtaining new validation data for characterizing the overall burning rate for cables is going to be very difficult. The feasibility of getting new validation data was ranked high because the Panelists felt that the capabilities will exist after new input data is collected. Phenomenon 1.I, *the flame spread rate along the cable tray located above the cabinet fire*, the second sub-phenomenon was ranked as high importance. The state of knowledge was ranked low for adequacy and availability while ranked medium for the feasibility of getting new input and validation data. Phenomenon 1.J, *fire growth on cable tray (i.e. HRR)*, the next sub-phenomenon was ranked as high importance. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data. Phenomenon 1.K, *Fire spread from burning cable tray to cabinet below (dripping, downward spread on the riser)*, the last sub-phenomenon was ranked as high importance. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data.

In Table B.62 the top level phenomenon 3, *predicting products of combustion* is shown with one sub-phenomenon that will be discussed further. The importance ranking for phenomenon 3.A, *particulate* was high. The model adequacy rankings were a low to medium. The available input and validation data were low while the feasibility of getting both new input and new validation data were ranked medium.

In Table B.62 the group 4 phenomena, *predicting fire suppression (manual fire brigade),* summary and results are shown. The sub-phenomenon 4.C, *actions (detection, notification, and suppression) by the non emergency responders,* was ranked with a high importance for all but one Panelist who ranked this as medium importance.

The state of knowledge rankings were low for adequacy and available input and validation data. The feasibility of obtaining new input and validation data was ranked as uncertain. The Panelists feel that this phenomenon is in the area of human reliability which is not in their areas of expertise. The next group of phenomena (5) is *damage to SSD cables* which is directly related to the figure of merit for this scenario. The sub-phenomenon, 5.C, *thermal (polymeric) decomposition of SSD cable (melting, charring, and electrical)* was ranked with a majority of high importance with two low and one medium importance rankings. Some of the Panelists could not agree on the importance ranking of this phenomenon. The Panelists who ranked this as low importance basis was because predicting if the cable will fail is more important that predicting the thermal decomposition. The differences are based on what the Panelists feel will be the dominate failure mechanisms for the cable. The state of knowledge rankings were low across all categories.

Table B.61: Level 1 PIRT Results and Summary for Scenario 2b (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
C. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	H	H	H	X	H	H	H		L-M	L	M	M	H
I. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	X	H	H	H		L	L	M	L	M
J. Fire Growth on Cable Tray (i.e., HRR)	H	H	H	X	H	H	H		L	L	M	L	M
K. Fire Spread from Burning Cable Tray to Cabinet Below (Dripping, Downward Spread on the Riser)	H	H	H	X	H	H	H		L	L	M	L	M

Table B.62: Level 1 PIRT Results and Summary for Scenario 2b (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Predicting Products of Combustion													
A. Particulate	H	H	H	X	H	H	H		L-M	L	M	L	M
4. Predicting Fire Suppression (Manual Fire Brigade)													
C. Actions (Detection, Notification, Suppression) by Non Emergency Responders	H	M	H	X	H	H	H		L	L	U	L	U
5. Damage to SSD Cables													
C.Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	H	H	X	H	L	M		L	L	L	L	L

Table B.63: Level 2 PIRT Results and Summary for Scenario 2b (1 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
A. Characterizing the Initiating Event (Ignition of Electrical Fire Start Point)	H	L	L	X	H	L	L		L	L	L	L	L
B. Characterizing the Incipient Stage and Transition to Open Flaming.	U	L	L	X	H	L	L		L	L	L	L	L
D. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics	H	H	H	X	H	H	H		M	M	H	M	H
E. Fire Propagation to Adjacent Cabinets (Including Subsequent Contribution to Fire HRR and POCs)	H	H	H	X	H	H	H		M	M	H	L	H
G. Ignition of the Overhead Cable Tray	H	H	H	X	H	H	H		M	M	H	M	H
H. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	X	H	H	H		M	M	H	M	H

Table B.64: Level 2 PIRT Results and Summary for Scenario 2b (2 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
2. Predicting Detection Response Time													
B. Response of the Detector	H	H	H	X	H	H	H		M	M	H	M	H
3. Predicting Products of Combustion													
B. CO	L	M	H	X	M	M	L		L-M	L	M	L	M
C. HCN	L	M	H	X	M	M	L		L-M	L	M	L	M
D. Acid Gases	L	M	M	X	M	M	L		L-M	L	M	L	M

Table B.65: Level 2 PIRT Results and Summary for Scenario 2b (3 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
4. Predicting Fire Suppression (Manual Fire Brigade)													
A. Emergency Response Time	H	H	H	X	H	H	H		M-H	M	H	M	H
B. Brigade Performance Based on Fire Size	H	H	H	X	H	H	H		M	L-M	H	L	H
5. Damage to SSD Cables													
A. Thermal Response of Cable	L	H	H	X	H	H	H		M	M	H	M	H
B. Electrical Degradation of SSD Cable	H	H	H	X	H	H	H		M	M	H	L	H
6. Predicting Enclosure Environment													
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	H	H	X	H	H	H		M	M	H	M	H

Table B.66: Level 4 PIRT Results and Summary for Scenario 2b (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Fire													
F. Flame Extension from Cabinet	H	H	H	X	H	H	H		H	L	H	L	H
2. Predicting Detection Response Time													
A. Smoke Transport from Source to Detector	H	H	H	X	H	H	H		H	H	NA	M	H
5. Damage to SSD Cables													
D. Ignition of Non-SSD Cable(s) in Same Tray	L	L	L	X	L	L	L		M	M	H	M	H
E. Mechanical Failure of SSD Target Tray	M	L	L	X	L	L	L		L	H	NA	L	H
F. Mechanical Failure of the Tray Above the Cabinets	H	L	L	X	L	L	L		L	H	NA	L	H

Table B.67: Level 4 PIRT Results and Summary for Scenario 2b (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
6. Predicting Enclosure Environment													
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	X	H	H	H		H	H	H	H	H
B. Heat Transfer to Room Enclosure Surfaces and Contents	M	M	M	X	M	M	H		H	H	H	H	H

B.3 Fire Scenario 2c Description

The PIRT Fire Scenario 2c is another variation of Scenario 2a. For this case the initiating event resulting in a fire is different. The initiating event is a high energy arcing fault in a medium voltage (4.16 kV) cabinet in the SWGR. The target still remains the SSD cables located in a cable tray 0.6 m (2 ft) above the cabinet of origin. Another picture of the switchgear room may be observed in Figure B.3; the red cabinet is depicted as the cabinet of fire origin.

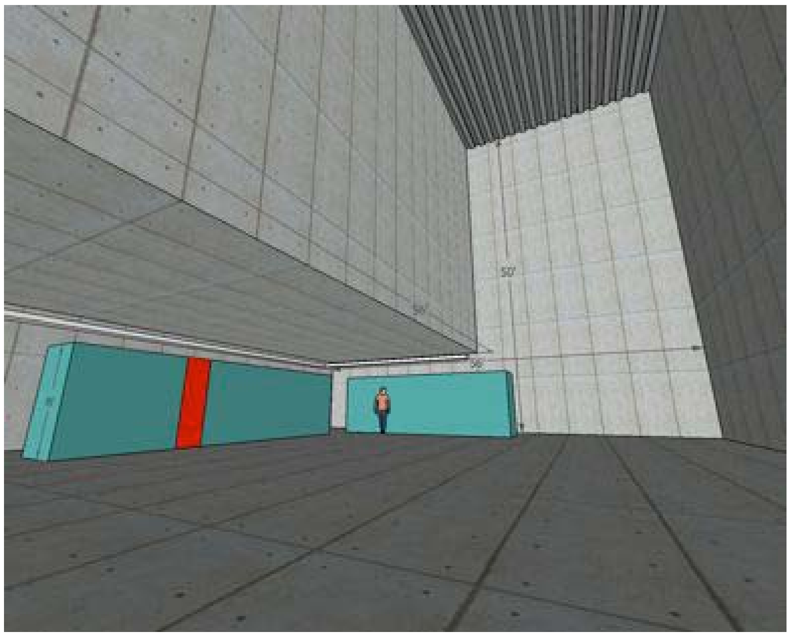


Figure 0-1: Generic View of Switchgear Room

B.3.1 Phenomena Identification

The list of phenomena identified for this scenario will be discussed in this section. The Panelists identified groups of phenomena that include sub-phenomena. The order of the groups of phenomena does not indict the level of importance. There was a new group of phenomena added for this scenario. This was *characterizing the initiating event (initial high energy arc fault)* which includes eight sub-phenomena. The sub-phenomenon *projectiles damaging the SSD cable* under the top level phenomenon *damage to SSD cable* was added to Scenario 2c. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *characterizing the initiating event (initial high energy arc fault)*.

A. Characterizing the electrical energy released by initial fault event.
B. “Blast” dynamics.
C. Ignition of any secondary materials due to electric arc.
D. Cabinet venting (blowing doors open, failing cable penetration seals) pressure effects of the initial fault.

E. Regarding cabinet contents due to initial fault.
F. Arc plasma burning through cabinet walls.
G. Projectiles.
H. Cascading faults.

Phenomena 2: *characterizing the fire*.
A. The development of the fire in the cabinet as characterized by its overall burning rate (i.e., total HHR).
B. Cabinet enclosure effects, the effects of ventilation on combustion dynamics.
C. Fire propagation to adjacent cabinets (including subsequent contribution to fire HRR and POCs).
D. Flame extension from cabinet.
E. Ignition of overhead cable tray.
F. Fire propagation along cable riser from cabinet to tray (vertically).
G. The flame spread rate along the cable tray located above the cabinet fire.

Phenomena 3: *predicting detection response time*.
A. Smoke transport from source to detector.
B. Survival of the smoke detectors given initial event (new phenomena from Scenario 2a).
C. Response of the detector

Phenomena 4: *predicting products of combustion*.
A. Production of smoke particulate.
B. Production of CO.
C. Production of HCN.
D. Production of Acid Gases.

Phenomena 5: *predicting fire suppression specifically to the manual fire brigade*.
A. Predicting the emergency response time.
B. Predicting the brigade performance based on fire size.
C. Predicting the actions (detection and notification) by non emergency responders (suppression was not taken into account for this scenario).

Phenomena 6: *damage to SSD cables*.
A. Thermal response of the cable.
B. Electrical degradation of SSD cable.
C. Thermal (polymeric) decomposition of SSD cable (melting, charring, electrical).
D. Ignition of non-SSD cable(s) in same tray.
E. Projectiles damaging the SSD cables.
F. Mechanical failure of tray

Phenomena 7: *predicting enclosure environment* is the next group of phenomena.
A. Heat and smoke transport (including other POCs).
B. Heat transfer to enclosure surfaces and contents.
C. Performance of ventilation system (airflow, operation of dampers, effects of POC on vent-flow).

Phenomena 8: *predicting structural* response.
A. Spalling fragments impacting cables.

B3.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table B.67. The listed phenomena with the importance rankings are listed in Table B.68 through Table B.75.[5] The column next to the importance rankings includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using randomly assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table B.67: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. Not necessary to model this parameter for this application.
Uncertain (U)	First order of importance to figure of merit.

[5] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

Table B.68: Importance Ranking for Scenario 2c, Characterizing the Initiating Event (Initial High Energy Arc Fault)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Characterizing the Initiating Event (Initial High Energy Arc Fault)								This includes the conditions in cabinet (e.g. pressure, temperature rise, and energy).
A. Characterizing the Electrical Energy Released by Initial Fault Event	H	H	H	X	H	H	H	
B. "Blast" Dynamics	M	H	H	X	H	H	H	Considered pressure and temperature profiles. Panelist 1's medium ranking is based on that the pressure effects are not going to be as extensive as the thermal effects.
C. Ignition of Any Secondary Materials Due to Electric Arc	H	H	H	X	H	H	H	
D. Cabinet Venting (Blowing Doors Open, Failing Cable Penetration Seals) Pressure Effects of the Initial Fault	M	H	H	X	H	H	H	Panelist 1's medium ranking based on that the pressure effects are not going to be as extensive as the thermal effects.
E. Rearranging Cabinet Contents Due to Initial Fault	M	M	M	X	M	M	M	
F. Arc plasma Burning Through Cabinet Walls	H	H	H	X	H	H	H	The importance rankings are high because the concerns with this phenomenon are the ventilation and fire spread effects to predicting the high energy arc fault.
G. Projectiles	L	L	L	X	L	L	L	
H. Cascading Faults	H	H	H	X	H	H	H	

Table B.69: Importance Ranking for Scenario 2c, Characterizing the Fire

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Characterizing the Fire								
A. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	H	H	H	X	H	H	H	
B. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics, Heating Enclosure, Re-Radiation	H	H	H	X	H	H	H	
C. Fire Propagation to Adjacent Cabinets	H	H	H	X	H	H	H	
D. Flame Extension from Cabinet	H	H	H	X	H	H	H	
E. Ignition of the Overhead Cable Tray	H	H	H	X	H	H	H	
F. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	X	H	H	H	
G. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	X	H	H	H	

Table B.70: Importance Ranking for Scenario 2c, Predicting Detection Response Time

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Predicting Detection Response Time								All of these phenomena are important because the panel is not sure if the initial event will be detected by plant personnel.
A. Smoke Transport from Source to Detector	H	H	H	X	H	H	H	
B. Survival of the Detector Given the Initial Event	H	H	H	X	H	H	H	
C. Response of the Detector	H	H	H	X	H	H	H	

Table B.71: Importance Ranking for Scenario 2c, Predicting Products of Combustion

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Predicting Products of Combustion								
A. Particulate	H	H	H	X	H	H	H	Panelist 2's high for just particulate is based on its larger impact on the responders in terms of manual suppression and detection. Panelist 3's basis for the high ranking is based on knowing the environment for the first responders being important.
B. CO	L	M	H	X	M	M	L	Panelist 7's high for particulate versus low for the others reflects the importance for manual detection, the lows are unimportant to the target, detection, and emergency responders.
C. HCN	L	M	H	X	M	M	L	
D. Acid Gases	L	M	M	X	M	M	L	

Table B.72: Importance Ranking for Scenario 2c, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Predicting Fire Suppression (Manual Fire Brigade)								
A. Emergency Response Time	H	H	H	X	H	H	H	It was clarified that this phenomenon included all the people that are a part of the emergency response procedure.
B. Brigade Performance Based on Fire Size	H	H	H	X	H	H	H	
C. Actions (Detection & Notification) by Non Emergency Responders	H	M	H	X	H	H	H	Panelist 2's medium is based on while this phenomenon is important, predicting the response time is weighed as more important.

Table B.73: Importance Ranking for Scenario 2c, Damage to SSD Cables

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Damage to SSD Cables								
A. Thermal Response of Cable	L	H	H	X	H	H	H	
B. Electrical Degradation of SSD Cable	H	H	H	X	H	H	H	The thermal response of cables and thermal decomposition of SSD cable are steps to achieve electrical degradation of SSD cable.
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	H	H	X	H	L	M	Panelist 6's low ranking that they presume that it is more important when the cable is going to fail.
D. Ignition of Non-SSD Cable(s) in Same Tray	H	H	H	X	H	H	H	
E. Projectiles Damaging the SSD Cable	L	L	L	X	L	L	L	
F. Mechanical Failure of Tray	H	L	L	X	L	L	L	Panelist 2's low is based on that cable tray will withstand the fire longer than the cable. Panelist 6 agrees that the cable is going to go fail before the tray. Panelist 1's high ranking is based on if the tray fails, then this phenomenon will directly impact fire propagation.

Table B.74: Importance Ranking for Scenario 2c, Predicting Enclosure Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
7. Predicting Enclosure Environment								
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	X	H	H	H	
B. Heat Transfer to Enclosure Surfaces and Contents	M	M	M	X	M	M	M	
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	M	H	X	H	H	M	Panelist 2's basis for the medium ranking due to the large space in the SWGR and how that will impact the overall ventilation.

Table B.75: Importance Ranking for Scenario 2c, Predicting Structural Response

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
8. Predicting Structural Response								
A. Spalling Fragments Impacting Cables	U	L	U	X	U	L	L	Panelist 6's low ranking is based on if the fire scenario is to the point of spalling the environment is going to be bad enough to have already destroyed the cable.

B.3.3 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge for the phenomena is identified. For this stage of the PIRT, the panel ranks the state of knowledge as a group (rather than as individuals). The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table B.79 through Table B.88 are the state of knowledge rankings for the identified phenomena for Scenario 2c.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First, is the general adequacy of the existing and generally available[6] fire models to deal with the identified phenomena. The second are, is the adequacy of data needed to support model development and model validation. Included with this second area is an assessment of the feasibility of getting new development and validation data. The feasibility question was not pursued for phenomena where the existing data availability was ranked "high."

The list below gives the five state of knowledge parameters and cites the table that gives the definitions of rankings for each.

1. Model Adequacy (Table B.76)
2. Available Input Data (Table B.77)
3. Feasibility of Getting New Input Data (Table B.78)
4. Available Data for Validation (Table B.77)
5. Feasibility of Getting New Validation Data (Table B.78)

This section also identifies key parameters associated with the scenario phenomena and may be illustrated in Table B.89 through Table B.95. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed for each key parameter. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., how important is the key parameter in the context of the associated phenomenon and what is the corresponding state of knowledge?).

[6] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table B.76: Model Adequacy Ranking Definitions

Model Adequacy Ranking Definitions	
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 B.77: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

Data Adequacy for Existing Input Data and Validation Data Ranking Definitions	
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 B.78: Data Adequacy for Potential to Develop New Data Ranking Definitions

Data Adequacy for Potential to Develop New Data Rankings Definitions	
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.

Table B.79: State of Knowledge Rankings for Scenario 2c, Characterizing the Initiating Event (Initial High Energy Arc Fault) (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Initiating Event (Initial High Energy Arc Fault)						
A. Characterizing the Electrical Energy Released by Initial Fault Event	H	H	H	H	NA[7]	
B. "Blast" Dynamics	L	L	M	L	M	
C. Ignition of Any Secondary Materials Due to Electric Arc	L	L	M	L	M	The rankings are based on the given knowledge of the arc fault event. Specifically the point between ignition and volatilization.
D. Cabinet Venting (Blowing Doors Open, Failing Cable Penetration Seals) Pressure Effects of the Initial Fault	H	H	H	H	H	This was ranked high because of the nature of the high energy arc fault for this scenario; it will be assumed the door is opened. If this scenario involved a lower energy case, the state of knowledge would be low.
E. Rearranging Cabinet Contents Due to Initial Fault	L	L	L	L	L	

[7] The Non-Applicable (NA) ranking is either explained in the notes column or if the ranking for the available input or available validation data is high then the feasibility of obtaining new data was not necessary to rank.

Table B.80: State of Knowledge Rankings for Scenario 2c, Characterizing the Initiating Event (Initial High Energy Arc Fault) (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Characterizing the Initiating Event (Initial High Energy Arc Fault) (Cont.)						
F. Arc plasma Burning Through Cabinet Walls	M	M	H	M	H	
G. Projectiles	L	L	L	L	L	The feasibility of getting new data is ranked low because there is a concern with the complexity of reproducing the same experiments. The ranking is low because reproducing the same experiment is going to be really tough and complex.
H. Cascading Faults	L-M	L	M	L	M	The low to medium model adequacy ranking is based on that the experts are aware that this phenomenon can happen, but the ability to predict this phenomenon does not exist.

Table B.81: State of Knowledge Rankings for Scenario 2c, Characterizing the Fire (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Characterizing the Fire						
A. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total HRR)	L	L	L	L	L	
B. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics, Heating Enclosure, Re-Radiation	L	L	M	L	M	The different rankings for Scenario 2c versus 2a and 2b are due to the initial arc event causing the rest of the fire scenario to have a different configuration. After the initial arc, there are many unknown parameters which include the amount of consumed contents and the displacement of the internal components.
C. Fire Propagation to Adjacent Cabinets	M	M	H	L	H	The Panelists ranked this phenomenon assuming that both the fire source is well characterized and the connections between the electrical cabinets are known.

Table B.82: State of Knowledge Rankings for Scenario 2c, Characterizing the Fire (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Characterizing the Fire (Cont.)						
D. Flame Extension from Cabinet	H	L	H	L	H	Assuming a well characterized source, i.e. the first cabinet. Also the excess pyrolysis is needed to be known. The availability of input data is low here because the enclosure environment is needed.
E. Ignition of the Overhead Cable Tray	M	M	H	M	H	Assuming a well characterized source with known flame extension
F. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	M	M	H	M	H	
G. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	L	L	M	L	M	The rankings are based on complications such as geometry, materials, and porosity.

Table B.83: State of Knowledge Rankings for Scenario 2c, Predicting Detection Response Time

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Predicting Detection Response Time						
A. Smoke Transport from Source to Detector	H	H	NA	M	H	
B. Survival of the Detector Given the Initial Event	L	L	L	L	L	
C. Response of the Detector	M	M	H	M	H	

Table B.84: State of Knowledge Rankings for Scenario 2c, Predicting Product of Combustion

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Predicting Products of Combustion						
A. Particulate	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
B. CO	L-M	L	M	L	M	For model adequacy; Panelist 1 and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
C. HCN	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L-M, the rest are M.
D. Acid Gases	L-M	L	M	L	M	For model adequacy; Panelist 1, Panelist 7, and Panelist 5 are low, Panelist 3 is L-M, the rest are M.

Table B.85: State of Knowledge Rankings for Scenario 2c, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
5. Predicting Fire Suppression (Manual Fire Brigade)						
A. Emergency Response Time	M-H	M	H	M	H	The range in model adequacy rankings based on that the panel felt that this phenomenon is outside the fire physics area.
B. Brigade Performance Based on Fire Size	M	L-M	H	L	H	Please note that this is a fire physics group and not a human factors group. The range in available input data ranking is that this data actually comes from incident events, so it is not all inclusive.
C. Actions (Detection and Notification) by Non Emergency Responders	L	L	U	L	U	This is outside the fire physics area.

Table B.86: State of Knowledge Rankings for Scenario 2c, Damage to SSD Cables

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
6. Damage to SSD Cables						
A. Thermal Response of Cable	M	M	H	M	H	
B. Electrical Degradation of SSD Cable	M	M	H	L	H	
C. Thermal (Polymeric) Decomposition of SSD Cable (Melting, Charring, Electrical)	L	L	L	L	L	
D. Ignition of Non-SSD Cable(s) in Same Tray	M	M	H	M	H	Assuming the environment is well known.
E. Projectiles Damaging the SSD Cable	L	L	L	L	L	
F. Mechanical Failure of Tray	L	H	NA	L	H	This phenomenon includes the mechanical failure of the tray causing damage to the SSD cable.

Table B.87: State of Knowledge Rankings for Scenario 2c, Predicting Enclosure Environment

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
7. Predicting Enclosure Environment						
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	H	H	
B. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	L	H	
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	M	M	H	M	H	The areas of weaknesses for available input data include fusible links on dampers and filter clogging.

Table B.88: State of Knowledge Rankings for Scenario 2c, Predicting Structural Response

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
8. Predicting Structural Response						
A. Spalling Fragments Impacting Cables	L	L	L	L	L	

Table B.89: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Initiating Event (Initial High Energy Arc Fault) (1 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Initiating Event (Initial High Energy Arc Fault)				
A. Characterizing the Electrical Energy Released by Initial Fault Event	Voltage/Current	H	H	Circuit voltage and available short circuit current.
	Geometry	H	H	
	Circuit Protection Performance	H	H	
	Duration	H	M-L	
B. "Blast" Dynamics	Initial Energy (i.e. the Item Above)	H	M-H	Medium state of knowledge ranking is based on how the correlations have uncertainty relative to the treatment of conservatism/safety factors/ best estimate and how this would affect this scenario.
	Enclosure Geometry	H	M	This parameter is specifically related to how the blast dynamics will be affected by the geometry.
	Response of Materials (e.g. Venting the Blast)	H	L	

Table B.90: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Initiating Event (Initial High Energy Arc Fault) (2 of 2)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Characterizing the Initiating Event (Initial High Energy Arc Fault) (Cont.)				
C. Ignition of Any Secondary Materials Due to Electric Arc	Pulse Nature of Input (i.e., Ablation vs. Ignition)	H	L	
D. Cabinet Venting (Blowing Doors Open, Failing Cable Penetration Seals) Pressure Effects of the Initial Fault	Door/Back Access Response	H	L	
	Seal Response	M	L	
	Fixed Side/Top Panel Response	H	L	

Table B.91: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Fire (1 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Characterizing the Fire				
A. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total Heat Release Rate)	Internal Partitions	H	H	If the external panels create the ventilation controlled condition, this phenomena is not important.
	Type, Location, and Configuration of Fuel (Bundling)	H	M	
	Characterizing the Proportion of Thermal Radiation versus Convective HRR.	L-M	H	Panelist 1's ranking is low for importance because it's a constant that's well known and varies little.
	Flame Structure and Plume Behavior within the Cabinet.	H	L	This parameter was ranked with high importance because it influences the spread of fire within the cabinet.

Table B.92: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Fire (2 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Characterizing the Fire (Cont.)				
B. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics, Heating Enclosure, Re-Radiation	Air Flow within and Through the Burning Electrical Cabinet; Specifically, the Effects of the Ventilation Openings, Open Versus Closed Doors, Ventilation Opening Size, etc., on this Behavior	H	M	
	Flame Structure and Plume Behavior within Cabinet.	H	L	
	Deformation of the Cabinet Boundary Panels	H	L	
C. Fire Propagation to Adjacent Cabinets	Deformation of the Cabinet Boundary Panels	H	L	

Table B.93: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Fire (3 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Characterizing the Fire (Cont.)				
E. Ignition of the Overhead Cable Tray	Pilot/Un-Pilot	M	M	
	Ignition Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	This key parameter includes both the conduction into cables and down the length of the cables.
	Physical Response (Melting, Dripping, Charring)	H	L	
F. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	Heat Conduction along Cables	M	M	
	Flame Length	H	M	
	HRR of Burning Section of Cable	H	M	
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	This key parameter depends on the ignition criteria of the unburned cable.

Table B.94: Key Parameters and Their Rankings for Scenario 2c, Characterizing the Fire (4 of 4)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Characterizing the Fire (Cont.)				
G. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	Flame Radiation ahead of the Flame Foot	H	M	
	Heat Conduction through Cable Bundles/Arrays	H	M	
	Physical Response (Melting, Dripping, Charring)	H	L	
	HRR of Burning Section of Cable	H	M	The modeling ability is low but the state of knowledge is better.
	Fire Spread Criteria (e.g., Critical Temperature, Mass Loss Rate)	H	M	
	Fire Retardant Coatings	H	M	
	Porosity (% Fill of Tray, Air Spaces between Cables)	H	L	
	Fire Retardant Materials (i.e. Cable Jackets)	H	M	

Table B.95: Key Parameters and Their Rankings for Scenario 2c, Predicting Fire Suppression (Manual Fire Brigade)

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
5. Predicting Fire Suppression (Manual Fire Brigade)				
A. Emergency Response Time	Procedural Verification of Fire before Calling Out Fire Brigade			

B.3.4 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 2c. The phenomena and their rankings were analyzed using four criteria that will be presented here. The first level phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table B.96 through B.97. Level two phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table B.98 through Table B.100. The third level phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. There is one sub-phenomenon for this level and it is shown in Table B.101. The fourth level are those phenomena that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking , or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table B.102 through B.103. The Level 1 phenomena are going to be discussed further in this section.

The first group of phenomena (1) that is going to be discussed in this section is the new phenomenon that was added with the alteration of Scenarios 2a to 2c. This phenomenon is *characterizing the initiating event (initial high energy arc fault)* which includes the conditions of the cabinet (e.g. explosive pressure, temperature rise, and energy) is shown in Table B.96. The first sub-phenomenon is 1.B, the *"blast" dynamics* was ranked as high importance by the panel except for Panelist 1 who ranked the phenomenon as medium importance. Panelist 1 feels that the thermal effects are going to be more extensive than the explosive pressure effects. The state of knowledge rankings were low for adequacy and availability of input and validation data. The feasibility of obtaining new input and validation data was ranked as medium. The next sub-phenomenon in Table B.96 is 1.C, the *ignition of any secondary materials due to electric arc* which was ranked with a high importance ranking with a low to medium state of knowledge ranking. The medium state of knowledge rankings were for the feasibility of obtaining new input and validation data. The final sub-phenomenon is 1.H, *cascading faults* which also has a high importance ranking. The state of knowledge rankings were low to medium for adequacy due to the Panelists opinion that they know this will happen but the ability to predict this phenomenon is poor. The available input and validation data were ranked low while the feasibility of obtaining new input and validation data were ranked medium.

The next group of phenomena (2) in Table B.96 is *characterizing the* fire. The first sub-phenomenon is 2.A, *the development of the fire in the cabinet as characterized by its overall burning rate (i.e., total HRR)*. The panel agreed on the importance ranking for this phenomenon as high with a low state of knowledge ranking. This is different from the state of knowledge for Scenario 2a which is due to the uncertainties with the initial electric arc event. The next sub-phenomenon is 2.B, *cabinet enclosure effects, the effects of ventilation on combustion dynamics.* The high importance ranking was agreed upon by the Panelists. The state of knowledge rankings were low for adequacy and available input and validation data. The medium rankings were for the feasibility of obtaining new input and validation data. The last sub-phenomenon for Table B.96 is 2.G, t*he flame spread rate along the cable tray located above the cabinet fire*, was ranked as high importance. The state of knowledge was ranked as low for adequacy and availability while ranked as medium for the feasibility of getting new input and validation data.

In Table B.97 the group of phenomena (3), *predicting detection response time* only has one sub-phenomena to be discussed further. This sub-phenomenon, 3.B, is *the survival of the detector given the initial event* which has a high importance ranking with a low state of knowledge. This phenomenon was ranked as high importance because the panel felt that predicting if the detectors would survive will directly effect the prediction of the overall time line of the event. The next top level phenomenon (4) is *predicting products of combustion*. The sub-phenomenon 4.A, is *particulate* which was ranked as high importance with a low to medium state of knowledge. The available input and validation data were low while the feasibility of getting both new input and new validation data were ranked medium.

Another group of phenomena (5) in Table B.97 is, *predicting fire suppression (manual fire brigade)*. The sub-phenomenon, 5.C, the *actions (detection, notification, suppression) by the non emergency responders* was ranked with a high importance for all but one Panelist who ranked this as medium importance. The state of knowledge rankings were ranked as low for adequacy and available input and validation data. The feasibility of obtaining new input and validation data was ranked as uncertain. The uncertain rankings are based on that this is a human reliability phenomenon and the experts are fire physics experts. The last top level phenomenon (6) is *damage to SSD cables* which is directly related to the figure of merit for this scenario. The sub-phenomenon, 6.C, *thermal (polymeric) decomposition of SSD cable (melting, charring, electrical)* was ranked with a majority of high importance; two medium and one low. The differences are based on what the Panelists feel will be the dominate failure mechanisms for the SSD cable. The state of knowledge rankings were all low for this phenomenon.

Table B.96: Level 1 PIRT Results and Summary for Scenario 2c (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Initiating Event (Initial High Energy arc Fault)													
B. "Blast" Dynamics	M	H	H	X	H	H	H		L	L	M	L	M
C. Ignition of Any Secondary Materials Due to Electric Arc	H	H	H	X	H	H	H		L	L	M	L	M
H. Cascading Faults	H	H	H	X	H	H	H		L-M	L	M	L	M
2. Characterizing the Fire													
A. The Development of the Fire in the Cabinet as Characterized by its Overall Burning Rate (i.e., Total HRR)	H	H	H	X	H	H	H		L	L	L	L	L
B. Cabinet Enclosure Effects, the Effects of Ventilation on Combustion Dynamics, Heating Enclosure, Re-Radiation	H	H	H	X	H	H	H		L	L	M	L	M
G. The Flame Spread Rate Along the Cable Tray Located Above the Cabinet Fire	H	H	H	X	H	H	H		L	L	M	L	M

Table B.97: Level 1 PIRT Results and Summary for Scenario 2c (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Predicting Detection Response Time													
B. Survival of the Detector Given the Initial Event	H	H	H	X	H	H	H		L	L	L	L	L
4. Predicting Products of Combustion													
A. Particulate	H	H	H	X	H	H	H		L-M	L	M	L	M
5. Predicting Fire Suppression (Manual Fire Brigade)													
C. Actions (Detection and Notification) by Non Emergency Responders	H	M	H	X	H	H	H		L	L	U	L	U
6. Damage to SSC Cables													
C. Thermal (Polymeric) Decomposition of SSC Cable (Melting, Charring, Electrical)	L	H	H	X	H	L	M		L	L	L	L	L

Table B.98: Level 2 PIRT Results and Summary for Scenario 2c (1 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Initiating Event (Initial High Energy arc Fault)													
E. Rearranging Cabinet Contents Due to Initial Fault	M	M	M	X	M	M	M		L	L	L	L	L
F. Arc plasma Burning Through Cabinet Walls	H	H	H	X	H	H	H		M	M	H	M	H
2. Characterizing the Fire													
C. Fire Propagation to Adjacent Cabinets	H	H	H	X	H	H	H		M	M	H	L	H
E. Ignition of the Overhead Cable Tray	H	H	H	X	H	H	H		M	M	H	M	H
F. Fire Propagation Along Cable Riser from Cabinet to Tray (Vertically)	H	H	H	X	H	H	H		M	M	H	M	H

Table B.99: Level 2 PIRT Results and Summary for Scenario 2c (2 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Predicting Detection Response Time													
C. Response of the Detector	H	H	H	X	H	H	H		M	M	H	M	H
4. Predicting Products of Combustion													
B. CO	L	M	H	X	M	M	L		L-M	L	M	L	M
C. HCN	L	M	H	X	M	M	L		L-M	L	M	L	M
D. Acid Gases	L	M	M	X	M	M	L		L-M	L	M	L	M
5. Predicting Fire Suppression (Manual Fire Brigade)													
A. Emergency Response Time	H	H	H	X	H	H	H		M-H	M	H	M	H
B. Brigade Performance Based on Fire Size	H	H	H	X	H	H	H		M	L-M	H	L	H

Table B.100: Level 2 PIRT Results and Summary for Scenario 2c (3 of 3)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
6. Damage to SSC Cables													
A. Thermal Response of Cable	L	H	H	X	H	H	H		M	M	H	M	H
B. Electrical Degradation of SSC Cable	H	H	H	X	H	H	H		M	M	H	L	H
D. Ignition of Non-SSC Cable(s) in Same Tray	H	H	H	X	H	H	H		M	M	H	M	H
7. Predicting Enclosure Environment													
C. Performance of Ventilation System (Airflow, Operation of Dampers, Effects of POC on Vent-Flow)	H	M	H	X	H	H	M		M	M	H	M	H

Table B.101: Level 3 PIRT Results and Summary for Scenario 2c

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
8. Predicting Structural Response													
A. Spalling Fragments Impacting Cables	U	L	U	X	U	L	L		L	L	L	L	L

Table B.102: Level 4 PIRT Results and Summary for Scenario 2c (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Characterizing the Initiating Event (Initial High Energy arc Fault)													
A. Characterizing the Electrical Energy Released by Initial Fault Event	H	H	H	X	H	H	H		H	H	H	H	NA
D. Cabinet Venting (Blowing Doors Open, Failing Cable Penetration Seals) Pressure Effects of the Initial Fault	M	H	H	X	H	H	H		H	H	H	H	H
G. Projectiles	L	L	L	X	L	L	L		L	L	L	L	L
2. Characterizing the Fire													
D. Flame Extension from Cabinet	H	H	H	X	H	H	H		H	L	H	L	H
3. Predicting Detection Response Time													
A. Smoke Transport from Source to Detector	H	H	H	X	H	H	H		H	H	NA	M	H

Table B.103: Level 4 PIRT Results and Summary for Scenario 2c (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
5. Predicting Fire Suppression (Manual Fire Brigade)													
C. Actions (Detection and Notification) by Non Emergency Responders	H	M	H	X	H	H	H		L	L	U	L	U
6. Damage to SSC Cables													
E. Projectiles Damaging the SSC Cable	L	L	L	X	L	L	L		L	L	L	L	L
F. Mechanical Failure of Tray	H	L	L	X	L	L	L		L	H	NA	L	H
7. Predicting Enclosure Environment				X									
A. Heat and Smoke Transport (Including Other Products of Combustion)	H	H	H	X	H	H	H		H	H	H	H	H
B. Heat Transfer to Enclosure Surfaces and Contents	M	M	M	X	M	M	M		H	H	H	H	H

APPENDIX C: PIRT FIRE SCENARIO 3

PIRT fire Scenario 3 has three different scenario variations that were evaluated, namely: lube oil pool fire, lube oil spray fire, and a lube oil pool fire with a different target than the first scenario.

C.1 Fire Scenario 3a Pool Fire Description

The pool fire for Scenario 3a will be discussed in this section. There is a pool of lube oil that ignites in the area of the main turbine lube oil tank which is located on the elevation below the operating deck. The dimensions of the operating deck are 69 m (228 ft) by 95 m (311 ft) by 15 m (50 ft) high and the columns located throughout the deck floor are 152 cm (60 in) wide, which is represented in Figure C.4. The ceiling beams are between 61 and 91 cm (24 to 36 in) deep which is illustrated in Figure C.7. The single fixed-pane, industrial glass widows on the exterior wall of the turbine building are 12 m (40 ft) high and depicted in Figure C.8. The postulated scenario located one elevation below the operating deck with dimensions of 99 m (326 ft) by 100 m (329 ft) by 4.6 m (15 ft) high. There is smoke detection on the ceiling of the operating deck. There is smoke detection and local suppression (fusible-link actuated water sprinkler system) one elevation below the vicinity of the lube oil tank and columns which is illustrated in Figure C.5. There is only natural ventilation in the turbine hall shown in Figure C.1. For this scenario the NPP is a two unit plant.

The main control room (MCR) is at the same elevation as the operating deck of the turbine building. The turbine building is separated from the MRC by a 0.9 m (3 ft) thick concrete wall. The failure of the structural steel in the turbine building and subsequent collapse will not pull the control building down. There is a 0.3 m (1 ft) hole in the wall that separates the MRC from the turbine building, which is depicted in Figure C.2. The difference in pressure between the MCR and the turbine building is between 0.005 and 0.009 psi or 31 to 62 Pa (1/8” and 1/4" H_2O). There are hatches, stairwells, and floor grating in the slab between these two elevations, which allows combustion products to flow up into the operating deck. C.2 presents one of the turbines on the operating deck and the postulated hole in the barrier to the MRC. The yellow cylinder in the figure is the tank of lube oil. Examples of lube oil tanks commonly found in NPP are shown in Figure C.10 and Figure C.11. A crane in the turbine building used to move the equipment is shown in Figure C.7. There are fusible link roof vents in the turbine building.

The pool fire for this scenario consists of 14,000 gallons (53,000 liters) of lube oil that leaked out of the tank into a dike. The leak is postulated on the pressurized side of the tank; the lube oil will come out very fast and very hot. The dike area’s dimensions are 6.1 m (20 ft) by 4.6 m (15 ft) wide. The target for this scenario is the equipment in the MCR; including safety related and safe shutdown (SSD) equipment. The figure of merit is damage to the safety related equipment controls in the MCR (How important are the identified phenomena to determining whether the MCR equipment will be damaged during the fire).

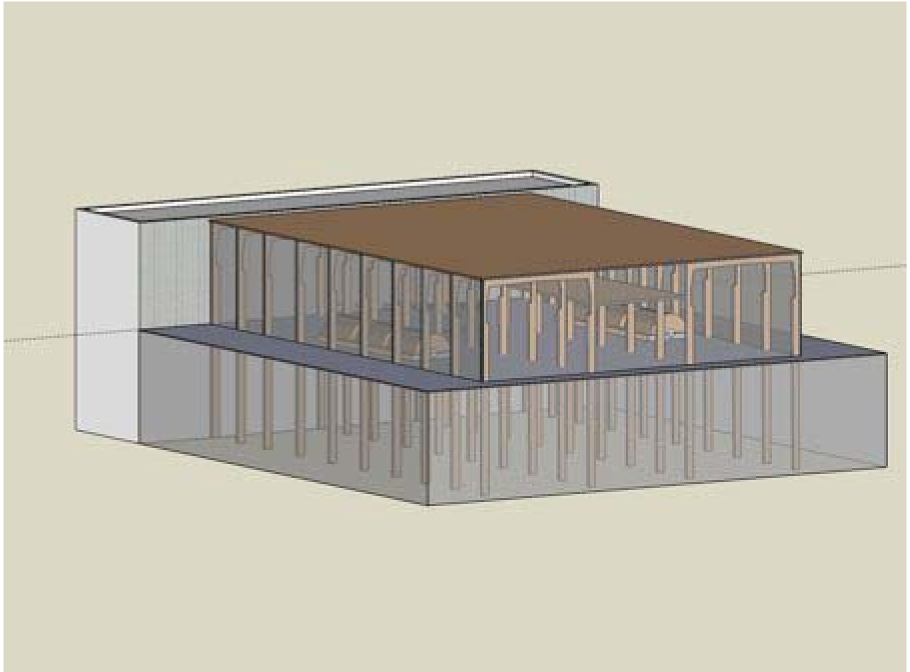


Figure C.1: Layout of Turbine Hall

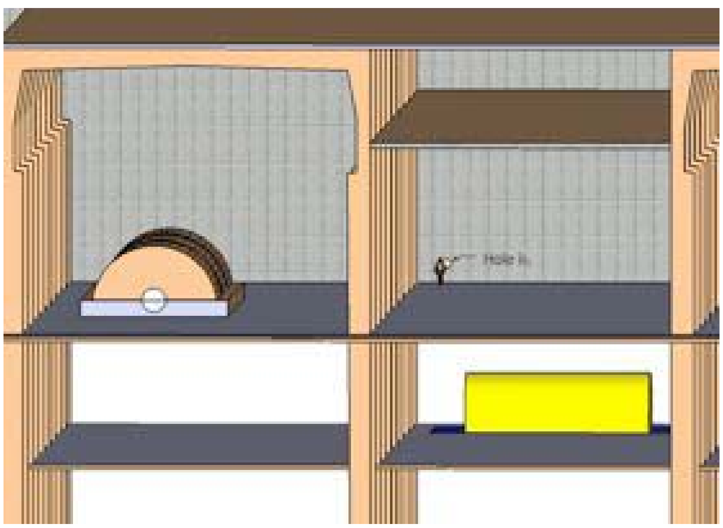


Figure C.2: Close-up of Turbine Hall

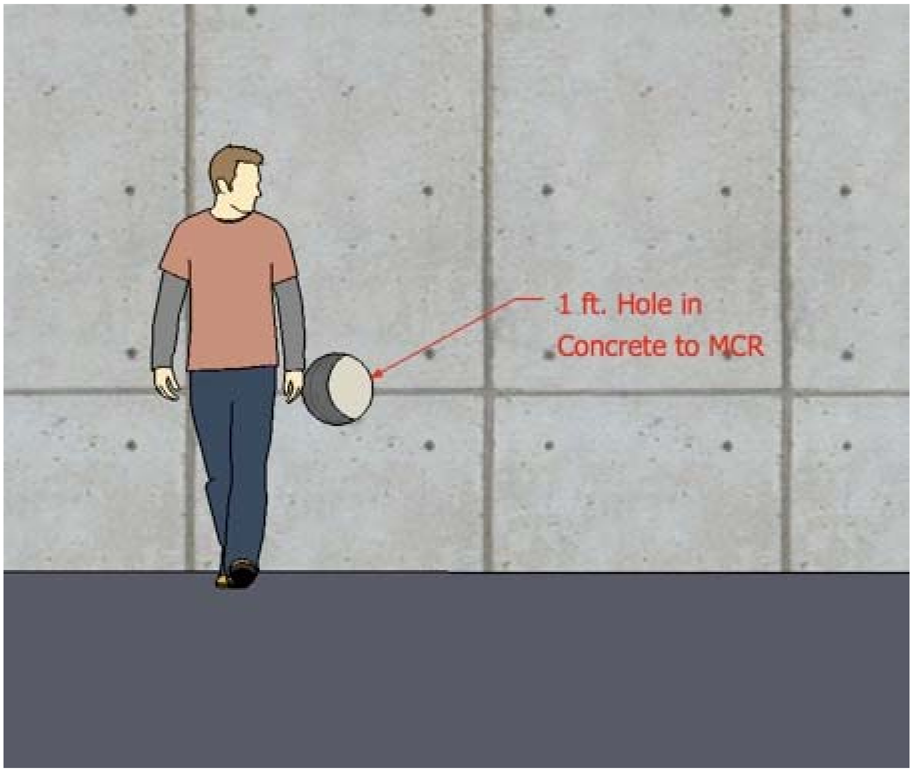


Figure C.3: Postulated Hole in Concrete Wall Connected to MCR

Figure C.4: Example of the Steel Beams in Turbine Hall

Figure C.5: View of Steel Beam Looking up at Ceiling Depicting Beam Sprinklers

Figure C.6: Example of the Open-Grate Stairs and Walkway with Sprinkler Underneath

Figure C.7: Example of the Roof Configuration in Turbine Hall

Figure C.8: Example of the Windows in Turbine Hall

Figure C.9: Example of Cable Trays in Turbine Hall

Figure C.10: Example of a Lube Oil Tank in Turbine Hall

Figure C.11: Second Example of a Lube Oil Tank in Turbine Hall

C.1.1 Phenomena Identification

The list of phenomena identified for this scenario will be discussed in this section. The Panelists identified groups of phenomena which include sub-phenomena. The order of the phenomena groups does not indicate the level of importance. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon1: the *fire source*.

A. Heat release rate (HRR) for the fire confined to the pool area.
B. Pool boil over after activation of suppression.
C. Water filling of the pool and spill over. This is more specific to if the sprinkler system activates and how there will be added volume in the dike spill area.
D. Water induced splattering of burning oil.
E. Effect of obstructions within the area of the pool on fire behavior and HRR.
F. Tank water-spray system effect on HRR reduction. This is specific to how the sprinkler system could have an impact on cooling the fire.
G. Particulate production, specifically smoke particulate.
H. Particulate scrubbing by the water spray. This phenomenon is specific to the effects of the sprinkler system on scrubbing down the smoke particulates.
I. Carbon monoxide (CO) production.

Phenomenon 2: *automatic water spray systems*.

A. Activation time of tank spray system.
B. Spray cooling of general environment by the tank spray system.
C. Activation time of sprinklers under deck.
D. Activation of too many sprinklers on under deck overwhelming the design basis for the sprinkler system.
E. Fire suppression by under deck sprinklers
F. Spray cooling of general environment by the sprinklers under deck
G. Activation time of water spray on columns.
H. Spray cooling of general environment by the water spray on columns.

Phenomenon 3: *detection (not tied to suppression system)*.

A. The smoke transport from source to detector.
B. Predicting the response of the detector.

Phenomenon 4: *building environment*.

A. Roof smoke vent operation.
B. Flow through roof smoke vents.
C. Window breakage creating new opening.
D. Flow through broken windows.
E. Heat and smoke transport internal to the building (including other products of combustion).
F. Heat absorption by the open grate operating deck (i.e. heat sink).
G. Heat transfer to enclosure surfaces and contents.
H. Natural ventilation in the building.
I. Effects of forced vent fans (if on/activated).
J. Ignition and burning of secondary combustibles.

Phenomenon 5: *scenario specified hole in MCR*. The sub-phenomena include:

A. Flow dynamics into and from MCR.
B. Smoke and heat transport within MCR.
C. Impact on MCR equipment.

Phenomenon 6: *thermal/mechanical response of the "3hr barrier"*.
A. Leakage through doors.
B. Fire induced breaching of the wall.
C. Leakage through cable penetrations.
D. Leakage through pipe penetrations.

C.1.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table C.1. The listed phenomena with the importance rankings are listed in Table C.2 through Table C.9.[1] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using a randomly assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table C.1: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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.

[1] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

Table C.2: Importance Ranking for Scenario 3a, Fire Source (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Fire Source								
A. Heat Release Rate for the Fire Confined to the Pool Area	H	H	H	H	H	H	H	
B. Pool Boil Over after Activation of Suppression	L	M	M	M	M	U	U	This phenomenon is more specific to the enhanced burning rate and surface area. Panelist 1 is uncertain about the research base on the topic but believes this is not going to happen (oils are clean and not contaminated, no problem with wide molecular weight range). Panelist 7 is unsure if this phenomenon even happens. Panelist 2's medium is based on that this phenomenon is a secondary effect.
C. Water Filling of the Pool and Spill Over	X	M	H	M	M	H	H	Panelist 1 disagrees with listing this as a phenomenon separate from "water induced splattering of burning oil" and therefore did not rank this phenomenon.
D. Water Induced Splattering of Burning Oil	H	M	M	M	M	M	M	
E. Effect of Obstructions within the Area of the Pool on Fire Behavior and HRR	L	M	M	L	M	M	M	
F. Tank Water Spray System Effect on HRR Reduction	L	M	L	L	L	L	M	

Table C.3: Importance Ranking for Scenario 3a, Fire Source (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Fire Source (Cont.)								
G. Particulate Production	H	H	H	H	H	H	H	This phenomenon was ranked high because the smoke production is relatively high importance to the figure of merit. This was ranked assuming there is flow into the MCR.
H. Particulate Scrubbing by the Water Spray	M	M	M	M	M	M	M	This phenomenon is specific to the water from the sprinkler system and predicting how this could scrub down the smoke particulates from the pool fire. Panelist 4 mentions that sprinkler systems are very ineffective at scrubbing.
I. CO Production	H	L	L	H	H	H	L	This phenomenon was ranked assuming flow into the MCR. The panel would like it to be known that all these products of combustion are important; these importance rankings are based on the specified scenario. The differences between the low and high rankings are based on the opinions of the self contained breathing apparatus (SCBA). Panelist 1's ranking is high because they do not have appreciation as to how robust the procedure is for putting on SCBA. Panelist 4 agrees with Panelist 1, if the SCBA fails they want to know how much CO is there. Panelist 6 does not even credit the SCBA, wants to know what the environment is like before the SCBA is put on.

Table C.4: Importance Ranking for Scenario 3a, Automatic Water Spray Systems (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Automatic Water Spray Systems								
A. Activation Time of Tank Spray System	L	L	L	L	L	L	L	Panelist 4's low is based on presuming that the fire is going to grow rapidly, so the modeling activation does not have a large impact (secondary effect). The actual activation time is going to happen within a narrow band of time, given no random failures.
B. Spray Cooling of General Environment by the Tank Spray System	L	M	M	M	L	M	M	
C. Activation Time of Sprinklers under Deck	L	L	L	L	L	L	L	Panelist 7 mentioned the activation of the sprinkler system will have a large impact on the fire scenario because of the effects on the burning rate. Panelist 4's feels the timing does not matter because it will be a full burning fire which will grow rapidly. The activation time is small compared to the time when the figure of merit will become important.
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the Sprinkler System.	L	M	M	M	M	M	M	This phenomenon is specific to whether or not and how many sprinkler heads actually open. Panelist 2's main concern is overwhelming the design basis for the sprinkler system which contains over 3000 sprinkler heads in entire turbine room. Panelist 6 supplied the system design information from NFPA 805 & 850.

Table C.5: Importance Ranking for Scenario 3a, Automatic Water Spray Systems (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Automatic Water Spray Systems (Cont.)								
E. Fire Suppression by Under Deck Sprinklers	L	H	H	H	H	H	H	Most of panel is ranking was high because they feel if it has an effect it will be very important to the scenario; therefore, the ability to do the analysis is important.
F. Spray Cooling of General Environment by the Sprinklers Under Deck	L	M	M	M	M	M	M	Panelist 1 feels none of the water systems should be given credit for this scenario because they are not designed for this.
G. Activation Time of Water Spray on Columns	L	L	L	L	L	L	L	
H. Spray Cooling of General Environment by the Water Spray on Columns	L	L	L	L	L	L	L	The panel thinks the spray cooling will not effect the general environment because they are designed to spray the surface of the beam rather than spraying into the room environment

Table C.6: Importance Ranking for Scenario 3a, Detection (Not Tied to Suppression System)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Detection (Not Tied to Suppression System)								
A. Smoke Transport from Source to Detector	L	L	L	L	L	L	L	
B. Response of the Detector	L	L	L	L	L	L	L	

Table C.7: Importance Ranking for Scenario 3a, Building Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Building Environment								
A. Roof Smoke Vent Operation	H	H	H	H	H	H	H	This phenomenon is specific to if and when the smoke vents operate.
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	H	
C. Window Breakage Creating New Opening	H	H	H	H	H	H	H	This phenomenon is specific to if and when the smoke vents operate.
D. Flow through Broken Windows	H	H	H	H	H	H	H	
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	H	
F. Heat Absorption by the Open Grate Operating Deck (i.e. Heat Sink)	L	L	L	L	L	L	L	Panelist 3's low ranking is due to the sprinklers below the deck that will dominate the deck cooling.
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	H	H	H	H	
H. Natural Ventilation	H	H	H	H	H	H	H	
I. Effects of Forced Vent Fans (If On/Activated)	H	H	H	H	H	H	H	
J. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	H	The proximity is going to make a big difference, but understanding if they ignite and burn are important.

Table C.8: Importance Ranking for Scenario 3a, Scenario Specified Hole to MCR

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Scenario Specified Hole to MCR								
A. Flow Dynamics to and from MCR	H	H	H	H	H	H	H	
B. Smoke and Heat Transport within MCR	H	H	H	H	H	H	H	
C. Impact on MCR Equipment	M	M	H	H	H	M	M	Panelist 2's medium ranking based on that the loss of habitability is going to be a concern before the electrical equipment is impacted.

Table C.9: Importance Ranking for Scenario 3a, Thermal/Mechanical Response of the “3hr Barrier”

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Thermal/Mechanical Response of the "3hr Barrier"								
A. Leakage through Doors	H	H	H	H	H	H	H	Panelist 2 and 4 mention that this phenomenon needs to be understood in terms of the relative significance compared to other leakage paths in the room. This phenomenon is directly related to the figure of merit for this scenario.
B. Fire Induced Breaching of the Wall	L	L	L	L	L	L	L	Panelist 4’s low ranking is based on the timescale; only because there is a physical hole before the fire starts.
C. Leakage through Cable Penetrations	H	H	H	H	H	H	H	
D. Leakage through Pipe Penetrations	H	H	H	H	H	H	H	

C.1.3 Phenomena State of Knowledge Ranking and Key Parameters

The next step after ranking the importance of the phenomena is to identify the state of knowledge. For this stage of the PIRT the panel ranks the state of knowledge as a group (rather than as individuals). The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table C.13 through Table C.21 are the state of knowledge rankings for the identified phenomena for the lube oil pool fire in Scenario 3a.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First, is the general adequacy of the existing and generally available[2] fire models to deal with the identified phenomena. The second are the adequacy of data needed to support model development and model validation in addition to the feasibility of obtaining new data. The issue of feasibility was not pursued for phenomena where the existing data availability was ranked "high."

The list below shows the five state of knowledge parameters and cites the table that include the definitions of rankings for each.

1. Model Adequacy (Table C.10)
2. Available Input Data (Table C.11)
3. Feasibility of Getting New Input Data (Table C.12)
4. Available Data for Validation (Table C.11)
5. Feasibility of Getting New Validation Data (Table C.12)

This section also identifies key parameters associated with the scenario phenomena and may be illustrated in Table C.22. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., the importance of key parameters in the context of the associated phenomenon and the corresponding state of knowledge).

[2] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table C.10: Model Adequacy Ranking Definitions

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 C.11: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., 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 C.12: Data Adequacy for Potential to Develop New Data Rankings Definitions

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.

Table C.13: State of Knowledge Rankings for Scenario 3a, Fire Source (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Fire Source						
A. Heat Release Rate for the Fire Confined to the Pool Area	H	H	NA[3]	H	NA	The HRR correlation was ranked.
B. Pool Boil Over after Activation of Suppression	L-M	L	L	L	L	For the model adequacy, there has been some work but that is not specifically related to this scenario and both Panelist 1 and Panelist 7 rankings are low.
C. Water Filling of the Pool and Spill Over	M	M	H	L	H	
D. Water Induced Splattering of Burning Oil	L	L	M	L	L	
E. Effect of Obstructions within the Area of the Pool on Fire Behavior and HRR	M	H	NA	M	H	
F. Tank Water Spray System Effect on HRR Reduction	L	L	M	L	L-M	The feasibility of getting new validation data was ranked as a range from low to medium.

[3] The Non-Applicable (NA) ranking is either explained in the notes column or if the ranking for the available input or available validation data is high then the feasibility of obtaining new data was not necessary to rank.

Table C.14: State of Knowledge Rankings for Scenario 3a, Fire Source (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Fire Source (Cont.)						
G. Particulate Production	L	L	M	L	L-M	The low rankings are based on the uncertainties with the water spray affecting the optical measurements. In the absence of the water spray, the phenomenon state of knowledge rankings would all improve by one level.
H. Particulate Scrubbing by the Water Spray	L	L	L	L	L	
I. CO Production	L	L	M	L	L-M	The low rankings are based on the uncertainties with the interaction of the water spray and CO. In the absent of the water spray, the phenomenon state of knowledge rankings would all improve one level.

Table C.15: State of Knowledge Rankings for Scenario 3a, Automatic Water Spray Systems (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Automatic Water Spray Systems						
A. Activation Time of Tank Spray System	M	H	NA	M	H	Tank spray systems are typically open head deluge systems. When the thermal detection system actuates, the deluge valve opens and all heads simultaneously spray water over the tank surface area.
B. Spray Cooling of General Environment by the Tank Spray System	H	M	H	M	M	For feasibility of obtaining new input data, this is a complicated high cost undertaking
C. Activation Time of Sprinklers under Deck	M	H	NA	M	H	For model adequacy, the first activation is easy while the next introduces more complexity with droplet interactions.
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the Sprinkler System.	M	H	NA	M	H	

Table C.16: State of Knowledge Rankings for Scenario 3a, Automatic Water Spray Systems (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Automatic Water Spray Systems(Cont.)						
E.Fire Suppression by Under Deck Sprinklers	L	M	H	L	H	The availability of input data was ranked medium based on the challenges of characterizing droplet size distribution. For the feasibility of obtaining new input and validation data, this will be an expensive and challenging.
F. Spray Cooling of General Environment by the Sprinklers Under Deck	H	M	H	M	M	The Panelists presume that the feasibility of obtaining new input data is a complicated high cost undertaking.
G. Activation Time of Water Spray on Columns	M	H	NA	M	H	The Panelists mentioned that the activation of the water spray system on the columns will not be the first system to activate for this scenario.
H. Spray Cooling of General Environment by the Water Spray on Columns	H	M	H	M	M	The Panelists presume that the feasibility of obtaining new input data is a complicated high cost undertaking.

Table C.17: State of Knowledge Rankings for Scenario 3a, Detection (Not Tied to Suppression System)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Detection (Not Tied to Suppression System)						
A. Smoke Transport from Source to Detector	H	H	NA	M	H	
B. Response of the Detector	M	M	M	M	M	

Table C.18: State of Knowledge Rankings for Scenario 3a, Building Environment (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Building Environment						
A. Roof Smoke Vent Operation	H	H	NA	M	H	
B. Flow through Roof Smoke Vents	H	H	NA	M	H	The rankings are based on the scenario specifics; vents are 65 feet above fire source.
C. Window Breakage Creating New Opening	L-M	L	L	L	L	If this phenomenon was cracking of a window, the model adequacy would be medium.
D. Flow through Broken Windows	H	H	NA	H	NA	
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	NA	M	H	Fundamentally there many obstacles in the compartment, which is a secondary effect to the overall fire growth.
F. Heat Absorption by the Open Grate Operating Deck (i.e., Heat Sink)	M	H	NA	M	H	
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	NA	M	H	
H. Natural Ventilation	H	H	NA	H	NA	

Table C.19: State of Knowledge Rankings for Scenario 3a, Building Environment (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Building Environment (Cont.)						
I. Effects of Forced Vent Fans (If On/Activated)	H	M	M	M	H	The feasibility of getting new input data was ranked medium due to the complexity of characterizing fans at high temperatures.
J. Ignition and Burning of Secondary Combustibles	M	M	M	M	H	The feasibility of getting new input data was ranked medium because is not difficult to run experiments, but to obtain data for model input will be a challenge.

Table C.20: State of Knowledge Rankings for Scenario 3a, Scenario Specified Hole to MCR

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
5. Scenario Specified Hole to MCR						
A. Flow Dynamics to and from MCR	M	H	NA	L	M	
B. Smoke and Heat Transport within MCR	H	H	NA	M	H	This is specific to predicting the environmental conditions rather than human response since it outside the area of expertise of the panel.
C. Impact on MCR Equipment	L	L	M	L	M	If the only materials in the MCR were cables, the state of knowledge rankings might be higher.

Table C.21: State of Knowledge Rankings for Scenario 3a, Thermal/Mechanical Response of the “3hr Barrier”

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
6. Thermal/Mechanical Response of the "3 Hour Barrier"						
A. Leakage through Doors	M	M	H	M	H	
B. Fire Induced Breaching of the Wall	L	L	L	L	L	
C. Leakage through Cable Penetrations	L	L	H	L	H	
D. Leakage through Pipe Penetrations	L	L	H	L	H	

Table C.22: Key Parameters and Their Rankings for Scenario 3a, Fire Source

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Fire Source				
A. Heat Release Rate for the Fire Confined to the Pool Area	Reduced Oxygen Concentration	M	M	
B. Pool Boil Over after Activation of Suppression	Initial Temperature of Oil	H	M	
	Pool Surface Temperature During Burning	H	M	
	Water Penetration through or Emulsification into Oil	H	L	
C. Water Filling of the Pool and Spill Over	Water Penetration through or Emulsification into Oil	H	H	
D. Particulate Production	Effect of Water Spray	H	L	
E. Particulate Scrubbing by the Water Spray	Droplet Size	H	L	

C.1.4 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT findings for Scenario 3a. The phenomena and their rankings were analyzed using four criteria that will be presented here. The first level phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table C.23. Level two phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table C.24. The third level phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. There are no Level 3 phenomena for this scenario. The fourth level are those phenomena that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking , or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table C.25 through Table C.28. The Level 1 phenomena are going to be discussed further in this section.

The first group of phenomena (1) in Table C.23 is the *fire source* and there are two sub-phenomenon associated with it. The first is 1.G, *particulate production* which was ranked high for importance and low for model adequacy. The available input and validation data were ranked low. The feasibility of obtaining new input data was ranked medium and the feasibility of getting new validation data was ranked low to medium. The second sub-phenomenon is 1.I, *CO production*, was placed in the Level 1 results category because of the majority of the Panelists ranked this as high importance (four high and three low rankings). The model adequacy was ranked low as well as the available input and validation data. The feasibility of obtaining new input data was ranked medium and the feasibility of getting new validation data was ranked low to medium.

The next group of phenomena (2) in Table C.23 is *automatic water spray systems* which has one sub-phenomenon, 2.E *fire suppression by under deck sprinklers,* which was ranked with a high importance by all but one Panelist. The one Panelist who ranked this low does not want to give credit to any suppression system for this scenario. The model adequacy was ranked as low because there is not much data to support a model of water cooling of a large object in a pool fire. The available input data was ranked medium while the availability of validation data was ranked low. The feasibility of getting new input and validation data was ranked high; the Panelists believed this could be collected by extending existing capabilities. *Building environment* phenomena group 4, is the next listed in Table C.23 with the sub-phenomenon, 4.C *window breakage creating new openings* associated with it. 4.C was ranked with a high importance by the panel with a low to medium model adequacy ranking. The remaining state of knowledge rankings were ranked low.

The fifth group of phenomena is the *scenario specified hole to MCR* which also has one sub-phenomenon associated with it. This sub-phenomenon is 5.C, *impact on the MCR equipment* which was given a medium to high importance ranking (four medium and three high rankings). The range of importance rankings were based on differing opinions of the Panelists with regard to the impact of the hole from the turbine room to the MCR. This phenomenon was also ranked with a low model adequacy for state of knowledge rankings. The availability of obtaining new input and validation data were also ranked as low. But the feasibly of getting new input and validation data was ranked as medium.

The final group of phenomena (6) in Table C.23 is the *thermal/mechanical response of the "3 hour barrier"* which has two sub-phenomena. The first is 6.C *leakage through cable penetrations* and the second is *leakage through pipe penetrations*. Both of these sub-phenomena were ranked the same for importance and state of knowledge. The importance rankings were high for all Panelists. The model adequacy rankings were low as well as the rankings for availability of input and validation data. The feasibility of obtaining new input and validation data were both ranked as high.

Table C.23: Level 1 PIRT Results and Summary for Scenario 3a

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
G. Particulate Production	H	H	H	H	H	H	H		L	L	M	L	L-M
I. CO Production	H	L	L	H	H	H	L		L	L	M	L	L-M
2. Automatic Water Spray Systems													
E. Fire Suppression by Under Deck Sprinklers	L	H	H	H	H	H	H		L	M	H	L	H
4. Building Environment													
C. Window Breakage Creating New Openings	H	H	H	H	H	H	H		L-M	L	L	L	L
5. Scenario Specified Hole to MCR													
C. Impact on MCR Equipment	M	M	H	H	H	M	M		L	L	M	L	M
6. Thermal/Mechanical Response of the "3hr Barrier"													
C. Leakage through Cable Penetrations	H	H	H	H	H	H	H		L	L	H	L	H
D. Leakage through Pipe Penetrations	H	H	H	H	H	H	H		L	L	H	L	H

Table C.24: Level 2 PIRT Results and Summary for Scenario 3a

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
B. Pool Boil Over after Activation of Suppression	L	M	M	M	M	U	U		L-M	L	L	L	L
C. Water Filling of the Pool and Spill Over	X	M	H	M	M	H	H		M	M	H	L	H
D. Water Induced Splattering of Burning Oil	H	M	M	M	M	M	M		L	L	M	L	L
H. Particulate Scrubbing by the Water Spray	M	M	M	M	M	M	M		L	L	L	L	L
4. Building Environment													
I. Effects of Forced Vent Fans (If On/Activated)	H	H	H	H	H	H	H		H	M	M	M	H
J. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	H		M	M	M	M	H
5. Scenario Specified Hole to MCR													
A. Flow Dynamics to and from MCR	H	H	H	H	H	H	H		M	H	NA	L	M
6. Thermal/Mechanical Response of the "3hr Barrier"													
A. Leakage through Doors	H	H	H	H	H	H	H		M	M	H	M	H

Table C.25: Level 4 PIRT Results and Summary for Scenario 3a (1 of 4)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
A. Heat Release Rate for the Fire Confined to the Pool Area	H	H	H	H	H	H	H		H	H	NA	H	NA
C. Water Filling of the Pool and Spill Over	X	M	H	M	M	H	H		M	M	H	L	H
E. Effect of Obstructions within the Area of the Pool on Fire Behavior and HRR	L	M	M	L	M	M	M		M	H	NA	M	H
F. Tank Water Spray System Effect on HRR Reduction	L	M	L	L	L	L	M		L	L	M	L	L-M

Table C.26: Level 4 PIRT Results and Summary for Scenario 3a (2 of 4)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
2. Automatic Water Spray Systems													
A. Activation Time of Tank Spray System	L	L	L	L	L	L	L		M	H	NA	M	H
B. Spray Cooling of General Environment by the Tank Spray System	L	M	M	M	L	M	M		H	M	H	M	M
C. Activation Time of Sprinklers under Deck	L	L	L	L	L	L	L		M	H	NA	M	H
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the System.	L	M	M	M	M	M	M		M	H	NA	M	H
F. Spray Cooling of General Environment by the Sprinklers Under Deck	L	M	M	M	M	M	M		H	M	H	M	M
G. Activation Time of Water Spray on Columns	L	L	L	L	L	L	L		M	H	NA	M	H
H. Spray Cooling of General Environment by the Water Spray on Columns	L	L	L	L	L	L	L		H	M	H	M	M

Table C.27: Level 4 PIRT Results and Summary for Scenario 3a (3 of 4)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Detection (Not Tied to Suppression System)													
A. Smoke Transport from Source to Detector	L	L	L	L	L	L	L		H	H	NA	M	H
B. Response of the Detector	L	L	L	L	L	L	L		M	M	M	M	M
4. Building Environment													
A. Roof Smoke Vent Operation	H	H	H	H	H	H	H		H	H	NA	M	H
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	H		H	H	NA	M	H
D. Flow through Broken Windows	H	H	H	H	H	H	H		H	H	NA	H	NA
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	H		H	H	NA	M	H
F. Heat Absorption by the Open Grate Operating Deck (i.e. Heat Sink)	L	L	L	L	L	L	L		M	H	NA	M	H
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	H	H	H	H		H	H	NA	M	H
H. Natural Ventilation	H	H	H	H	H	H	H		H	H	NA	H	NA

Table C.28: Level 4 PIRT Results and Summary for Scenario 3a (4 of 4)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
5. Scenario Specified Hole to MCR													
B. Smoke and Heat Transport within MCR	H	H	H	H	H	H	H		H	H	NA	M	H
6. Thermal/Mechanical Response of the "3hr Barrier"													
B. Fire Induced Breaching of the Wall	L	L	L	L	L	L	L		L	L	L	L	L

C.2 Fire Scenario 3b Fire Description

PIRT fire Scenario 3b description is very similar to Scenario 3a. The difference is how the lube oil is leaking out of the tank. For this scenario the lube oil is leaving the tank in a spray pattern. Therefore, there is a high pressure spray of lube oil leaving the tank that ignites. The remaining parts of the scenario specifically the target and figure of merit are exactly the same as described in Scenario 3a.

C.2.1 Phenomena Identification

The list of phenomena identified for this scenario will be discussed in this section. The Panelists identified groups of phenomena which included sub-phenomena. The order of the phenomena groups does not indicate the level of importance. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *fire source*.

A. HRR for spray fire
B. Pool boil over after activation of suppression
C. Effect of obstructions within the area of the spray on fire behavior and HRR
D. Tank water spray system effect on HRR reduction
E. Particulate production
F. Particulate scrubbing by the water spray
G. CO production

Phenomenon 2: *automatic water spray systems*. :

A. Activation time of tank spray system
B. Spray cooling of general environment by the tank spray system
C. Activation time of sprinklers under deck
D. Activation of too many sprinklers on under deck overwhelming the design basis for the sprinkler system
E. Fire suppression by under deck sprinklers
F. Spray cooling of general environment by the sprinklers under deck
G. Activation time of water spray on columns
H. Spray cooling of general environment by the water spray on columns

Phenomenon 3: *detection (not tied to suppression system)*.

A. Smoke transport from source to detector
B. Response of the detector

Phenomenon 4: *building environment*. :

A. Roof smoke vent operation
B. Flow through roof smoke vents
C. Window breakage creating new opening
D. Flow through broken windows
E. Heat and smoke transport internal to the building (including other products of combustion)

F. Heat absorption by the open grate operating deck (i.e. heat sink)
G. Heat transfer to enclosure surfaces and contents
H. Natural ventilation
I. Effects of forced vent fans (if on/activated)
J. Ignition and burning of secondary combustibles

Phenomenon 5: *scenario specified hole in MCR*.

A. Flow dynamics to and from MCR
B. Smoke and heat transport within MCR
C. Impact on MCR equipment

Phenomenon 6: *thermal/mechanical response of the "3hr barrier"*.

A. Leakage through doors
B. Fire induced breaching of the wall
C. Leakage through cable penetrations
D. Leakage through pipe penetrations

C.2.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table C.29. The listed phenomena with the importance rankings are listed in Table C.30 through Table C.36. The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their ranking. The process involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Table C.29: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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 C.30: Importance Ranking for Scenario 3b, Fire Source

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Fire Source								
A. Heat Release Rate of the Spray Fire	H	H	H	H	H	H	H	
B. Pool Boil Over After Activation of Suppression	L	L	L	L	L	L	L	The Panelists basis for low ranking is that they presume that since it is a spray fire, not all of the lube oil will go into the dike area; leaving volume for the water in the spray system. This phenomenon requires formation of a deep pool (at least 1 inch).
C. Unconfined Spill (Oil Flow)	H	H	H	H	H	H	H	
D. Effect of Obstructions on Spray Fire Behavior and HRR	H	H	H	H	H	H	H	
E. Tank Water Spray System Effect on HRR Reduction	L	L	L	L	L	L	L	The Panelists feel that the water spray nozzles directed towards the lube oil tank will be ineffective for a spray fire.
F. Particulate Production	H	H	H	H	H	H	H	This phenomenon was ranked assuming that there is airflow into the MCR. The rankings are high because the smoke production is relatively high importance to the figure of merit.
G. Particulate Scrubbing by the Water Spray	M	M	M	M	M	M	M	This phenomenon is meant as scrubbing and its depletion of the particulates. Panelist 4 mentions that sprinkler systems are very ineffective at scrubbing.
H. CO Production	H	L	L	H	H	H	L	This phenomenon was ranked assuming flow into the MCR. The panel would like it to be known that all these products of combustion are important; these importance rankings are based on the specified scenario.

Table C.31: Importance Ranking for Scenario 3b, Automatic Water Spray Systems (1 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Automatic Water Spray Systems								
A. Activation Time of Tank Spray System	L	L	L	L	L	L	L	This phenomenon is more specific to when this system activates. Panelist 4 presumes that this fire is going to grow rapidly and therefore modeling the activation time does not have a large impact on the overall timeline of the fire scenario.
B. Spray Cooling of General Environment by the Tank Spray System	L	M	M	M	L	M	M	
C. Activation Time of Sprinklers Under Deck	L	L	L	L	L	L	L	Panelist 7's mention that activation of the sprinkler system will have a large impact on the fire scenario because it directly affects the burning rate. Panelist 4's low ranking based on that the timing does not matter because it will be a full burning fire; this fire will grow rapidly.
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the Sprinkler System.	L	M	M	M	M	M	M	This phenomenon is specific to whether or not the sprinkler heads open. It also includes how many of the sprinkler heads actual actuate. Panelist 2's main concern is overwhelming the design basis for the sprinkler system (over 3000 sprinkler heads in entire turbine room). Panelist 1's basis for a low ranking is that this phenomenon is going to be low compared to the overall output of the fire. Panelist 6 supplied sprinkler design criteria for turbine rooms in NPP information from NFPA 805 & 850.

Table C.32: Importance Ranking for Scenario 3b, Automatic Water Spray Systems (2 of 2)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Automatic Water Spray Systems (Cont.)								
E. Fire Suppression by Under Deck Sprinklers	L	L	L	L	L	L	L	The low rankings by all the Panelists is based on the presumption that the sprinkler will not be effective in suppressing this fire.
F. Spray Cooling of General Environment by the Sprinklers Under Deck	L	M	M	M	M	M	M	Panelist 1 feels none of the water systems should be given credit for this scenario because they are not designed for this type of fire.
G. Activation Time of Water Spray on Columns	L	L	L	L	L	L	L	
H. Spray Cooling of General Environment by the Water Spray on Columns	L	L	L	L	L	L	L	The panel thinks the spray cooling will not effect the general environment because they are designed to spray the surface of the beam rather than large sprays into the environment.

Table C.33: Importance Ranking for Scenario 3b, Detection (Not Tied to Suppression System)

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Detection (Not Tied to Suppression System)								
A. Smoke Transport from Source to Detector	L	L	L	L	L	L	L	
B. Response of the Detector	L	L	L	L	L	L	L	

Table C.34: Importance Ranking for Scenario 3b, Building Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Building Environment								
A. Roof Smoke Vent Operation	H	H	H	H	H	H	H	This phenomenon is specific to if and when the vents operate.
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	H	
C. Window Breakage Creating New Opening	H	H	H	H	H	H	H	This phenomenon is specific to if and when the vents operate.
D. Flow through Broken Windows	H	H	H	H	H	H	H	
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	H	
F. Heat Absorption by the Open Grate Operating Deck (e.g. Heat Sink)	L	L	L	L	L	L	L	Panelist 3 states that their low ranking is due to the presumption that the sprinklers below the open deck will dominate in the cooling of the open deck. Due to the sprinklers below the deck will dominate the deck cooling.
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	H	H	H	H	Panelist 4 mentions that they are just interested in what the heat is going to do to the concrete wall to the MCR.
H. Natural Ventilation	H	H	H	H	H	H	H	
I. Effects of Forced Vent Fans (If On/Activated)	H	H	H	H	H	H	H	
J. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	H	The panel mentions that the proximity of the secondary combustibles will make a difference when predicting this phenomenon. However understanding if the secondary combustibles ignite and burn is important.

Table C.35: Importance Ranking for Scenario 3b, Scenario Specified Hole to MCR

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
5. Scenario Specified Hole to MCR								
A. Flow Dynamics to and from MCR	H	H	H	H	H	H	H	
B. Smoke and Heat Transport within MCR	H	H	H	H	H	H	H	
C. Impact on MCR Equipment	M	M	H	H	H	M	M	Panelist 2's medium ranking based on that the loss of habitability is going to happen first.

Table C.36: Importance Ranking for Scenario 3b, Thermal/Mechanical Response of the "3hr Barrier"

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
6. Thermal/Mechanical Response of the "3hr Barrier"								
A. Leakage through Doors	H	H	H	H	H	H	H	The basis for the high importance ranking from the panel is that this phenomenon is the base case in understanding the change in risk when the "hole" is found. So understanding the leakage through the doorways is important to understand the relative importance of the postulate hole between the turbine building and the MCR.
B. Fire Induced Breaching of the Wall	L	L	L	L	L	L	L	Panelist 4's low ranking is based on the timescale only because there is a physical hole before the fire starts.
C. Leakage through Cable Penetrations	H	H	H	H	H	H	H	
D. Leakage through Pipe Penetrations	H	H	H	H	H	H	H	

C.2.3 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge for the phenomena is identified. For this stage of the PIRT, the panel ranks the state of knowledge as a group (rather than as individuals). The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table C.40 through Table C.49 are the state of knowledge rankings for the identified phenomena for Scenario 3b.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First, is the general adequacy of the existing and generally available[4] fire models to deal with the identified phenomena. The second are the adequacy of data needed to support model development and model validation in addition to the feasibility of obtaining new data. The issue of feasibility was not pursued for phenomena where the existing data availability was ranked "high."

The list below shows the five state of knowledge parameters and cites the table that includes the definitions of rankings for each.

1. Model Adequacy (Table C.37)
2. Available Input Data (Table C.38)
3. Feasibility of Getting New Input Data (Table C.39)
4. Available Data for Validation (Table C.38)
5. Feasibility of Getting New Validation Data (Table C.39)

This section also identifies key parameters associated with the scenario phenomena and may be illustrated in Table C.50. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., the importance of key parameters in the context of the associated phenomenon and the corresponding state of knowledge).

[4] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table C.37: Model Adequacy Ranking Definitions

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 C.38: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., 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 C.39: Data Adequacy for Potential to Develop New Data Rankings Definitions

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.

Table C.40: State of Knowledge Rankings for Scenario 3b, Fire Source (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Fire Source						
A. Heat Release Rate of the Spray Fire	L-H	L-H	L	L	L	The model adequacy and available input data rankings depend on the geometry and size of spray. The Panelists' example of a non-complex variable for this phenomenon is good atomization and no contact with the surfaces.
B. Pool Boil Over After Activation of Suppression	L-M	L	L	L	L	The Panelists mention that some research has been done for pool boil over but it is not directly related to this scenario. Because of this Panelist 1 and 7 ranked the model adequacy as low.
C. Effect of Obstructions on Spray Fire Behavior and HRR	M	L	L	L	L	

Table C.41: State of Knowledge Rankings for Scenario 3b, Fire Source (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
D. Tank Water Spray System Effect on HRR Reduction	L	L	M	L	L-M	
E. Particulate Production	L	L	M	L	L-M	The low rankings are based on the uncertainties with the water spray affecting the optical measurements.
F. Particulate Scrubbing by the Water Spray	L	L	L	L	L	
G. CO Production	L	L	M	L	L-M	The interaction of CO with the spray fire is the basis for the state of knowledge rankings. In the case where the environment was dry, then the rankings would improve one level.

Table C.43: State of Knowledge Rankings for Scenario 3b, Automatic Water Spray Systems (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Automatic Water Spray Systems						
A. Activation Time of Tank Spray System	M	H	NA	M	H	The panel mentions that for model adequacy, predicting the first sprinkler activation is easy. The following sprinkler activations introduce more complexity with the droplet interactions.
B. Spray Cooling of General Environment by the Tank Spray System	H	M	H	M	M	For feasibility of obtaining new input data, this is a complicated high cost undertaking
C. Activation Time of Sprinklers Under Deck	M	H	NA	M	H	The panel mentions that for model adequacy, predicting the first sprinkler activation is easy. The following sprinkler activations introduce more complexity with the droplet interactions.
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the Sprinkler System.	M	H	NA	M	H	

Table C.44: State of Knowledge Rankings for Scenario 3b, Automatic Water Spray Systems (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Automatic Water Spray Systems (Cont.)						
E. Fire Suppression by Under Deck Sprinklers	L	M	H	L	H	Most of panel is ranking was high because they feel if it has an effect it will be very important to the scenario; therefore, the ability to do the analysis is important.
F. Spray Cooling of General Environment by the Sprinklers Under Deck	H	M	H	M	M	The feasibility of obtaining new input data is a complicated high cost undertaking.
G. Activation Time of Water Spray on Columns	M	H	NA	M	H	The Panelists presume that the activation of the column sprinklers will not be the first to actuate.
H. Spray Cooling of General Environment by the Water Spray on Columns	H	M	H	M	M	The feasibility of obtaining new input data is a complicated high cost undertaking.

Table C.45: State of Knowledge Rankings for Scenario 3b, Detection (Not Tied to Suppression System)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Detection (Not Tied to Suppression System)						
A. Smoke Transport from Source to Detector	H	H	NA	M	H	
B. Response of the Detector	M	M	M	M	M	

Table C.46: State of Knowledge Rankings for Scenario 3b, Building Environment (1 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Building Environment						
A. Roof Smoke Vent Operation	H	H	NA	M	H	
B. Flow through Roof Smoke Vents	H	H	NA	M	H	The rankings are based on the scenario specifics; vents are 65 feet above fire source.
C. Window Breakage Creating New Opening	L-M	L	L	L	L	If this phenomenon was only cracking of a window, the model adequacy would be medium.
D. Flow through Broken Windows	H	H	NA	H	NA	
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	NA	M	H	Fundamentally, there are a lot of obstacles in the compartment; this is a secondary effect to the overall fire growth.
F. Heat Absorption by the Open Grate Operating Deck (e.g. Heat Sink)	M	H	NA	M	H	
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	NA	M	H	
H. Natural Ventilation	H	H	NA	H	NA	

Table C.47: State of Knowledge Rankings for Scenario 3b, Building Environment (2 of 2)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Building Environment (Cont.)						
I. Effects of Forced Vent Fans (If On/Activated)	H	M	M	M	H	The feasibility of getting new input data was ranked medium because of the issue of characterizing fans at high temperatures.
J. Ignition and Burning of Secondary Combustibles	M	M	M	M	H	The feasibility of getting new input data was ranked medium because is not difficult to run experiments, but to obtain data for model input will be a challenge.

Table C.48: State of Knowledge Rankings for Scenario 3b, Scenario Specified Hole to MCR

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
5. Scenario Specified Hole to MCR						
A. Flow Dynamics to and from MCR	M	H	NA	L	M	The Panelists rankings are based on a comparison of between the postulate hole versus the thickness of the three hour barrier (3 ft).
B. Smoke and Heat Transport within MCR	H	H	NA	M	H	This is specific to predicting the environment conditions, not human response which is deemed outside the area of expertise of the panel.
C. Impact on MCR Equipment	L	L	M	L	M	The Panelists mentioned that if the control room was a room with just cable, the state of knowledge rankings might be higher.

Table C.49: State of Knowledge Rankings for Scenario 3b, Thermal/Mechanical Response of the “3hr Barrier”

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
6. Thermal/Mechanical Response of the "3hr Barrier"						
A. Leakage through Doors	M	M	H	M	H	
B. Fire Induced Breaching of the Wall	L	L	L	L	L	
C. Leakage through Cable Penetrations	L	L	H	L	H	
D. Leakage through Pipe Penetrations	L	L	H	L	H	

Table C.50: Key Parameters and Their Rankings for Scenario 3b, Fire Source

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Fire Source				
A. Heat Release Rate of the Spray Fire	Reduced Oxygen Concentration	M	M	
B. Pool Boil Over After Activation of Suppression	Initial Temperature of Oil	H	M	
	Pool Surface Temperature During Burning	H	M	
	Water Penetration through or Emulsification into Oil	H	L	
C. Unconfined Spill (Oil Flow)	Water Penetration through or Emulsification into Oil	H	H	
E. Particulate Production	Effect of Water Spray	H	L	
F. Particulate Scrubbing by the Water Spray	Droplet Size	H	L	

C.2.4 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 3b. The phenomena and their rankings were analyzed using four criteria that will be presented here. The Level 1 phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These phenomena are shown in Table C.51. The Level 2 phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These phenomena are shown in Table C.52. The Level 3 phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. There are no Level 3 phenomena for this scenario. The Level 4 phenomena are those that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking, or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table C.53 through Table C.55. The Level 1 phenomena are going to be discussed further in this section.

The first group of phenomena in Table C.51 is 1, *fire source* and there are two sub-phenomenon associated with it. The first sub-phenomenon is 1.A, *heat release rate of the spray fire* which was ranked as high importance. The model adequacy was ranked from low to high as well ad the available input data. This range of ranking is based on that the Panelists feel that this ranking will depend on the geometry and size of the spray droplets which were not specified for this scenario. The feasibility of getting new input and validation data, as well as the available validation data were all ranked low. The second is 1.E, *particulate production* which was ranked high for importance and low for model adequacy. The available input and validation data were ranked low. The feasibility of obtaining new input data was ranked medium and the feasibility of getting new validation data was ranked low to medium.

The next group of phenomena (4) in Table C.51 is b*uilding environment* with the sub-phenomenon 4.C, *window breakage creating new openings* associated with it. This sub-phenomenon was ranked with a high importance by the panel with a low to medium model adequacy ranking. The rest of the state of knowledge ranking parameters were ranked low.

The fifth group of phenomena is *scenario specified hole to MCR* which also has one sub-phenomenon associated with it. This sub-phenomenon is 5.C, *impact on the MCR equipment* which was given a medium to high importance ranking (four medium and three high rankings). It was also ranked with a low model adequacy for state of knowledge rankings. The availability of obtaining new input and validation data were also ranked as low. But the feasibly of getting new input and validation data was ranked as medium.

The final group of phenomena (6) in Table C.51 is *thermal/mechanical response of the "3hr barrier"* which has two sub-phenomenon associated with it. The first is 6.C, *leakage through cable penetrations* and the second is 6.D, *leakage through pipe penetrations*. Both these sub-phenomena were ranked the same for importance and state of knowledge. The importance rankings were high for all Panelists. The model adequacy rankings were low as well as the rankings for availability of input and validation data. The feasibility of obtaining new input and validation data were both ranked as high.

Table C.51: Level 1 PIRT Results and Summary for Scenario 3b

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
A. Heat Release Rate of the Spray Fire	H	H	H	H	H	H	H		L-H	L-H	L	L	L
E. Particulate Production	H	H	H	H	H	H	H		L	L	M	L	L-M
4. Building Environment													
C. Window Breakage Creating New Opening	H	H	H	H	H	H	H		L-M	L	L	L	L
5.Scenario Specified Hole to MCR													
C. Impact on MCR Equipment	M	M	H	H	H	M	M		L	L	M	L	M
6. Thermal/Mechanical Response of the "3hr Barrier"													
C. Leakage through Cable Penetrations	H	H	H	H	H	H	H		L	L	H	L	H
D. Leakage through Pipe Penetrations	H	H	H	H	H	H	H		L	L	H	L	H

Table C.52: Level 2 PIRT Results and Summary for Scenario 3b

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
C. Effect of Obstructions on Spray Fire Behavior and HRR	H	H	H	H	H	H	H		M	L	L	L	L
F. Particulate Scrubbing by the Water Spray	M	M	M	M	M	M	M		L	L	L	L	L
G. CO Production	H	L	L	H	H	H	L		L	L	M	L	L-M
4. Building Environment													
J. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	H		M	M	M	M	H
5. Scenario Specified Hole to MCR													
A. Flow Dynamics to and from MCR	H	H	H	H	H	H	H		M	H	NA	L	M
6. Thermal/Mechanical Response of the "3hr Barrier"													
A. Leakage through Doors	H	H	H	H	H	H	H		M	M	H	M	H

Table C.53: Level 4 PIRT Results and Summary for Scenario 3b (1 of 3)

Phenomenon	Importance Ranking							State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source												
B. Pool Boil Over After Activation of Suppression	L	L	L	L	L	L	L	L-M	L	L	L	L
D. Tank Water Spray System Effect on HRR Reduction	L	L	L	L	L	L	L	L	L	M	L	L-M
2. Automatic Water Spray Systems												
A. Activation Time of Tank Spray System	L	L	L	L	L	L	L	M	H	NA	M	H
B. Spray Cooling of General Environment by the Tank Spray System	L	M	M	M	L	M	M	H	M	H	M	M
C. Activation Time of Sprinklers Under Deck	L	L	L	L	L	L	L	M	H	NA	M	H
D. Activation of too Many Sprinklers on Under Deck Overwhelming the Design Basis for the Sprinkler System	L	M	M	M	M	M	M	M	H	NA	M	H
E. Fire Suppression by Under Deck Sprinklers	L	L	L	L	L	L	L	L	M	H	L	H
F. Spray Cooling of General Environment by the Sprinklers Under Deck	L	M	M	M	M	M	M	H	M	H	M	M
G. Activation Time of Water Spray on Columns	L	L	L	L	L	L	L	M	H	NA	M	H
H. Spray Cooling of General Environment by the Water Spray on Columns	L	L	L	L	L	L	L	H	M	H	M	M

Table C.54: Level 4 PIRT Results and Summary for Scenario 3b (2 of 3)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Detection (Not Tied to Suppression System)													
A. Smoke Transport from Source to Detector	L	L	L	L	L	L	L		H	H	NA	M	H
B. Response of the Detector	L	L	L	L	L	L	L		M	M	M	M	M
4. Building Environment													
A. Roof Smoke Vent Operation	H	H	H	H	H	H	H		H	H	NA	M	H
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	H		H	H	NA	M	H
D. Flow through Broken Windows	H	H	H	H	H	H	H		H	H	NA	H	NA
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	H		H	H	NA	M	H
F. Heat Absorption by the Open Grate Operating Deck (e.g. Heat Sink)	L	L	L	L	L	L	L		M	H	NA	M	H
G. Heat Transfer to Enclosure Surfaces and Contents	H	H	H	H	H	H	H		H	H	NA	M	H
H. Natural Ventilation	H	H	H	H	H	H	H		H	H	NA	H	NA
I. Effects of Forced Vent Fans (If On/Activated)	H	H	H	H	H	H	H		H	M	M	M	H

Table C.55: Level 4 PIRT Results and Summary for Scenario 3b (3 of 3)

Phenomenon	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
5. Scenario Specified Hole to MCR													
A. Flow Dynamics to and from MCR	H	H	H	H	H	H	H		M	H	NA	L	M
6. Thermal/Mechanical Response of the "3hr Barrier"													
B. Fire Induced Breaching of the Wall	L	L	L	L	L	L	L		L	L	L	L	L

C.3 Fire Scenario 3c Description

PIRT fire Scenario 3c is similar to Scenario 3a with the difference being the change in the target and figure of merit. The target is the structural steel in the turbine building. The figure of merit is the damage to the structural steel in the turbine building leading to collapse (How important are the identified phenomena in determining whether the structural steel in the turbine building will collapse?).

C.3.1 Phenomena Identification

The list of phenomena identified for Scenario 3c will be discussed in this section. The Panelists identified groups of phenomena which include sub-phenomena. The order of the phenomena groups does not indicate the level of importance. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: the *heat transfer to the structure*.

A. Convective transfer to structural elements
B. Radiative transfer to structural elements
C. Thermal response of structural elements

Phenomenon 2: *structural response*.

A. Evolution of material properties
B. Generation stresses due to thermal expansion
C. Deformations
D. Localized failures
E. Global failures
F. Load redistribution

Phenomenon 3: *exposure environment*.

A. Roof smoke vent operation
B. Flow through roof smoke vents
C. Window breakage creating new ventilation opening
D. Flow through broken windows
E. Heat and smoke transport internal to the building (including other products of combustion)
F. Natural ventilation
G. Effects of forced vent fans (if on/activated)
H. Ignition and burning of secondary combustibles

C.3.2 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table C.56. The listed phenomena with the importance rankings are listed in Table C.57 through Table C.59.[5] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their ranking. The process

[5] Note that one of the Panelists was unable to attend a part of the panel meetings, hence, this Panelist did not participate in the ranking of phenomena for Scenario 3c.

involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences which are noted in the tables.

Table C.56: Phenomena Importance Ranking Definitions	
High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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 C.57: Importance Ranking for Scenario 3c, Heat Transfer to the Structure

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Heat Transfer to the Structure								
A. Convective Transfer to Structural Elements	L	M	U	H	U	U	X	Given bar-joists/trusses (small characteristic length scale).
	L	L	U	M	U	U	X	Given solid sections.
B. Radiative Transfer to Structural Elements	H	H	H	H	H	H	X	This phenomenon is temperature dependent.
C. Thermal Response of Structural Elements	H	H	H	H	H	H	X	

Table C.58: Importance Ranking for Scenario 3c, Structural Response

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Structural Response								
A. Evolution of Material Properties	H	H	H	H	H	H	X	
B. Generation Stresses Due to Thermal Expansion	H	H	H	H	H	H	X	
C. Deformations	H	H	H	H	H	H	X	Panelist 1 believes that deformation is an inseparable part of structural analysis.
D. Localized Failures	NA	L	L	L	L	L	X	Horizontal members. Assuming you can fail these before the analysis starts.
	NA	H	H	H	H	H	X	Vertical members
E. Global Failures	H	H	H	H	H	H	X	
F. Load Redistribution	H	H	H	H	H	H	X	

Table C.59: Importance Ranking for Scenario 3c, Exposure Environment

Phenomenon Description	Importance Ranking							Additional Comments on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3. Exposure Environment								
A. Roof Smoke Vent Operation	L	L	L	L	L	L	X	This phenomenon is specific to if and when the smoke vents operate. The Panelists presume that the smoke vents are going to be open long before structurally significant temperatures are reached.
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	X	
C. Window Breakage Creating New Ventilation Opening	H	H	H	H	H	H	X	This phenomenon is specific to if and when the smoke vents operate. The Panelists presume that the smoke vents are going to be open long before structurally significant temperatures are reached.
D. Flow through Broken Windows	H	H	H	H	H	H	X	
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	X	
F. Natural Ventilation	H	H	H	H	H	H	X	
G. Effects of Forced Vent Fans (If On/Activated)	L	L	L	L	L	L	X	This phenomenon was ranked low because the vent fans will be have burnt out at temperatures when there will be structural failure.
H. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	X	

C.3.3 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge for the phenomena is identified. For this stage of the PIRT, the panel ranks the state of knowledge as a group (rather than as individuals). The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Table C.64 through Table C.65 are the state of knowledge rankings for the identified phenomena for Scenario 3c.

The Panelists were asked to evaluate five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First is the general adequacy of the existing and generally available[6] fire models to deal with the identified phenomena. The second are the adequacy of data needed to support model development and model validation in addition to the feasibility of obtaining new data. The issue of feasibility was not pursued for phenomena where the existing data availability was ranked "high."

The list below shows the five state of knowledge parameters and cites the table that includes the definitions of rankings for each.

1. Model Adequacy (Table C.60)
2. Available Input Data (Table C.61)
3. Feasibility of Getting New Input Data (Table C.62)
4. Available Data for Validation (Table C.61)
5. Feasibility of Getting New Validation Data (Table C.62)

This section also identifies key parameters associated with the scenario phenomena and may be illustrated in Table C.66 through Table C.67. The Panelists identified key parameters for certain phenomena which are shown in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., the importance of key parameters in the context of the associated phenomenon and the corresponding state of knowledge).

[6] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table C.60: Model Adequacy Ranking Definitions

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 C. 61: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., 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 C. 62: Data Adequacy for Potential to Develop New Data Rankings Definitions

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.

Table C.63: State of Knowledge Rankings for Scenario 3c, Heat Transfer to the Structure

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
1. Heat Transfer to the Structure						
A. Convective Transfer to Structural Elements	H	H	NA	H	NA	Given bar-joists/trusses (small characteristic length scale).
	H	H	NA	H	NA	Given solid sections.
B. Radiative Transfer to Structural Elements	H	H	NA	H	NA	
C. Thermal Response of Structural Elements	H	H	NA	H	NA	For model adequacy; with the thermal response there is an issue with coupling of the structure impact and gas phase. Post processing coupling for this scenario would be sufficient, which reflects the high model adequacy.

Table C.64: State of Knowledge Rankings for Scenario 3c, Structural Response

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Structural Response						
A. Evolution of Material Properties	H	H	NA	H	NA	
B. Generation Stresses due to Thermal Expansion	H	H	NA	H	NA	
C. Deformations	H	H	NA	H	NA	
D. Localized Failures	H	H	NA	H	NA	Horizontal members
	H	H	NA	H	NA	Vertical members
E. Global Failures	H	H	NA	H	NA	
F. Load Redistribution	H	H	NA	H	NA	

Table C.65: State of Knowledge Rankings for Scenario 3c, Exposure Environment

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
3. Exposure Environment						
A. Roof Smoke Vent Operation	H	H	NA	M	H	
B. Flow through Roof Smoke Vents	H	H	NA	M	H	The rankings are based on the scenario specifics; vents are 65 ft above source.
C. Window Breakage Creating New Opening	L-M	L	L	L	L	If this phenomenon was cracking of a window, the model adequacy would be medium.
D. Flow through Broken Windows	H	H	NA	H	NA	
E. Heat and Smoke Transport Internal to the Building (Including other Products of Combustion)	H	H	NA	M	H	Fundamentally, there are a lot of obstacles in the compartment; this is a secondary effect to the overall fire growth.
F. Natural Ventilation	H	H	NA	H	NA	
G. Effects of Forced Vent Fans (If On/Activated)	H	M	M	M	H	The feasibility of getting new input data was ranked medium because the experiments will not be difficult to run.
H. Ignition and Burning of Secondary Combustibles	M	M	M	M	H	The feasibility of getting new input data was ranked medium because the experiments will not be difficult to run.

Table C.66: Key Parameters and Their Rankings for Scenario 3c, Heat Transfer to the Structure

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Heat Transfer to the Structure				
A. Thermal Response of Structural Elements	Mass per Unit Length	H	H	The variation with temperature are relatively narrow compared to other parameters (hence evolution of thermal properties not listed)
	Conductivity	L	H	The ranking for importance is due to that fact that the structure is not insulated and the conductivity is very high.
	Specific Heat	H	H	
	Heat Transfer through Joints	L	H	The required precision for predicting this scenario is low.

Table C.67: Key Parameters and Their Rankings for Scenario 3c, Structural Response

Phenomenon Description	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Structural Response				
A. Evolution of Material Properties	Yield Stress	H	H	
	Young's Modulus	H	H	
	Coefficient of Thermal Expansion	H	H	
	Shear Strength	H	H	
B. Generation Stresses due to Thermal Expansion	Nature of the Restraints on Structural Elements	H	M	
C. Deformations	Dead Load	H	H	This is a boundary condition for entire super category.
	Live Load	H	H	This is a boundary condition for entire super category.
D. Localized Failures	Buckling (Flange)	H	H	
	Connection Failure	H	M	
E. Global Failures	Horizontal Failure	H	H	
	Vertical Failure	H	H	

C.3.3 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 3c. The phenomena and their rankings were analyzed using four criteria that will be presented here. The Level 1 phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These results are shown in Table C.68. The Level 2 phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These results are shown in Table C.69. The Level 3 phenomena are those that were deemed uncertain in their rankings by the Panelists for importance ranking and/or state of knowledge rankings. This level is deemed necessary to explore the phenomenon further. The Level 3 phenomena are shown in Table C.70. The Level 4 phenomena are those that were given one of the following overall rankings; high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking, or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table C.71 through Table C.72. The Level 1 phenomena are going to be discussed further in this section.

From this analysis there was only one phenomenon that was placed in the Level 1 PIRT results. This phenomenon is shown in Table C.68 under phenomena group 3, *exposure environment*. The sub-phenomenon is 3.C, *window breakage creating new ventilation opening* which was ranked as high importance and a low to medium model adequacy. The Panelists mentioned that predicting if the windows break is the issue. The timing of when the window break is not as important. The availability of input and validation data as well as the feasibility of obtaining new input and validation data were all ranked as low.

Table C.68: Level 1 PIRT Results and Summary for Scenario 3c

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Exposure Environment													
C. Window Breakage Creating New Ventilation Opening	H	H	H	H	H	H	X		L-M	L	L	L	L

Table C.69: Level 2 PIRT Results and Summary for Scenario 3c

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Exposure Environment													
H. Ignition and Burning of Secondary Combustibles	H	H	H	H	H	H	X		M	M	M	M	H

Table C.70: Level 3 PIRT Results and Summary for Scenario 3c

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Heat Transfer to the Structure													
A. Convective Transfer to Structural Elements (Bar-Joists/Trusses, Small Characteristic Length Scale)	L	M	U	H	U	U	X		H	H	NA	H	NA
A. Convective Transfer to Structural Elements (Given Solid Sections)	L	L	U	M	U	U	X		H	H	NA	H	NA

Table C.71: Level 4 PIRT Results and Summary for Scenario 3c (1 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Heat Transfer to the Structure													
B. Radiative Transfer to Structural Elements	H	H	H	H	H	H	X		H	H	NA	H	NA
C. Thermal Response of Structural Elements	H	H	H	H	H	H	X		H	H	NA	H	NA
2. Structural Response													
A. Evolution of Material Properties	H	H	H	H	H	H	X		H	H	NA	H	NA
B. Generation Stresses Due to Thermal Expansion	H	H	H	H	H	H	X		H	H	NA	H	NA
C. Deformations	H	H	H	H	H	H	X		H	H	NA	H	NA
D. Localized Failures (Horizontal Members)	NA	L	L	L	L	L	X		H	H	NA	H	NA
D. Localized Failures (Vertical Members)	NA	H	H	H	H	H	X		H	H	NA	H	NA
E. Global Failures	H	H	H	H	H	H	X		H	H	NA	H	NA
F. Load Redistribution	H	H	H	H	H	H	X		H	H	NA	H	NA

Table C.72: Level 4 PIRT Results and Summary for Scenario 3c (2 of 2)

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
3. Exposure Environment													
A. Roof Smoke Vent Operation	L	L	L	L	L	L	X		H	H	NA	M	H
B. Flow through Roof Smoke Vents	H	H	H	H	H	H	X		H	H	NA	M	H
D. Flow through Broken Windows	H	H	H	H	H	H	X		H	H	NA	H	NA
E. Heat and Smoke Transport Internal to the Building (Including Other Products of Combustion)	H	H	H	H	H	H	X		H	H	NA	M	H
F. Natural Ventilation	H	H	H	H	H	H	X		H	H	NA	H	NA
G.. Effects of Forced Vent Fans (If On/Activated)	L	L	L	L	L	L	X		H	M	M	M	H

APPENDIX D: PIRT FIRE SCENARIO 4

D.1 Fire Scenario 4 Description

The final PIRT fire Scenario given to the Panelists was a fire in a naturally ventilated annulus region at a NPP which is generically depicted in Figure D.1. The area between the inside shield building wall and the outside steel containment shell is 1.8 meters (6 feet). The highest point in the annulus region is 46 meters (150 feet) above grade level. There are smoke detectors located 21 meters (70 feet) above grade on the wall of the shield building. Sprinkler heads with heat collectors on a loop are located 17 meters (55 feet) above grade around the annulus space. For more information on the heat collectors, the panel was directed to *Information Notice (IN) 02-24, "Potential Problems with Heat Collectors on Fire Protection Sprinklers"*[1]*.* Cabling for the safe-shutdown equipment is routed to containment through the annulus from adjacent buildings, like the auxiliary building.

The fire is located in cable tray A, which is depicted as the left cable tray in Figure D.2 and Figure D.3. The targets for Scenario 4 are the safe shut down (SSD) cables located in tray B. The figure of merit is damage to the redundant SSD cables in cable tray B (i.e. the importance of the identified phenomena in rendering both trains of SSD equipment non-functional).

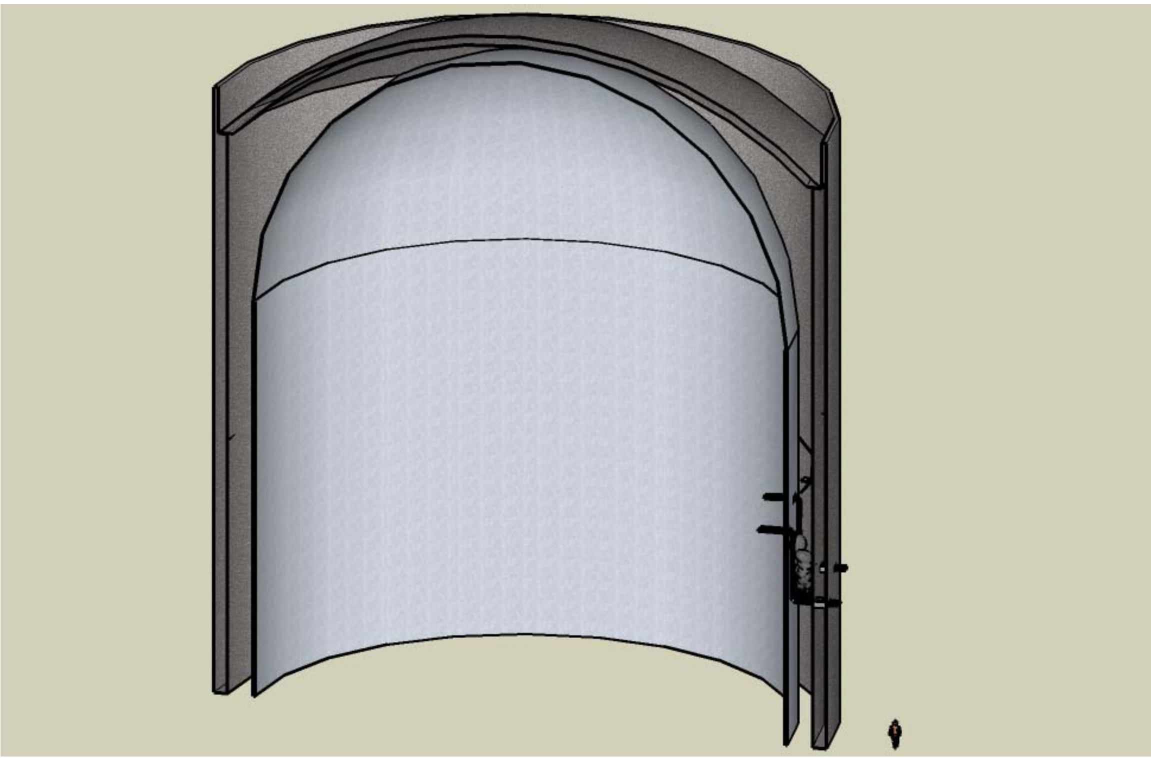


Figure D.1: Scenario 4 Annulus Region

[1] Information Notice (IN) 02-24, "Potential Problems with Heat Collectors on Fire Protection Sprinklers", U.S. NRC, July 19, 2002 (http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/2002/).

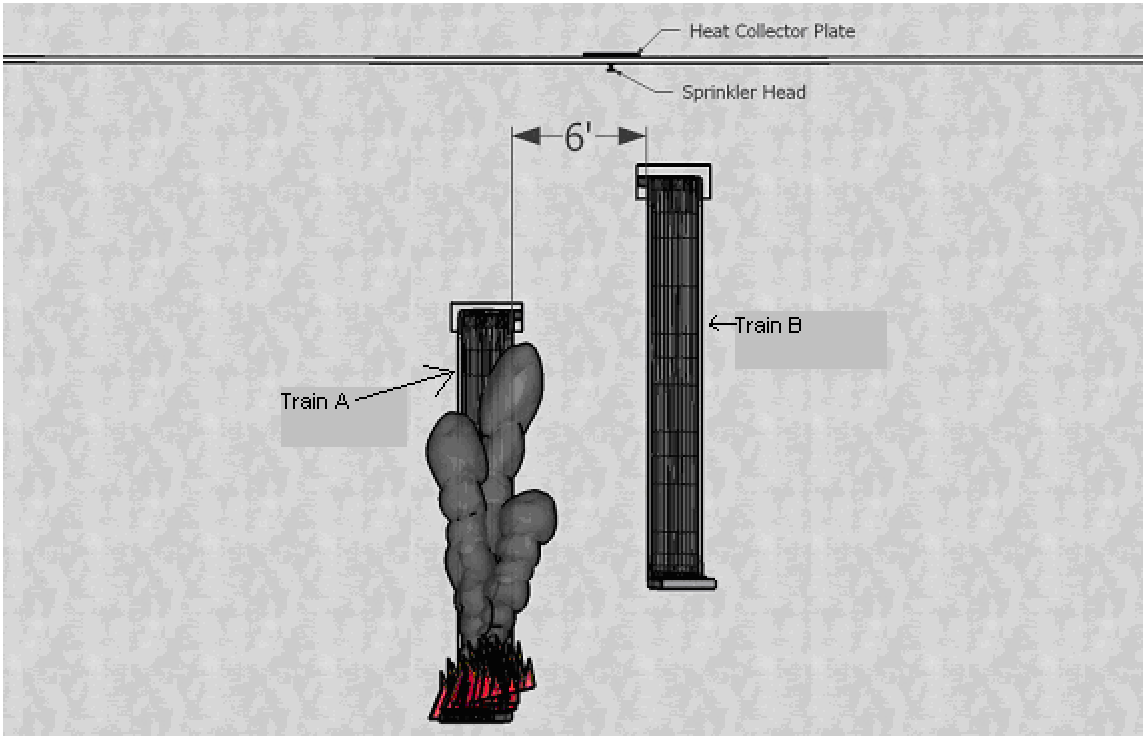


Figure D.2: Two-Dimension View of Cable Fire for Scenario 4

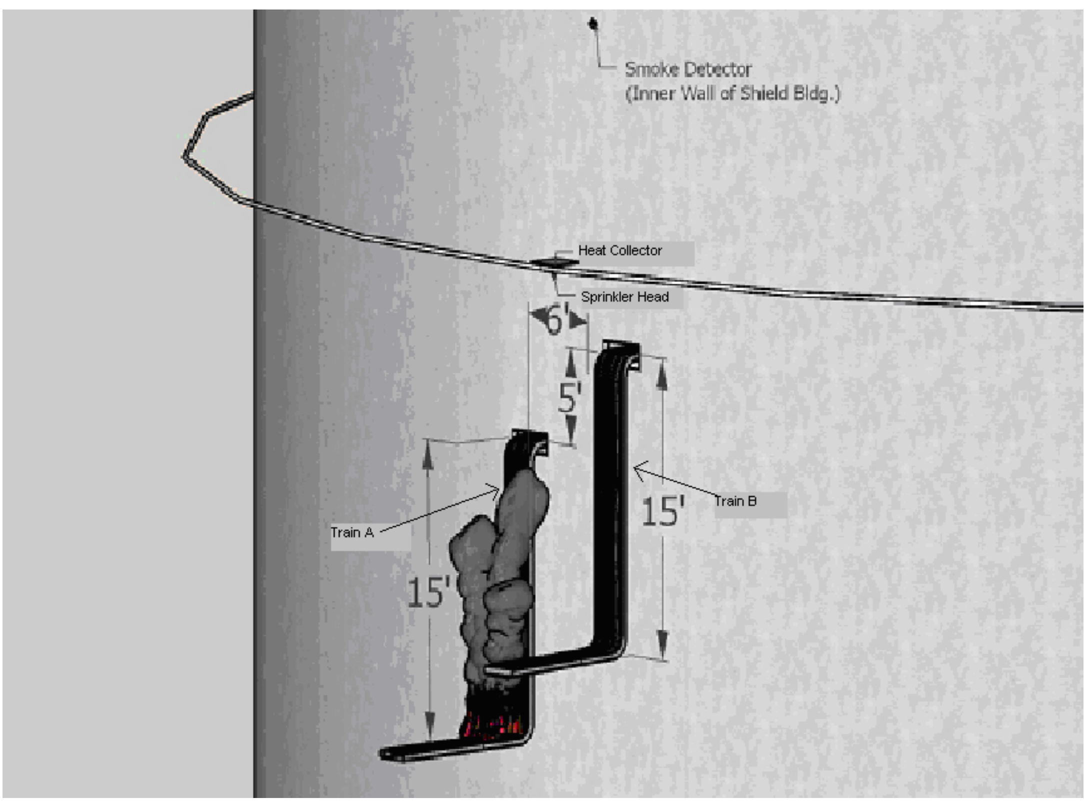


Figure D.3: Three-Dimension View of Cable Fire for Scenario 4

D.2 Phenomena Identification

The list of phenomena identified for Scenario 4 will be discussed in this section. The Panelists identified group of phenomena that include sub-phenomena. The order of the phenomena groups does not indicate the level of importance. Below identified phenomena are identified and the sub-phenomena are included as bullets under the phenomenon as lettered items. Note that later in the report that some sub-phenomena are referred to in shorter phrases but retain the number and letter designations for clarity.

Phenomenon 1: *fire source*.
A. Fire spread along cables
B. Heat release rate (HRR) of the fire
C. Burnout of cable bundle

Phenomenon 2: *plume flow/sprinkler*.
A. Plume geometry
B. Activation of sprinkler specifically by the plume
C. Spray trajectory of the sprinkler
D. Cooling of target by water spray
E. Suppression of fire by water spray
F. Sprinkler activation by radiation

Phenomenon 3: *thermal radiation to target (*i.e.,*2nd cable bundle which includes the SSD cables)*.
A. Radiative output of the fire
B. Radiative transfer to target

Phenomenon 4: *target response.*
A. Cable ignition
B. Electrical failure before ignition
C. Convective cooling of target
D. Radiative cooling of target
E. Thermal response of target (temperature)

D.3 Phenomena Importance Ranking

The importance ranking definitions that were given to the Panelists are shown in Table D.1. The listed phenomena with the importance rankings are listed in Table D.2 through Table D.5.[2] The column next to the importance ranking includes additional notes by the panel members. Each panel member gave their individual ranking. The process involved attempts to reach consensus among the panel, but sometimes they were unable to agree. For some phenomena there were strong differences of opinion which are noted in the tables.

Note that in the presentation of panel results, the identities of the individual Panelists have been obscured. That is, the Panelists are identified using a randomly

[2] Note that if a Panelist did not supply a ranking for a phenomenon this was marked with an X.

assigned letter code rather than by name. The letter code is P1 through P7 for Panelists 1 through 7.

Table D.1: Phenomena Importance Ranking Definitions

High (H)	First order of importance to figure of merit.
Medium (M)	Secondary importance to figure of merit.
Low (L)	Negligible importance to figure of merit. 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 D.2: Importance Ranking for Scenario 4, Fire Source

Phenomenon Description	Importance Ranking							Notes on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
1. Fire Source								
A. Fire Spread along Cables	H	H	H	H	H	H	X	
B. HRR	H	H	H	H	H	H	X	
C. Burnout	H	H	H	H	H	H	X	

Table D.3: Importance Ranking for Scenario 4, Plume Flow/Sprinkler

Phenomenon Description	Importance Ranking							Notes on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
2. Plume Flow/Sprinkler								
A. Plume Geometry	H	H	H	H	H	H	X	This phenomenon is important to predict that presumption of the panel thinking that the sprinkler head will not activate.
B. Activation of Sprinkler	H	H	H	H	H	H	X	
C. Spray Trajectory	H	H	H	H	H	H	X	
D. Cooling of Target by Water Spray	H	H	H	H	H	H	X	The wetting from the suppression system is sufficient to prevent damage. The Panelists state that this phenomenon is a question of yes or no. Therefore, the panel feels a high precision answer is not needed.
E. Suppression of Fire by Water Spray	H	H	H	H	H	H	X	It is important to note that either cooling of the target by water spray or the suppression of the fire by water spray represents success. So the relative importance would be driven by which phenomenon dominates.
F. Sprinkler Activation by Radiation	U	L	M	L	L	L	X	If the sprinkler activates by radiation, the target bundle will have already failed or the first bundle will be close to burnout; this condition is late in the Scenario.

Table D.4: Importance Ranking for Scenario 4, Thermal Radiation to Target (2nd Cable Bundle)

Phenomenon Description	Importance Ranking							Notes on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
3 Thermal Radiation to Target (2nd Cable Bundle)								
A. Radiative Output of the Fire	H	H	H	H	H	H	X	
B. Radiative Transfer to Target	H	H	H	H	H	H	X	

Table D.5: Importance Ranking for Scenario 4, Target Response

Phenomenon Description	Importance Ranking							Notes on Importance Ranking
	P1	P2	P3	P4	P5	P6	P7	
4. Target Response								
A. Cable Ignition	M	M	M	M	M	M	X	
B. Electrical Failure Before Ignition	H	H	H	H	H	H	X	
C. Convective Cooling of Target	H	H	H	H	H	H	X	
D. Radiative Cooling of Target	H	H	H	H	H	H	X	
E. Thermal Response of Target (Temperature)	H	H	H	H	H	H	X	

D.4 Phenomena State of Knowledge Ranking and Key Parameters

After ranking the importance of the phenomena, the state of knowledge must be identified. The panel ranks the state of knowledge as a group (rather than as individuals) during this phase of the PIRT. The panel aims for consensus but in some cases one or more Panelist disagreed with the final state of knowledge ranking. These cases are noted in the tables. Tables D.9 through Table D.12 are the state of knowledge rankings for the identified phenomena for Scenario 4.

The Panelists were asked to assess five different parameters for the state of knowledge assessment. The parameters are intended to solicit panel opinions in two main areas. First is the general adequacy of the existing and generally available[3] fire models to deal with the identified phenomena. The second is the adequacy of data needed to support model development and model validation. Included with this second area is an assessment of the feasibility of getting new development and validation data. The feasibility question was not pursued for phenomena where the existing data availability was ranked "high."

The list below shows the five state of knowledge parameters and cites the table that includes the definitions of rankings for each.

1. Model Adequacy (Table D.6)
2. Available Input Data (Table D.7)
3. Feasibility of Getting New Input Data (Table D.8)
4. Available Data for Validation (Table D.7)
5. Feasibility of Getting New Validation Data (Table D.8)

This section identifies key parameters, which may be found in Table D.13 through Table D.15. The Panelists did not identify key parameters for all the phenomena; only those phenomena for which key parameters were identified are listed in these tables. Once the panel has identified the key parameters, both the importance ranking and general state of knowledge ranking were performed for each key parameter. The rankings were judged by the panel in the context of the related phenomenon associated with the key parameter (i.e., how important is the key parameter in the context of the associated phenomenon and what is the corresponding state of knowledge?).

---

[3] The panel was asked to consider model adequacy based on those fire modeling tools that are readily available to a typical fire modeling practitioner associated with NPP fire analysis including both the NRC staff and licensees. The requirement to pay a licensing fee was not considered a barrier to availability.

Table D.6: Model Adequacy Ranking Definitions

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 D.7: Data Adequacy for Existing Input Data and Validation Data Ranking Definitions

High (H)	A high resolution database (i.e., 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 D.8: Data Adequacy for Potential to Develop New Data Rankings Definitions

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.

Table D.9: State of Knowledge Rankings for Scenario 4, Fire Source

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of GettingObtaining New Input Data	Available Data for Validation of Models	Feasibility of GettingObtaining New Validation Data	
1. Fire Source						
A. Fire Spread Along Cables	L	L	M	L	M	
B. HRR	L	L	M	L	M	
C. Burnout	L	L	M	L	M	

Table D.10: State of Knowledge Rankings for Scenario 4, Plume Flow/Sprinkler

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Plume Flow/Sprinkler						
A. Plume Geometry	H	H	NA[4]	M	H	These rankings are based on assuming a well specified fire source.
B. Activation of Sprinkler	H	H	NA	H	NA	These rankings are based on assuming a well specified fire source and plume.
C. Spray Trajectory	M-H	L	H	M	H	The model adequacy rankings are based on the panel's opinion of not needing a high level of detail.
D. Cooling of Target by Water Spray	M	H	NA	L	M	This phenomenon has a number of complicated issues. There is available data; however, it is very simplified.

[4] The Non-Applicable (NA) ranking is either explained in the notes column or if the ranking for the available input or available validation data is high then the feasibility of obtaining new data was not necessary to rank.

Table D.11: State of Knowledge Rankings for Scenario 4, Thermal Radiation to Target (2nd Cable Bundle)

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
2. Plume Flow/Sprinkler (Cont.)						
E. Suppression of Fire by Water Spray	L	L	M	L	L	The low rankings are based on the vertical array of the cable bundle. Panelist 6 mentions that there is testing that shows the water density of 0.3 g/m^3 is sufficient to suppress the cable bundle.
F. Sprinkler Activation by Radiation	H	L	H	L	H	
3. Thermal Radiation to Target (2nd Cable Bundle)						
A. Radiative Output of the Fire	M	L	H	L	H	This phenomenon is very scale dependent.
B. Radiative Transfer to Target	H	H	NA	L	H	The panel's judgment for this Scenario is no participating media between source and target.

Table D.12: State of Knowledge Rankings for Scenario 4, Target Response

Phenomenon Description	State of Knowledge Rankings					Notes on State of Knowledge
	Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data	
4. Target Response						
A. Cable Ignition	M	M	H	M	H	The medium adequacy ranking is based on the level of accuracy needed to predict cable ignition is lower here than in previous Scenarios.
B. Electrical Failure Before Ignition	M	M	H	L	H	
C. Convective Cooling of Target	H	H	NA	H	NA	
D. Radiative Cooling of Target	H	H	NA	H	NA	
E. Thermal Response of Target (Temperature)	H	H	NA	M	H	

Table D.13: Key Parameters and Their Rankings for Scenario 4, Fire Source

Phenomenon	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
1. Fire Source				
A. HRR	Flame Length/Geometry	H	M	

Table D.14: Key Parameters and Their Rankings for Scenario 4, Plume Flow/Sprinkler

Phenomenon	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
2. Plume Flow/Sprinkler				
B. Activation of Sprinkler	Effect of Heat Collector	L	H	The importance should be very low.
C. Spray Trajectory	Drop Size Distribution	H	M	
	Initial Velocity Distribution	H	L	
	Initial Trajectory Distribution	H	L	

Table D.15: Key Parameters and Their Rankings for Scenario 4, Thermal Radiation to Target (2nd Cable Bundle)

Phenomenon	Key Parameters			Notes on Key Parameters
	Key Parameters	Importance	State of Knowledge	
3. Thermal Radiation to Target (2nd Cable Bundle)				
A. Radiative Output of the Fire	Radiative Fraction	H	M	
B. Radiative Transfer to Target	Emissitity of the Target	H	H	
	View Factor	H	H	These rankings are assuming the flame geometry is known.

D.5 PIRT Analysis and Summary

This section will include the analysis and summary of the PIRT for Scenario 4. The phenomena and their rankings were analyzed using four criteria that will be presented here. The first level phenomena are those that were ranked with an overall high level of importance with an overall low state of knowledge. These results are shown in Table D.16. Level two phenomena are those that were ranked with a high importance and a medium state of knowledge or ranked with a medium importance and a low state of knowledge. These results are shown in Table D.17. The third level phenomena are those that were deemed uncertain in their importance and/or state of knowledge rankings by the Panelists. This level is deemed necessary to explore the phenomenon further. There are no Level 3 phenomenon. The fourth level are those phenomena that were given one of the following overall rankings: high importance with a high state of knowledge ranking, medium importance with either a medium or high state of knowledge ranking , or a low importance ranking with either a low, medium, or high state of knowledge ranking. These phenomena are summarized in Table D.18. The Level 1 phenomena are going to be discussed further in this section.

The first group of phenomena in Table D.16 is the *fire source* with three sub-phenomena associated with. The rankings for all three sub-phenomena are the same for both the importance and state of knowledge rankings. These three sub-phenomena are 1.A, 1.B, and 1.C, which are *fire spread along cables, HRR,* and burnout respectively. The importance rankings were high. The model adequacy rankings were low along with the availability of input and validation data. However, the feasibility of obtaining new input and validation data were ranked medium.

The second and final top level phenomenon in Table D.16 is *plume flow/sprinkler* with one sub-phenomenon associated with it. This sub-phenomenon is 2.E, *suppression of fire by water spray*, which was ranked as high importance and a low for model adequacy. The available input and validation data were ranked as low. The feasibility of obtaining new input data was ranked medium while the feasibility of obtaining new validation data was ranked low. The detailed results of Scenario 4 were presented in this Appendix. The cross-Scenario analysis was performed for the Level 1 phenomena and can be found in the main report.

Table D.16: Level 1 PIRT Results and Summary for Scenario 4

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
1. Fire Source													
A. Fire Spread along Cables	H	H	H	H	H	H	X		L	L	M	L	M
B. HRR	H	H	H	H	H	H	X		L	L	M	L	M
C. Burnout	H	H	H	H	H	H	X		L	L	M	L	M
2. Plume Flow/Sprinkler													
E. Suppression of Fire by Water Spray	H	H	H	H	H	H	X		L	L	M	L	L

Table D.17: Level 2 PIRT Results and Summary for Scenario 4

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
2. Plume Flow/Sprinkler													
C. Spray Trajectory	H	H	H	H	H	H	X		M-H	L	H	M	H
3. Thermal Radiation to Target (2nd Cable Bundle)													
A. Radiative Output of the Fire	H	H	H	H	H	H	X		M	L	H	L	H
4. Target Response													
B. Electrical Failure Before Ignition	H	H	H	H	H	H	X		M	M	H	L	H

Table D.18: Level 4 PIRT Results and Summary for Scenario 4

Phenomenon Description	Importance Ranking								State of Knowledge Rankings				
	P1	P2	P3	P4	P5	P6	P7		Model Adequacy	Available Input Data	Feasibility of Getting New Input Data	Available Data for Validation of Models	Feasibility of Getting New Validation Data
2. Plume Flow/Sprinkler													
A. Plume Geometry	H	H	H	H	H	H	X		H	H	NA	M	H
B. Activation of Sprinkler	H	H	H	H	H	H	X		H	H	NA	H	NA
D. Cooling of Target by Water Spray	H	H	H	H	H	H	X		M	H	NA	L	M
F. Sprinkler Activation by Radiation	U	L	M	L	L	L	X		H	L	H	L	H
3. Thermal Radiation to Target (2nd Cable Bundle)													
B. Radiative Transfer to Target	H	H	H	H	H	H	X		H	H	NA	L	H
4. Target Response													
A. Cable Ignition	M	M	M	M	M	M	X		M	M	H	M	H
C. Convective Cooling of Target	H	H	H	H	H	H	X		H	H	NA	H	NA
D. Radiative Cooling of Target	H	H	H	H	H	H	X		H	H	NA	H	NA
E. Thermal Response of Target (Temperature)	H	H	H	H	H	H	X		H	H	NA	M	H

APPENDIX E: PANEL AND MODERATOR RESUME AND PUBLICATIONS

This appendix includes the resumes and list of publications that were supplied by the individual panelists and the moderator.

Fire Science
and Technology
Inc.

VYTENIS BABRAUSKAS, Ph.D.

CURRICULUM VITAE
(revised 26 October 2007)

Education

Graduate
University of California, Berkeley, Ph.D., Fire Protection Engineering, 1976. Dr. Babrauskas was the first person ever to be awarded a Ph.D. degree in Fire Protection Engineering.
University of California, Berkeley, M.S., Structural Engineering, 1972.

Undergraduate
Swarthmore College, A.B., Physics, 1968. Also, concentration in electrical engineering.

Professional experience

1993 - present : Fire Science and Technology Inc., President. Dr. Babrauskas founded FSTI in 1993 as an organization devoted to fire safety research & development and for consulting on fire safety issues.
2002: Worcester Polytechnic Institute. Adjunct Professor, Spring Semester. Taught Special Topics-Ignition Phenomena in the Dept. of Fire Protection Engineering.
1998 : University of British Columbia. Lecturer, Winter Session. Taught fire dynamics to Master's degree students in the Fire Protection Engineering program.
1977 - 1993 : National Institute of Standards and Technology (NIST), Center for Fire Research/BFRL, Fire Prevention Engineer (note that prior to 1988 NIST was called the U.S. National Bureau of Standards). At NIST, Dr. Babrauskas headed up various programs and research groups in the area of materials flammability, fire toxicity, test method development, upholstered furniture flammability, building code fire safety requirements, and fire resistance.

1973 - 1976 : U. of California, Fire Test Laboratories, Research Specialist. During his work at UCB, Dr. Babrauskas specialized in fire modeling, test furnace design and fundamental studies on fire endurance.
1969 - 1971 : U. S. Army Corps of Engineers, Philadelphia, Civil Engineer. Dr. Babrauskas designed roads, bridges, and waterworks for the Army Corps of Engineers.
1968 - 1969 : University of Pennsylvania, Assistant instructor, Physics department. Dr. Babrauskas taught laboratory courses to physics undergraduates at the University of Pennsylvania.

9000 - 300th Place SE ■ Issaquah, WA 98027-8832 ■ USA
☎ (425) 222-9499 ■ FAX: (425) 222-9477 ■ *e-mail:* vytob@doctorfire.com

Highlights of professional achievements

Dr. Babrauskas is a ranking international authority on the measurement of heat release from fires (which tries to answer the question, *How fast do things burn?*). In 1982 he developed the Furniture Calorimeter, which has become the medium-scale test method specified in various ASTM, NORDTEST, and Underwriters Laboratories standards. He then developed the primary method currently being used on a world-wide basis for bench-scale measurement of heat release rates. For the development of this instrument, the Cone Calorimeter, he was awarded the Department of Commerce Bronze medal in 1986. His invention was also recognized in his receiving the *R&D 100 Award* for it in 1988. The Cone Calorimeter is today considered the most important bench-scale tool for determining "how fast things burn." It is used in approximately 200 laboratories in over 30 countries. The Cone Calorimeter standards issued by ASTM, NFPA, and ISO have been based on his works.

In 1992, the textbook **Heat Release in Fires**, Babrauskas and Grayson, eds., was published. This major work reviews the entire state of the art of measuring and predicting the growth of fires, based on quantitative engineering methods and on the newest experimental techniques, many of which were developed by Dr. Babrauskas. This is the only available monograph on the subject today.

Dr. Babrauskas has contributed significantly to advancing the state of the art in quantifying the fire hazards associated with **toxicity**. He headed the research team developing the new radiant-heating test method for toxic potency, the first such to be based on effective full-scale validation with room fires. He also developed a methodology for consistently handling carbon monoxide in relation to toxicity contributions from other fire gases. The dominant role of carbon monoxide in fire gas toxicity can now be more easily studied with another of Dr. Babrauskas' instruments, the phi-meter.

Fires from furniture and furnishings were first quantified in the course of Dr. Babrauskas research at NIST. The first predictive methods in this area were also his contribution. He remains very active in this area and has served as consultant to European laboratories investigating furniture flammability. His latest contribution in this area is the textbook **Fire Behavior of Upholstered Furniture and Mattresses**, published in 2001.

In the fire modeling area, Dr. Babrauskas was the first U.S. scientist to develop and make available to the public a computer program for modeling fires—COMPF was released in 1975. Subsequently, he released an enhanced version, COMPF2, in 1979. The enhanced version was the first fire model to include a realistic representation of the burning of liquid pool fires in rooms. He also contributed material to the major NIST fire model HAZARD I.

Dr. Babrauskas' earliest contributions to fire safety were in the fire endurance area. His Ph.D. dissertation was in this area and remains one of the essential references in the scientific study of post-flashover fires and of fire test methods.

Since his founding of FSTI, Dr. Babrauskas specialized in fire safety R&D and in serving as a fire science consultant to fire investigations and fire litigations. In the R&D area, he has been a technical consultant to three major, multi-national fire safety research projects organized by the

European Commission: CBUF, TOXFIRE, and FIPEC. CBUF (Combustion Behaviour of Upholstered Furniture) focused on characterizing furniture fire performance and developing fire models and fire test methods for this category of product. TOXFIRE focused on developing firefighting guidance for fires in chemical and pesticide warehouses, with an emphasis on toxic products of combustion and pollution of air and water. FIPEC (Fire Performance of Electric Cables) was organized to develop fire testing and fire modeling techniques for proper assessment of electric cable flammability. In addition, under the auspices of his own firm, Dr. Babrauskas organized numerous full-scale and bench-scale fire tests on diverse construction products, where the focus has been in assessing strategies for describing the fire toxicity aspects of products.

In 2003, Dr. Babrauskas published a massive **Ignition Handbook**. This 1116-page handbook is the first ever to be published on this topic and was developed as a resource intended to serve fire safety engineers, fire investigators, forensic scientists, insurance company personnel, chemical engineers, and other professionals concerned with fire and explosion safety.

In 2005, the became the first-ever consultant that ASTM formally retained to assist in the process of development of their fire test standards and was tasked with distilling recommendations for ASTM standards from the research findings on the fire and collapse of the World Trade Center.

Dr. Babrauskas has served as editor to two editions (2003 and 2007) of **Fire Science Applications to Fire Investigations**. This is the only extensive, up-to-date collection of research papers on the topics of fire investigation and forensic applications of fire science.

Society memberships

American Society for Testing and Materials (since 1973) The Combustion Institute (since 1975) International Association of Fire Safety Science (since 1989) International Association of Arson Investigators (since 1996) International Code Council; formerly ICBO (since 1993) National Fire Protection Association (since 1975) Society of Fire Protection Engineers (since 1991; grade of Fellow)

Technical committee participation

ASTM Committee D-9 on Electrical and Electronic Insulating Materials, Member (1991-). ASTM Committee D-20 on Plastics, Member (1996-). ASTM Committee E-5 on Fire Standards (1973 -); served as Chairman of Subcommittee E-5.21
on Smoke and Combustion Products (1998 – 2003). ASTM Committee E-27 on Hazard Potential of Chemicals, Member (1999-). ASTM Committee E-30 on Forensic Sciences, Member (2004-). International Association of Fire Safety Science – management Committee (2005-) ISO Technical Commission of Fire Safety, TC 92/SC 1/WG 2 Working Group on Ignitability,

Assigned U.S. expert. NFPA Technical Committee on Fire Investigations, NFPA 921, Member (2006-). NFPA Safety to Life/Technical Committee on Furnishings and Contents, Member (1994-). SFPE Standards Making Committee on Calculating Fire Exposures to Structures Calculating Fire

Exposures to Structures, Member (2004-). SFPE Task Group on Fire Exposures, Member (2002-2004). UL Standards Technical Panel STP 723 Surface Burning Testing of Building Materials, Member
(2003-). UL Standards Technical Panel STP 1040 Fire Tests of Insulated Wall Constructions, Member (2004-). UL Standards Technical Panel STP 1820 Fire Tests of Pneumatic Tubing and Plastic Sprinkler Pipe for Flame and Smoke Characteristics (2005-).

Editorial positions

FIRE SAFETY JOURNAL, Regional Editor for North America FIRE AND MATERIALS, Member of Editorial Board JOURNAL OF FIRE SCIENCES, Member of Editorial Board JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT, Member of Editorial Board.

Professional awards

- Arthur B. Guise Medal, Society of Fire Protection Engineers, 2004
- Vilhelm Sjölin Award, Forum for International Cooperation on Fire Research, 2002
- Jack Bono Engineering Communications Award, SFPE, 1997
- Research Award for Foreign Specialists (Building Research Institute, Japan), 1997
- The S. H. Ingberg Award, ASTM, 1995
- The Edward Bennett Rosa Award (NIST), 1992
- ASTM Award of Recognition, 1991
- Interflam Trophy Award (Interflam Conferences), 1990
- Building and Fire Research Laboratory Communicator Award (NIST), 1990
- ASTM Award of Appreciation, 1989
- R&D 100 Award, for developing the Cone Calorimeter, 1988
- Research Award for Foreign Specialists (Building Research Institute, Japan), 1988
- Department of Commerce Bronze Medal, 1986

Inventions

The Cone Calorimeter. An instrument for measuring fire properties of materials and products in bench scale. It is currently in the main technique for making this measurement that is in use by laboratories worldwide.

The furniture calorimeter (open-burning products calorimeter). This instrument measures the fire property of furniture items, stored goods, appliances, and other less-than-room sized commodities. It is currently in use in several dozen laboratories worldwide.

The radiant furnace fire toxicity test. This apparatus was jointly developed at several institutions. Dr. Babrauskas headed the NIST development team. It is a bench-scale test used to determine the fire toxicity properties of materials and products.

The phimeter. This instrument determines the real-time combustion equivalence ratio of fires. It is used in studies of fire toxicity.

Engineering standards

The following standards in the fire safety area were primarily developed by Dr. Babrauskas or were based on his inventions:

- ASTM E 1354 (Cone Calorimeter)
- ISO 5660 (Cone Calorimeter)
- NFPA 271 (Cone Calorimeter)
- NFPA 269 (fire toxicity)
- ASTM E 1474 (furniture test, bench-scale)
- NFPA 272 (furniture test, bench-scale)
- UL 1056 (furniture test, large-scale)
- NFPA 267 (mattress test)
- ASTM E 1590 (mattress test)
- ASTM E 1357 (furniture test, large-scale)
- NFPA 266 (furniture test, large-scale)
- NORDTEST NT FIRE 032 (furniture test, large-scale)
- CAN/ULC-S135 (combustibility of materials and products)
- MIL-STD-2031 SH (naval composites)
- NASA NHB 8060.1C (elevated oxygen material test)
- ASTM F 1550M (bench-scale test for prison mattresses and furniture)

Science and engineering expertise and work areas

- instrument design
- physics
- heat transfer
- civil/structural engineering
- electrical engineering
- combustion science
- analytical chemistry: methods for gas analysis
- infrared spectroscopy
- full-scale engineering performance testing

Within fire safety science and fire protection engineering:

- fire resistance
- fire toxicity
- fire testing
- electrical fires
- furniture flammability
- fire corrosivity
- ignitability
- self-heating and spontaneous combustion
- failure analysis
- ignition of fires from electric faults and failures
- flame spread

- explosions
- heat release rate
- computer fire modeling
- pool fires
- smoke production
- computer methods for handling of fire test data
- design and development of fire test apparatuses and instrumentation

Fire modeling

Dr. Babrauskas was the first U.S. scientist to publish a computer fire model (COMPF, issued in 1975). He contributed material to the major NIST fire model HAZARD I. His model for liquid pool fires is the most commonly used one. During 1993-1994, as technical consultant for the major European research program on upholstered furniture flammability CBUF, he played a pivotal role in developing the three different furniture fire models which were produced. He has developed numerous methods for fire hazard analysis which have been published in various technical journals.

Teaching

Dr. Babrauskas has given hundreds of lectures and presentations. He has taught graduate-level engineering courses at the University of British Columbia and at Worcester Polytechnic Institute. In recent years, he has been regularly teaching classes to fire investigators on fire science principles, as applied to origin-and-cause investigation of fires. He developed the unique **Electrical Fires 102** course, which is the only advanced course on investigation of electrical fires focusing on the fundamental underlying principles.

Publications

Dr. Babrauskas has published over 250 papers and reports in the field of fire safety science and engineering. His textbook **Heat Release in Fires** is the first and only book on this important subject. His **Ignition Handbook** is the only handbook on the topic of ignition and is one of the largest handbooks published on any safety topic. He authored the first monograph devoted to the topic of upholstered furniture flammability while at NIST; a second edition of this work was published commercially in 2001. He also authored the first comprehensive state-of-the-art review of flammability test methods for wires and cables. His Ph.D. dissertation on **Fire Endurance in Buildings** is still considered as one of the pivotal references in its field. Dr. Babrauskas has contributed chapters to both the NFPA and the SFPE Handbooks.

A selected list of publications is as follows. The complete listing is available on request.

Babrauskas, V., Ignition: A Century of Research and an Assessment of Our Current Status, *J. Fire Protection Engineering* **17**, 165-183 (2007).

Babrauskas, V., Gray, B. F., and Janssens, M. L., Prudent Practices for the Design and Installation of Heat-Producing Devices near Wood Materials, *Fire & Materials* **31**, 125-135 (2007).

Babrauskas, V., Engineering Design and Analysis Using Computer Models: Are We Going Too Fast or not Fast Enough?, pp. 1-9 in *Proc. Interflam 2007*, Vol. 1, Interscience Communications Ltd., London (2007).

Babrauskas, V., and Simonson, M., Fire Behaviour of Plastic Parts in Electrical Appliances—Standards versus Required Fire Safety Objectives, *Fire & Materials* **31**, 83-96 (2007).

Babrauskas, V., ed., **Fire Science Applications to Fire Investigations**, 2nd ed. (CD-ROM book), Interscience Communications Ltd., London (2007).

Babrauskas, V., Unexposed-face Temperature Criteria in Fire Resistance Tests: A Reappraisal, *Proc. Fire and Materials 2007*, Interscience Communications Ltd., London (2007).

Babrauskas, V., The Principles of Electrical Fires, pp. 45-51 in *IFSI 2006 - Proc. 2nd Intl. Symp. on Fire Investigation Science and Technology*, Natl. Assn. of Fire Investigators, Sarasota FL (2006).

Babrauskas, V., Mechanisms and Modes for Ignition of Low-voltage, PVC-insulated Electrotechnical Products, *Fire & Materials* **30**, 150-174 (2006).

Babrauskas, V., Effective Heat of Combustion for Flaming Combustion of Conifers, *Canadian J. Forest Research* **36**, 659-663 (2006).

Babrauskas, V., Ignition of Solids—What Have We Learned in a Half-Century of Research? pp. 89-97 in *Flame Retardants 2006*, Interscience Communications Ltd, London (2006).

Babrauskas, V., Charring Rate of Wood as a Tool for Fire Investigations, *Fire Safety J.* **40**, 528554 (2005).

Babrauskas, V., Some Basic Facts About Ignition Events During Fueling of Motor Vehicles at Filling Stations, *California Fire/Arson Investigator* 16, 25 (Apr. 2005).

Babrauskas, V., Truck Insurance v. MagneTek: Lessons to Be Learned Concerning Presentation of Scientific Information, *Fire & Arson Investigator* **55**:2, 9-10 (Oct. 2004).

Armstrong, A., Babrauskas, V., Holmes, D. L., Martin, C., Powell, R., Riggs, S., and Young, L. D., The Evaluation of the Extent of Transporting or “Tracking” an Identifiable Ignitable Liquid (Gasoline) throughout Fire Scenes during the Investigative Process, *J. Forensic Sciences* **49**, 741-748 (2004).

Babrauskas, V., Arc Beads from Fires: Can ‘Cause’ Beads Be Distinguished from ‘Victim’ Beads by Physical or Chemical Testing? *J. Fire Protection Engineering* **14**, 125-147 (2004).

Babrauskas, V., Electrical Discharges through Air: What Voltage Is Required to Cause Arcs and Sparks? *Fire Findings* **12**:1, 1-4 (Winter 2004).

Babrauskas, V., Cone Calorimeter Annotated Bibliography, 2003 edition, Fire Science Publishers, Issaquah WA (2004).

Babrauskas, V., Peacock, R. D., and Reneke, P. A., Defining Flashover for Fire Hazard Calculations. Part II. *Fire Safety J.* **38**, 613-622 (2003).

Babrauskas, V., A Hazardous Electrical Connector, *Fire & Arson Investigator* **53**:4, 9 (July 2003).

Babrauskas, V., **Ignition Handbook**, Fire Science Publishers/Society of Fire Protection Engineers, Issaquah WA (2003).

Babrauskas, V., **Ignition Handbook Database** (CD-ROM), Fire Science Publishers, Issaquah WA (2003).

Babrauskas, V., Upholstered Furniture and Mattresses, pp. 8-243 to 8-267 in **Fire Protection Handbook**, 19th ed., National Fire Protection Assn., Quincy MA (2003).

Babrauskas, V., Tables and Charts, pp. A-1 to A-21 in **Fire Protection Handbook**, 19th ed., National Fire Protection Assn., Quincy MA (2003).

Babrauskas, V., Ignition of Wood: A Review of the State of the Art, *J. Fire Protection Engineering* **12**, 163-189 (2002).

Babrauskas, V., How Do Electrical Wiring Faults Lead to Structure Ignitions? *Fire and Arson Investigator* **52**:3, 39-45, 49 (Apr. 2002).

Babrauskas, V., Heat Release Rates, pp. 3-1 to 3-37 in **SFPE Handbook of Fire Protection Engineering**, 3rd ed., National Fire Protection Assn., Quincy MA (2002).

Krasny, J. F., Parker, W. J., and Babrauskas, V., **Fire Behavior of Upholstered Furniture and Mattresses**, William Andrew Publishing, Norwich NY (2001).

Babrauskas, V., Positive-Pressure Door Testing: Research and Code Implementation, *Building Standards* **69**, 26-28, 30, 41 (Jul./Aug. 2000).

Babrauskas, V., Fire Test Methods for Evaluation of Fire-Retardant Efficacy in Polymeric Materials, pp. 81-113 in A. F. Grand and C. A. Wilkie, eds., **Fire Retardancy of Polymeric Materials**, Marcel Dekker, New York (2000).

Babrauskas, V., No Exit: The Performance Track of the Coming International Building Code Will Be Good for Engineers and Property Owners, but Will It Be Good for Fire Safety? *Fire Chief* **44**, 50-58 (Mar. 2000).

Babrauskas, V., Daems, D., and Berrier, R., Large-Scale Fire Tests Examining the Safety of Various Insulated Steel Roof Deck Constructions, pp. 355-366 in *Interflam '99*, Interscience Communications Ltd., London (1999).

Babrauskas, V., Ensuring the Public's Right to Adequate Fire Safety under Performance-Based Building Codes, pp. 167-175 in *Proc. 1998 Pacific Rim Conf. and 2nd Intl. Conf. on Performance-Based Codes and Fire Safety Design Methods*, International Code Council/SFPE (1998).

Babrauskas, V., and Krasny, J. F., Upholstered Furniture Transition from Smoldering to Flaming, *J. Forensic Sciences* **42**, 1029-1031 (1997).

Babrauskas, V., The Role of Heat Release Rate in Describing Fires, *Fire and Arson Investigator* **47**, 54-57 (June 1997).

Babrauskas, V., Fire Modeling Tools for Fire Safety Engineering: Are They Good Enough? *J. Fire Protection Engineering* **8**, 87-95 (1996). [This paper was awarded the *Jack Bono Engineering Communications Award* by SFPE for the best paper published in their Journal during 1996.]

Babrauskas, V., Facade Fire Tests: Towards an International Test Standard, *Fire Technology* **32**, 219-230 (1996).

Babrauskas, V., The Results of a Major Upholstered Furniture Fire Study, *NFPA J.* **90**, 84-88 (July/Aug 1996).

Babrauskas, V., A Comparative Examination of the Fire Performance of Pipe Insulation, *Process Safety Progress* **15**, 114-120 (1996).

Babrauskas, V., Wall insulation products: Full-scale tests versus evaluation from bench-scale toxic potency data, pp. 257-274 in *Interflam '96*, Interscience Communications Ltd, London (1996).

Babrauskas, V., Sandwich Panel Fire Performance—Full-scale and Bench-scale Assessments, pp. 1-21 in *Proc. Fourth Intl. Fire and Materials Conf.*, Interscience Communications Ltd., London (1995).

Babrauskas, V., The Generation of CO in Bench-scale Fire Tests and the Prediction for Real-scale Fires, *Fire and Materials* **19**, 205-213 (1995).

Babrauskas, V., Designing Products for Fire Performance: The State of the Art of Test Methods and Fire Models, *Fire Safety J.* **24**, 299-312 (1995).

Babrauskas, V., The Development and Evolution of the Cone Calorimeter: A Review of 12 Years of Research and Standardization, pp. 3-22 in *Fire Standards in the International Marketplace, ASTM STP 1163,* Arthur F. Grand, Ed., American Society for Testing and Materials, Philadelphia (1995).

Peacock, R. D., Reneke, P. A., Jones, W. W., Bukowski, R. W., and Babrauskas, V., New Concepts for Fire Protection of Passenger Rail Transportation Vehicles, *Fire and Materials* **19**, 71-87 (1995).

Bukowski, R. W., and Babrauskas, V., Developing Rational, Performance-based Fire Safety Requirements in Model Building Codes, *Fire and Materials* **18**, 173-191 (1994).

Grayson, S. J., Babrauskas, V., and Hirschler, M. M., New International Standard will Have Major Impact on Japanese Plastics Standards, *J. Japanese Assn. for Fire Science and Technology* **44**, No. 3 (whole number 210), 6-10 (May/June 1994). Text is in Japanese.

Babrauskas, V., Toxic Hazard from Fires: A Simple Assessment Method, *Fire Safety J.* **20**, 1-14 (1993).

Snell, J. E., Babrauskas, V., and Fowell, A. J., Elements of a Framework for Fire Safety Engineering, pp. 447-456 in INTERFLAM '93, Interscience Communications Ltd, London (1993).

Babrauskas, V., How Will Europe's Unified Standards Affect US Building Products? *NFPA J.* **86**, 45-49 (Sep. /Oct. 1992).

Babrauskas, V., and Grayson, S. J., eds., **Heat Release in Fires**, Elsevier Applied Science Publishers, London (1992).

Babrauskas, V., Peacock, R. D., Braun, E., Bukowski, R. W., and Jones, W. W., Fire Performance of Wire and Cable: Reaction-to-fire Tests—A Critical Review of the Existing Methods and of New Concepts (NIST Technical Note 1291). Natl. Inst. Standards and Technology, Gaithersburg (1991).

Babrauskas, V., and Peacock, R. D., Heat Release Rate: The Single Most Important Variable in Fire Hazard, *Fire Safety J.* **18**, 255-272 (1992).

Babrauskas, V., and Richardson, L., Determining Non-combustibility through Heat Release Rate Measurement, pp. 11-12 in *Heat Release and Fire Hazard: First US Symposium*, San Diego, CA 1991. Interscience Communications Ltd, London (1991).

Babrauskas, V., Damant, G., and Nurbakhsh, S., Heat Release Rate Testing of Mattresses: Full-Scale Measurements and Bench-scale Predictions, pp. 61-63 in *Heat Release and Fire Hazard: First US Symposium*, San Diego, CA, 1991. Interscience Communications Ltd, London (1991).

Babrauskas, V., Effective Measurement Techniques for Heat, Smoke, and Toxic Fire Gases, *Fire Safety J.* **17**, 13-26 (1991).

Ryan, J. D., Babrauskas, V., O'Neill, T. J., and Hirschler, M. M., Performance Testing for the Corrosivity of Smoke, pp. 75-88 in *Characterization and Toxicity of Smoke* (STP 1082), American Society for Testing and Materials, Philadelphia (1990).

Babrauskas, V., Smoke and Gas Evolution Rate Measurements on Fire-retarded Plastics with the Cone Calorimeter, *Fire Safety J.* **14**, 135-142 (1989).

Babrauskas, V., Harris, R. H., Jr., Gann, R. G., Levin, B. C., Lee, B. T., Peacock, R. D., Paabo, M., Twilley, W., Yoklavich, M. F., and Clark, H. M., Fire Hazard Comparison of Fire-Retarded and Non-Fire-Retarded Products (NBS Special Publication SP 749). [U. S.] Natl. Bur. Stand. (1988).

Nyden, M. R., and Babrauskas, V., Use of FTIR Spectroscopy for Multi-Component Quantitation in Combustion Technology, pp. 107-1 to 107-4 in 1987 Combined Technical Meetings: Eastern Section, the Combustion Institute, and The Center for Fire Research Annual Conference on Fire Research, Gaithersburg, MD (1987).

Babrauskas, V., Smoke and Gas Evolution Rate Measurements on Plastics with the Cone Calorimeter, pp. 20-1 to 20-10 in *Flame Retardants '87* Conference, The Plastics and Rubber Institute, London (1987).

Babrauskas, V., Fire-Related Standards and Testing, pp. 31-41 and 119-130 in *Spacecraft Fire Safety* (NASA Conference Publication 2476), NASA Lewis Research Center, Cleveland, OH (1987).

Babrauskas, V., and Parker, W. J., Ignitability Measurements with the Cone Calorimeter, *Fire and Materials* **11**, 31-43 (1987).

Babrauskas, V., Chapter 21.5, Fire Modeling and Analysis—Room Fire Temperature Computations, pp. 21-31 to 21-35 in *Fire Protection Handbook*, A. E. Cote and J. L. Linville, eds., National Fire Protection Assn., Quincy, MA (1986).

Babrauskas, V., and Krasny, J. F., Fire Behavior of Upholstered Furniture (NBS Monograph 173). [U. S.] Natl. Bur. Stand. (1985).

Quintiere, J. G., Babrauskas, V., Cooper, L., Harkleroad, M., Steckler, K., and Tewarson, A., The Role of Aircraft Panel Materials in Cabin Fires and Their Properties. Federal Aviation Admin. Report DOT/FAA/CT-84/30. FAA, Atlantic City Airport (1985).

Babrauskas, V., Pillow Burning Rates, *Fire Safety J.* **8**, 199-200 (1984/85).

Babrauskas, V., Development of the Cone Calorimeter – A Bench Scale Heat Release Rate Apparatus Based on Oxygen Consumption, *Fire and Materials* **8**, 81-95 (1984).

Babrauskas, V., Estimating Large Pool Fire Burning Rates, *Fire Technology* **19**, 251-261 (November 1983).

Babrauskas, V., Will the Second Item Ignite? *Fire Safety J.* **4**, 281-292 (1981/82). Also issued as report NBSIR 81-2271.

Babrauskas, V., Estimating Room Flashover Potential, *Fire Technology* **16**, 94-103, 112 (1980).

Babrauskas, V., Flame Lengths Under Ceilings, *Fire and Materials* **4**, 119-126 (1980).

Babrauskas, V., Fire Tests and Hazard Analysis of Upholstered Chairs, *Fire J.* **74**, 35-39 (March 1980).

Babrauskas, V., and Wickström, U. G., Thermoplastic Pool Compartment Fires, *Combustion and Flame* **34**, 195-201 (1979).

Babrauskas, V., and Williamson, R. B., The Historical Basis of Fire Resistance Testing, *Fire Technology* **14**, 184-194, 205 (August 1978).

Babrauskas, V., Fire Endurance in Buildings (Ph. D. dissertation). Univ. of California, Berkeley (1976).

Babrauskas, V., COMPF: A Program for Calculating Post-flashover Fire Temperatures (UCB FRG 75-2). Fire Research Group, University of California, Berkeley (1975).

CRAIG L. BEYLER, Ph.D., Technical Director

EDUCATION:

Ph.D. in Engineering Science, Harvard University, 1983
M.S. in Mechanical Engineering, Cornell University, 1980
M.Sc. in Fire Safety Engineering, University of Edinburgh, 1978
B.S. in Fire Protection Engineering, University of Maryland, 1976
B.S. in Civil Engineering, Cornell University, 1975

PROFESSIONAL EXPERIENCE:

Technical Director, Hughes Associates, Inc., 1990–present. Responsible for technical quality of fire protection design, research, and development projects and professional development of engineering staff. Project manager for a variety of fire protection R&D/T&E programs. Development and use of analytical methods in fire dynamics, fire chemistry, fire detection, fire suppression, smoke and heat venting. Development of mathematical fire models and modeling techniques for specialized applications, including zone and field models. Risk and hazard analysis for a wide range of specialized applications.

Principal, Fire Science Technologies, 1987–1990. Development of compartment fire models including computer-based models and simple correlationally-based models for ships and buildings. Preparation and presentation of a five-day short course for the HAZARD I hazard analysis package. Litigation support for a range of fire situations.

Assistant Professor of Fire Protection Engineering and Mechanical Engineering, Worcester Polytechnic Institute, 1985–1987. Taught graduate courses in Combustion, Fire Dynamics, and Fire Chemistry. Advised MS thesis work for FPE graduate students. Research in fire dynamics including compartment fire growth, smoke movement, pool fire radiation as well as fault tree approaches to link fire growth predictions to performance based fire safety objectives. Chaired a committee to totally restructure the graduate courses in the FPE degree programs and instituted an ongoing seminar program.

Visiting Scientist, Fire Research Station at Borehamwood, England, 1984–1985. Conducted experimental and theoretical investigations of piloted ignition of solid fuels. Prepared a review paper of the state-of-the-art of knowledge of plume and ceiling jet flows.

Postdoctoral Fellow, Harvard University, 1983–1984. Conducted an extensive experimental program to study the effect of oxygen starvation effects on the generation of projects of combustion, especially carbon monoxide, in a compartment fire environment. Experimental and theoretical studies of hot layer ignition in compartment fires.

Research Associate, Department of Fire Protection Engineering, University of Maryland, 1976–1977.

Engineer (part-time), Center for Fire Research, National Bureau of Standards, 1975–1976.

Security Clearance: DOD Top Secret
DOE "Q" (inactive)

Hughes Associates, Inc. 3610 Commerce Drive, Suite #817, Baltimore, MD 21227 Tel: (410) 737-8677 cbeyler@haifire.com

PROFESSIONAL STANDING:

<u>Committees, Boards, and Panels</u>:

International Association for Fire Safety Science
Chairman, International Association for Fire Safety Science, 2005 to present
Vice Chair, International Association for Fire Safety Science, 2002 to 2005
Program Committee Chair, International Association for Fire Safety Science–8th International Symposium, 2003 to 2005
Program Committee, International Association for Fire Safety Science–7th International Symposium, 2001–2002
Awards Committee, International Association for Fire Safety Science–4th and 5th International Symposia

Society of Fire Protection Engineers
Member, SFPE Technical Steering Committee, 1998 to present
Chair, SFPE Task Group on Engineering Practices: Radiation from Fires, 1996 to present
Chair, SFPE Task Group on Engineering Practices, 1996–1998
Member, Research Committee, Society of Fire Protection Engineers, 1988–1995
Member, Engineering Education Committee, Society of Fire Protection Engineers, 1983–1995

National Fire Protection Association
Toxicity Technical Advisory Committee, National Fire Protection Association, 2002 to present
Member, Guide for Fire and Explosive Investigations, NFPA 921, 1998 to present
Task Group for NFPA 204: Guide for Smoke and Heat Venting, 1996 to present
Alternate Member, Smoke Management Systems, National Fire Protection Association, 1996 to present
Task Group for NFPA 92B: Guide for Smoke Management in Malls, Atria, and Large Spaces, 1992 to present
Member, Contents and Furnishings Committee, National Fire Protection Association, 1992 to present
Member, Subcommittee on Fire Detection Design Methods, 72 EM, National Fire Protection Association, 1983–1988

Academic Advisory Boards
Advisory Board, University of Maryland, Dept. of Fire Protection Engineering, 2003 to present
Advisory Board, Worcerster Polytechnic Institute, Center for Firesafety Studies, 2000 to present
Industrial Advisory Board, Oklahoma State University, Fire Protection and Safety Engineering Technology Department, 1998 to present

Government Evaluation Boards
Panel Member, Board on Assessment of NIST Programs, National Research Council, 1999 to 2005
National Academy of Science, Committee to Identify Innovative Research Needs to Foster Improved Fire Safety in the US, 2001–2002

<u>Society Memberships:</u>
Member, National Fire Protection Association, 1987 to present
Member, International Association for Fire Safety Science, 1985 to present
Member, Society of Fire Protection Engineers, 1983 to present
Member, Combustion Institute, 1980 to present
Member, Salamander Honorary Fire Protection Engineering Society, 1977 to present

<u>Technical Journals and Books</u>:
Founding Editor, *Journal of Fire Protection Engineering*, 1988–1992
Member, Editorial Advisory Board, *Fire Safety Journal*, 2004 to present
Member, Editorial Advisory Board, *Journal of Fire Protection Engineering*, Society of Fire Protection Engineers, 1992 to present
Member, Editorial Advisory Board, *Fire Technology*, 1984 to present
Co-editor, *SFPE Handbook of Fire Protection Engineering*, 1st, 2nd, and 3rd editions, 1984 to present
Reviewer, *Combustion and Flame*, *Fire Safety Journal*, *Journal of Fire Science*, *Fire and Materials*, *IAFSS International Symposia*, *Combustion Institute International Symposia*

<u>Honors</u>:
Arthur B. Guise Medal, Society of Fire Protection Engineers, 2000
Harold E. Nelson Service Award, Society of Fire Protection Engineers, 2005
Fellow, Society of Fire Protection Engineers, 1999
Hat's Off Award, Society of Fire Protection Engineers, 1995
Jack Bono Engineering Communications Award, with Curt Ewing and Homer Carhart, 1995
Special Commendation Award, Society of Fire Protection Engineers, 1995
Special Commendation Award, Society of Fire Protection Engineers, 1993
President's Award, Society of Fire Protection Engineers, 1990
Director's Award, Society of Fire Protection Engineers, 1989

10/05

SELECTED PUBLICATIONS LIST

Craig L. Beyler, Ph.D.

Beyler, C.L. and Gratkowski, M.T., "Low-Voltage (14VAC) Electrical Circuit Fire Initiation," *ISFI 2006 Proceedings Addendum*, International Symposium on Fire Investigation Science and Technology, Cincinnati, OH, June 26–28, 2006, pp. 15–23.

Beyler, C.L., Gratkowski, M.T., and Sikorski, J., "Radiant Smoldering Ignition of Virgin Plywood and Plywood Subjected to Prolonged Heating," *ISFI 2006 Proceedings Addendum*, International Symposium on Fire Investigation Science and Technology, Cincinnati, OH, June 26–28, 2006, pp. 3–14.

Beyler, C., "Self-heating properties of styrene-butadiene rubber," *Fire and Materials,* **30** (3), May/June 2006,
pp. 215–222.

Beyler, C.L., Fay, T., Gratkowski, M., Campbell, B., and Hartman, J.R., "Ignition studies of cerium nitrate treated towels," *Fire and Materials,* **30** (3), May/June 2006, pp. 223–240.

Gratkowski, M.T., Dembsey N.A., and Beyler, C.L., "Radiant smoldering ignition of plywood," *Fire Safety Journal,* 41, May 2006, pp 427–443.

Beyler, C., "A brief history of the prediction of flame extinction based upon flame temperature," *Fire and Materials*, **29** (6), September 2005, pp. 425–427.

Beyler, C., "Toxicity Assessment of Products of Combustion of Flexible Polyurethane Foam*," Fire Safety Science – Proceedings of the 8th International Symposium*, Gottuk, D. and Lattimer, B. (eds.), International Association of Fire Safety Science, Beijing, China, September 2005, pp. 1047–1058.

Lattimer, B. and Beyler, C., "Heat Release Rates of Fully-developed Fires in Railcars*," Fire Safety Science – Proceedings of the 8th International Symposium*, Gottuk, D. and Lattimer, B. (eds.), International Association of Fire Safety Science, Beijing, China, September 2005, pp. 1169–1180.

Beyler, C., "Relationship Between Structural Fire Protection Design and Other Elements of Fire Safety Design," *NET-SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures: Proceedings*, Almand, K.H. and Phan, L.T. (eds.), NISTIR 7133, National Institute for Standards and Technology, Gaithersburg MD, 2004, pp. 100–106.

Lattimer, B.Y., Hunt, S.P., Wright, M.T., and Beyler, C., "Corner Fire Growth in a Room with a Combustible Lining," *Fire Safety Science–Proceedings of the Seventh International Symposium – June 16-21, 2002*, Evans, D. (ed.), International Association for Fire Safety Science, 2003, pp. 419–430.

Beyler, C., White, D., Peatross, M., Trellis, J., Li, Sonny, Luers, A., and Hopkins, D., "Assessment of the Fire Exposure in the Airplane Impact Areas of the Two World Trade Center Towers," *Design Structures for Fire – Structural Forensic Conference held September 30 - October 1, 2003 at the Radisson Plaza Lord Baltimore*, Society of Fire Protection Engineers, Bethesda, MD, 2003, pp. 65–74.

Gottuk, D., Peatross, M., Roby, R., and Beyler, C., "Advanced Fire Detection Using Multi-Signature Alarm Algorithms," *Fire Safety Journal,* **37**, 2002, pp. 381–394.

Reneke, P., Peatross, M., Jones, W., Beyler, C., and Richards, R., "A Comparison of CFAST Predictions to USCG Real-Scale Fire Tests," *Journal of Fire Protection Engineering*, **11** (1), 2001, pp. 43–68.

Beyler, C.L., "Fire Safety Challenges in the 21st Century," *Journal of Fire Protection Engineering*, **11** (1), 2001, pp. 4–15.

Beyler, C.L., and Cooper, L.Y., "Interaction of Sprinklers with Smoke and Heat Vents," *Fire Technology*, **37** (1), 2001, pp. 9–35.

Forssell, E.W., Back, G.G., Beyler, C.L., DiNenno, P.J., Hansen, R., and Beene, D., "An Evaluation of the International Maritime Organization's Gaseous Agents Test Protocol," *Fire Technology*, **37** (1), 2001, pp. 37–67.

Back, G.G., Beyler, C.L., and Hansen, R., "The Capabilities and Limitations of Total Flooding Water Mist Fire Suppression Systems in Machinery Space Applications," *Fire Technology*, **36** (1), 2000, pp. 8–23.

White, D.A., Beyler, C.L., Williams, F.W., and Tatem, PA., "Modeling Missile Propellant Fires in Shipboard Compartments," *Fire Safety Journal*, **34**, 2000, pp. 321–341.

Back, G.G., Beyler, C.L., and Hansen, R., "Quasi-Steady-State Model for Predicting Fire Suppression in Spaces Protected by Water Mist Systems," *Fire Safety Journal*, **35** (4), November 2000, pp. 327–362.

White, D., Beyler, C.L., Fulper, C., and Leonard, J., "Flame Spread on Aviation Fuels," *Fire Safety Journal*,
28, 1997, pp. 1–31.

Beyler, C.L., Hunt, S.P, and Iqbal, N., "A Computer Model of Upward Flame Spread on Vertical Surfaces," *Fire Safety Science–Proceedings of the Fifth International Symposium*, Y. Hasemi (ed.), International Association for Fire Safety Science, London, England, March 1997, pp. 297–308.

Peatross, M.J. and Beyler, C.L., "Ventilation Effects on Compartment Fire Characterization," *Fire Safety Science–Proceedings of the Fifth International Symposium*, Y. Hasemi (ed.), International Association for Fire Safety Science, London, England, March 1997, pp. 403–414.

Beyler, C.L., "Flammability Limits of Premixed and Diffusion Flames," *SFPE Handbook of Fire Protection Engineering*, Second Edition, NFPA, Quincy, MA, Chapter 2-9, 1995, pp. 2-147–2-159, (First Edition, 1988, Chapter 1-17, pp. 1-286–1-297.)

Beyler, C.L. and Hirschler, M.M., "Thermal Decomposition of Polymers," *SFPE Handbook of Fire Protection Engineering*, Second Edition, NFPA, Quincy, MA, Chapter 1-7, 1995, pp. 1-99 - 1-119, (First Edition, Beyler (sole author), Chapter 1-12, 1988, pp. 1-165–1-178.)

Gottuk, D.T., Roby, R.J., and Beyler, C.L., "The Role of Temperature on Carbon Monoxide Production in Compartment Fires," *Fire Safety Journal*, **24**, June 1995, pp. 315–331.

Back, G., Beyler, C., Tatem, P, and DiNenno, P, "Wall Incident Heat Flux Distributions Resulting from an Adjacent Fire," *Fire Safety Science–Proceedings of the Fourth International Symposium*, International Association of Fire Safety Science, Boston, MA, 1994, pp. 241–252.

Ewing, C.T., Beyler, C.L., and Carhart, H.W., "Extinguishment of Class B Flames by Thermal Mechanisms; Principles Underlying a Comprehensive Theory; Prediction of Flame Extinguishing Effectiveness," *Journal of Fire Protection Engineering*, **6** (1), 1994, pp. 23–54.

Peatross, M.J., and Beyler, C.L., "Thermal Environment Prediction in Steel-Bounded Preflashover Compartment Fires," *Fire Safety Science–Proceedings of the Fourth International Symposium*, International Association of Fire Safety Science, Boston, MA, 1994, pp. 205–216.

Gottuk, D.T., Roby, R.J., and Beyler, C.L., "A Study of Carbon Monoxide and Smoke Yields from Compartment Fires," *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA., 1993.

Beyler, C.L., "A Unified Model of Fire Suppression," *Journal of Fire Protection Engineering*, **4** (1), 1992, pp. 5-16.

DiNenno, P.J. and Beyler, C.L., "Fire Hazard Assessment of Composite Materials: The Use and Limitations of Current Hazard Analysis Methodology," *Fire Hazard and Fire Risk Assessment, ASTM STP 1150*, Marcelo H. Hirschler (ed.), American Society for Testing and Materials, Philadelphia, PA, 1992, pp. 87–99.

Gottuk, D.T., Roby, R.J., Peatross, M.J., and Beyler, C.L., "Carbon Monoxide Production in Compartment Fires," *Journal of Fire Protection Engineering*, **4** (4), 1992.

Beyler, C.L., "Analysis of Compartment Fires with Overhead Forced Ventilation," *Fire Safety Science–Proceedings from the Third International Symposium*, Elsevier Applied Science, NY, 1991, pp. 291–300.

Fitzgerald, R.W., Richards, R.C., and Beyler, C.L., "Firesafety Analysis of Polar Icebreaker Replacement Design," *Journal of Fire Protection Engineering*, **3** (4), 1991, pp. 137–150.

Skelly, M.J., Roby, R.J., and Beyler, C.L., "An Experimental Investigation of Glass Breakage in Compartment Fires," *Journal of Fire Protection Engineering*, **3** (1), 1991, pp. 25–34.

Deal, S. and Beyler, C.L., "Correlating Preflashover Room Fire Temperatures," *Journal of Fire Protection Engineering*, **2** (2), 1990, pp. 33–48.

Shanley, J., and Beyler, C.L., "Horizontal Vent Flow Modeling with Helium and Air," *Second International Symposium on Fire Safety Science*, Hemisphere Publishing Co., 1989, pp. 305–314.

Shokri, M. and Beyler, C.L., "Radiation from Large Pool Fires," *Journal of Fire Protection Engineering*, **1** (4), 1989, pp. 141–149.

Thomson, H.E., Drysdale, D.D., and Beyler, C.L., "An Experimental Evaluation of Critical Surface Temperature as a Criterion for Piloted Ignition of Solid Fuels," *Fire Safety Journal*, **13**, 1988, p. 185.

Beyler, C.L., "Fire Plumes and Ceiling Jets," *Fire Safety Journal*, **11**, 1986, p. 53.

Beyler, C.L., "Major Species Production by Diffusion Flames in a Two Layer Compartment Fire Environment," *Fire Safety Journal*, **10**, 1986, p. 47.

Beyler, C.L., "Major Species Production by Solid Fuels in a Two Layer Compartment Fire Environment," *First International Symposium on Fire Safety Science*, Hemisphere Publishing Co., 1986, p. 431.

Beyler, C.L., "A Design Method for Flaming Fire Detection," *Fire Technology*, **20** (4), 1984, p. 5.

Beyler, C.L., "Ignition and Burning of a Layer of Incomplete Combustion Products," *Combustion Science and Technology*, **39**, 1984, p. 287.

Beyler, C.L. and Gouldin, F.C., "Flame Structure in a Swirl Stabilized Combustor Inferred by Radiant Emission Measurements," *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1981, p. 1011.

Beyler, C.L., "An Evaluation of Sprinkler Discharge Calculation Methods, *Fire Technology*, **13** (3), 1977, p. 185.

07/06

Combustion
Science & Engineering, Inc.
www.csefire.com
8940 Old Annapolis Road • Suite L • Columbia • MD • 21045-2129 • Tel: 410/884-3266 • Fax: 410/884-3267

DOUGLAS J. CARPENTER, MScFPE, C.F.E.I., P.E.

EDUCATION:

M.S., Fire Protection Engineering, Worcester Polytechnic Institute, Worcester, MA, 1996.
B.S., Mechanical Engineering, University of Vermont, Burlington, VT, 1992.
A.S., Mechanical Engineering, Vermont Technical College, Randolph Center, VT, 1984.

THESIS:

Carpenter, D. J., "An Investigation into the Validity of Modeling Post-Flashover Fires and Flame Extension from Openings with the Fire Field Model JASMINE", Worcester Polytechnic Institute, August 1996.

PROFESSIONAL EXPERIENCE:

Vice President and Principal Engineer, Combustion Science & Engineering, Inc., Columbia, MD, 1998 to present. Responsibilities include fire investigations, fire reconstruction analyses, and performing fire hazard analyses utilizing computer fire modeling including both zone models and Computational Fluid Dynamics (CFD). Applied quantitative and performance-based fire hazard analysis skills to a wide range of projects including nuclear production reactors and facilities at DOE's Savannah River Site, building atria, manufacturing operations, transportation vehicles, airports, as well as United States research facilities and airport operations in Antarctica. Developed a flame-spread model for use in a CFD model of burning vehicles. Developed and taught classes and seminars in fire investigation, performance-based fire safety design, and computer fire modeling for such organizations as the Society of Fire Protection Engineers (SFPE) and the International Council of Building Officials (ICBO). Panel Member for Nuclear Regulatory Commission's PIRT (Phenomenon Identification Ranking Table) review process associated with computer fire modeling in the commercial nuclear environment.

Staff Engineer, Hughes Associates, Inc., Baltimore, MD, 1996 to 1998.
Conducted in-house cone calorimeter tests for code equivalency evaluations and fire litigation support. Performed fire hazard analysis for military aircraft hush houses to determine technical requirements for alternative suppression system to existing Halon 1301 systems. Performed a review of fire hazards and fire suppression system options for the Halifax Class frigates of the Canadian Navy. Developed a computer program for the military evaluating alternative systems for existing Halon 1301 systems. Performed a comprehensive evaluation of the military's current Halon 1211 replacement program.

Conducted on-scene fire investigations and computer fire modeling in support of fire litigation work. Conducted experiments that mapped the heat flux of Halogen Torchiere Lamps for development of a model to determine ignition potential of adjacent combustibles.

Fire Protection Engineer, Office of Polar Programs, National Science Foundation, Arlington, VA, 1995-1996. Assisted engineers in examining fire protection engineering issues associated with Amundsen-Scott South Pole, McMurdo, and Palmer Stations in Antarctica. Projects emphasized equivalent levels of protection for fire hazards and life safety using a systems and performance-based engineering approach in this unique and challenging environment. Actively involved with the fire protection specification and design for the proposed new research station at the South Pole as part of the South Pole Redevelopment Project (SPRP). Conducted a fire risk assessment of buildings in McMurdo Station, which included computer fire modeling. Conducted on-site visits of McMurdo and Amundsen-Scott South Pole Station.

Fire Protection Engineer, ABASCO Services, Inc., Augusta, GA, 1993.
Six-month graduate internship. Responsible for developing a framework for an alternative methodology to the average combustible loading method for fire barrier analysis. Reviewed and provided written critique for proposed on-site work connected with fire protection at the Department of Energy's Savannah River Site.

Fire Protection Engineer, MBS Fire Technology, Inc., Worcester, MA, 1993.
Six-month graduate internship. Part of a team responsible for writing a revision of a fire hazard analysis for a nuclear production reactor using a performance-based approach. Provided recommendations for alternative methods to using Halon 1301 for fire protection within the reactor environment. Reviewed and provided written critique for proposed on-site work connected with fire protection at the Department of Energy's Savannah River Site.

PROFESSIONAL REGISTRATION AND CERTIFICATION:

Certified Fire and Explosion Investigator, National Association of Fire Investigators, 2005.
Professional Engineer (P.E.), State of Maryland, License No. 32633.

HONORS:

Antarctic Service Medal of the United States of America, May, 1999.
Salamander Honorary Fire Protection Engineering Society May 1995.
Campus Safety Association Scholarship Award, May 1995.
Percy Bugbee Fire Protection Engineering Scholarship, May 1995.
M&M Protection Consultants Scholarship, May 1994.
Deans List at University of Vermont: Fall 1988, 1991, Spring 1992.

PROFESSIONAL MEMBERSHIP:

Reviewer, Fire Technology, 2007 – present.
Reviewer, Fire Safety Journal, 2007 – present.
Member, International Association for Fire Safety Science (IAFSS)
Member, National Fire Protection Association (NFPA)
Member, Society of Fire Protection Engineers (SFPE)
Member, National Association of Fire Investigators (NAFI)
Member, International Association of Arson Investigators (IAAI)
Member, DC/MD Chapter, International Association of Arson Investigators
Member, American Society of Mechanical Engineers (ASME)
Member, Building Officials Code Administration (BOCA)
Member, NFPA 92B Task Group, 1998
Member, SFPE Task Group on Computer Model Evaluation, 1998-present
Member, SFPE Educational Committee, 1999 – present
Member, IAAI Fire & Arson Investigator Editorial Review Board, 2006 - present
Member, Lexington Who's Who, 1999/2000
Alternate Member, NFPA 921, *Guide for Fire and Explosion Investigations*, 2000 – present
Associate Member, Engineering Sciences, American Academy of Forensic Sciences (AAFS), 2006
Member, Arson Review Committee (ARC), The Innocence Project, NYC, 2005 – present.

CONTINUING EDUCATION:

FPE 580L "**Case Studies in Fire Safety Engineering Science**", Worcester Polytechnic Institute, Advanced Distance Learning Network (ADLN), 16-week course, Instructor: Dr. Patrick J. Pagni, University of California at Berkley, Fall, 2000.

"**Smoke Management for Atria and Other Large Spaces**", one-day course sponsored by the Society of Fire Protection Engineers (SFPE), and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Baltimore, MD, October 6, 2000.

INSTRUCTOR:

"Advanced Fire Dynamics", Adjunct Lecturer for graduate level distance learning course for the Department of Fire Protection Engineering at the University of Maryland, December 2004 – present.

"**Introduction to Fire Modeling**", two-day course sponsored by the Society of Fire Protection Engineers (SFPE), **Atlanta, GA**, November 12 –13, 1998; **Baltimore, MD** May 13 –14, 1999, **Baltimore, MD** October 2 – 3, 2000, **Idaho Falls, Idaho**, May 7 - 8, 2002.

"**Introduction to Fire Modeling**", one-day course sponsored by the International Fire Code Institute (IFCI), the International Conference of Building Officials (ICBO), and the

Society of Fire Protection Engineers (SFPE), **St. Paul, MI**, November 17 & 19, 1998; **Tacoma, WA**, January 28, 1999.

"Engineering Design Alternatives", one-day course sponsored by the International Fire Code Institute (IFCI), the International Conference of Building Officials (ICBO), and the Society of Fire Protection Engineers (SFPE), **Tacoma, WA**, January 29, 1999; **Dallas, TX**, April 7, 1999.

"The Fire Safety Engineering Method", five-day course sponsored by Canadian Association of Building Code Officials, **Winnipeg, Canada**, May 30th - June 4th, 1999.

"Advanced Computer Fire Modeling", two-day course sponsored by the Society of Fire Protection Engineers (SFPE), **New Orleans, LA**, November 11 – 12, 1999; **Baltimore, MD**, October 4 – 5, 2000, **Santa Fe, NM,** March 14 – 15, 2002.

"Introduction to Fire Dynamics Simulator (FDS) and Smokeview", three-day course sponsored by the Society of Fire Protection Engineers (SFPE), **Baltimore/Washington**, September 16 – 18, 2002, **Las Vegas**, March 23 – 25, 2004, **Chicago**, September 21-23, 2004, **Hawaii**, February 1-3, 2005, **Chicago**, August 14 -16, 2006.

"Advanced Fire Dynamics Simulator (FDS) and Smokeview", three-day course sponsored by the Society of Fire Protection Engineers (SFPE), **San Diego**, October 19 – 21, 2005, **Baltimore**, October 18 – 20, 2006, **Las Vegas**, October 16 – 19, 2007.

SELECTED PUBLICATIONS AND PRESENTATIONS:

Presentations (Non-Peer Reviewed):

Carpenter, D. J., **"Fire Protection in Antarctica,"** presented to the Chesapeake Chapter of the Society of Fire Protection Engineers, **College Park, Maryland**, April 30, 1998; New England Chapter of the Society of Fire Protection Engineers, **Boston, MA**, February 7, 2000.

Carpenter, D. J. and Hamer, A. J., **"The Modeling of Experimental Compartment Fires Using Computational Fluid Dynamics,"** presented at the 1998 STAR-CD North America User's Conference, **Detroit, MI**, May 19-20, 1998.

Carpenter, D. J., **"The Use of Quantitative Tools in Fire Investigation,"** presented to the Vermont Chapter of the International Association of Arson Investigators, **Randolph Center, VT**, December 3, 1998; New Jersey Chapter of the International Association of Arson Investigators, **Morristown, NJ**, June 18, 1999.

Carpenter, D. J., Beller, D., and Sapochetti, J., **"Using the "Scientific Method" in the Analysis of the Cause and Origin of the Fire at the Cococnut Grove: Development of a New Hypothesis"**, NFPA World Fire Safety Congress and Exposition, **Baltimore, MD**, May 16-20, 1999.

Carpenter, D. J., and Roby, R. J., "**Advanced Investigation and Technology: Application and Presentation of Fire Modeling in Arson Investigations**," presented to the National Society of Professional Insurance Investigators 1999 Advanced Insurance Fraud Seminar, **Cincinnati, OH**, November 11, 1999.

Watts, J. M., Jr., and Carpenter, D. J., "**Fire Dynamics and Fire Modeling & Human Behavior in Fire and Performance-Based Fire Safety Evaluation**", State of Vermont, Department of Labor, **Rutland, VT**, January 31st, 2000.

West, L. E., Reiter, D. A., and Carpenter, D. J., "**Forensic Fire Investigation**", The 2000 Claims Conference, Professional Loss Research Bureau (PLRB), **Chicago, IL**, March 26 – 29, 2000.

Conference Poster Sessions (Editorially Reviewed):

Carpenter, D. J., and DiNenno, P. J., "**Halon Alternative Selection Tool Software**", *Proceedings of the Halon Alternatives Technical Working Conference*, May 6-8, 1997, Albuquerque, NM.

Carpenter, D. J., and Barnett, J. R., "**The Modeling of Fire Tests Conducted at the National Research Council of Canada Using the Fire Field Model JASMINE**," presented at the International Conference on Fire Research and Engineering, Orlando, FL, September 10-15, 1995.

Conference Papers (Editorially Reviewed):

Carpenter, D. J., Roby, R. J., and Torero, J. L., "**The Use of Toxicity Data in the Reconstruction and Analysis of Fires**," *Proceedings of the 2nd International Symposium on Fire Investigation Science and Technology*, National Association of Fire Investigators, University of Cincinnati, June 28 – 30, 2006.

Carpenter, D. J., Roby, R. J., and Torero, J. L., "**Training Versus Education: The Case for the Development of a National Curriculum for Fire Investigators**," *Proceedings of the 2nd International Symposium on Fire Investigation Science and Technology*, National Association of Fire Investigators, University of Cincinnati, June 28 – 30, 2006.

Ferrino-McAllister, J. L., Carpenter, D. J., and Roby, R. J., "**Comparison of Gasoline Weathering on Carpet Samples Exposed to Various Thermal Environments**," *Proceedings of the 2nd International Symposium on Fire Investigation Science and Technology*, National Association of Fire Investigators, University of Cincinnati, June 28 – 30, 2006.

Sutula, J. A., Carpenter, D. J., Anderson, J., and Cometto, A., "**The Use of Animation as an Aid in the Presentation of Results of Computational Fluid Dynamics Modeling in Fire Reconstruction Analysis**," *Proceedings of the 2nd International Symposium on Fire*

Investigation Science and Technology, National Association of Fire Investigators, University of Cincinnati, June 28 – 30, 2006.

Carpenter, D. J., and Cummings, W., "**Performance-Based Analysis of ARFF Requirements for Air-Fields at McMurdo and South Pole Stations, Antarctica,**" NFPA World Safety Conference, Dallas, TX, May 18-21, 2003.

Carpenter, D. J. and Zhang, W., "**Validation of Fire Modeling by Fire Dynamic Simulator for Fire Protection Engineering**," NFPA World Safety Conference, Dallas, TX, May 18-21, 2003.

Zhang, W., N. L. Ryder, R. J. Roby, and D. J. Carpenter, "**Modeling of the Combustion in a Compartment Fire by Large Eddy Simulation Approach,**" *Proceedings of the Chemical and Physical Processes in Combustion*, Eastern States Section of the Combustion Institute Fall Technical Meeting, Hilton Head, SC, December 2001.

Sutula, J. A., Carpenter, D. J., and Roby, R. J., "**Use of the FDS Model to Analyze Two Competing Scenarios in an Alleged Arson Case,**" presented at 3rd Technical Symposium on Computer Applications in Fire Protection Engineering, Society of Fire Protection Engineers, Baltimore, MD, September 2001.

Zhang, W., Hamer, A. J., Klassen, M. S., Carpenter, D. J., and Roby, R. J., "**Verification of the Turbulence Statistics for Fire Dynamic Simulator in a Room Fire,**" presented at 3rd Technical Symposium on Computer Applications in Fire Protection Engineering, Society of Fire Protection Engineers, Baltimore, MD, September 2001.

Zhang, W., Hamer, A., Klassen, M., Carpenter, D., and Roby, R., "**Turbulence Statistics in a Fire Room Model by Large Eddy Simulation,**" presented at 2nd Joint Meeting of the U.S. Sections of the Combustion Institute, Oakland, CA, March 2001.

Carpenter, D. J., "**Development of a Waiver/Deviation Process for Determining Equivalent Fire Protection at United States Research Stations in Antarctica,**" presented at the International Conference on Performance-Based Fire Safety Codes and Design Methods, **Ottawa, Canada**, September 23-26, 1996.

Journal Publications (Peer Reviewed):

Zhang, W., Olenick, S. M., Klassen, M. S., Carpenter, D. J., and Roby, R. J., "A Smoke Detector Activation Algorithm for Large Eddy Simulation Fire Modeling," in preparation for submission to *Fire Safety Journal.*

Olenick, S. M., and Carpenter, D. J., "**An Updated International Survey of Computer Models fro Fire and Smoke,**" Journal of Fire Protection Engineering, Vol. 13, No. 2, 2003.

Zhang, W., Hamer, A., Klassen, M., Carpenter, D., and Roby, R., "**Turbulence Statistics in a Fire Room Model by Large Eddy Simulation,**" *Fire Safety Journal*, 37, pp. 721-752, 2002.

Wade, C. A., and Carpenter, D. J., "**A Performance-Based Analysis of an Industrial Facility Containing Flammable Liquid Storage,**" *Journal of Fire Protection Engineering*, Vol. 9, No. 2, 1998.

Carpenter, D. J., and Wade, C. A., "**A Performance-Based Fire Hazard Analysis of an Industrial Process Using Pressurized Hydraulic Fluids,**" in preparation for submission to the *Journal of Fire Protection Engineering*.

Published Reports:

DiNenno, P. J., Verdonik, D. P., and Carpenter, D. J., "**U.S. Navy Halon 1211 Replacement Plan Part I - Development of Halon 1211 Alternatives,**" Navy Research Laboratory (NRL), NRL/MR/6180-99-8410, November 1, 1999.

Mawhinney, J. R., and Carpenter, D. J., "**A Review of Fire Hazards and Fire Suppression Options for the Halifax Class Frigates of the Canadian Navy,**" Client Report A-4424.1, for Department of National Defence, National Research Council Canada, Ottawa, Canada, March 10, 1997.

Amy, J., Carpenter, D. J., and Pucci, W. E., "**Alternative Combustible Loading: Conceptual Matrix Development and Implementation (U)**", WSRC-RP-93-1445, Westinghouse Savannah River Company, Savannah River Site, Akien, SC, October 29, 1993.

Carpenter, D. J., "**Alternative Combustible Loading: An Overview and Methodology Framework (U)**", WSRC-RP-93-1194, Westinghouse Savannah River Company, Savannah River Site, Akien, SC, September 30, 1993.

David D. Evans

Education

Case Western Reserve University, B.S.,
Thermal and Fluid Sciences
Harvard University, M.S.,
Mechanical Engineering
Harvard University, Ph.D.,
Engineering

Present Position

Executive Director
Society of Fire Protection Engineers

After completing his undergraduate and graduate education, he joined the Chemical and Plastics Research Division of Union Carbide Corporation where he supervised research in product flammability. At Union Carbide, Dr. Evans gained extensive experience with both established and evolving fire test methods.

Dr. Evans was successful in competition for a National Research Council Postdoctoral Fellowship and in 1976 came to the National Institute of Standards and Technology to study smoldering combustion. At NIST, he also undertook studies of the largely ignored effect of response time on fire test measurements. This work continued after joining the permanent staff of the Center for Fire Research, and was focused on understanding the performance of fire sprinkler systems with regard to both response time and water spray fire suppression effectiveness. The first predictive method for engineering calculation of sprinkler response time in fires, DETACT, developed by Dr. Evans was implemented on programmable calculators and later on personal computers. Subsequent to his appointment as Head of the Fire Suppression Research Group, a first generation fire suppression model was developed by Dr. Evans for engineering analysis of the fire suppression performance of sprinkler systems.

In 1995, Dr. Evans became Chief of the Fire Safety Engineering Division. In this position he has focused NIST resources to address the development of technology for advanced fire fighting and fire protection engineering analysis. Major programs under his direct leadership have been the study and demonstration of new technology water spray injection systems for reduction of fire effects and extinguishment of gas-well blowout fires; the develop new measurement and predictive methods to characterize the burning and smoke plume from intentional burning of oil spills; and the development of a new technology fire dynamics simulator with applications to sprinkler system performance in large facilities.

In 2004, Dr. Evans left government service to provide leadership at the Society of Fire Protection Engineers (SFPE) as the third executive director of that international organization. Dr. Evans is a Fellow of SFPE and past-president of the Society. Under his leadership, the organization has expanded its international membership and established new regional chapters in Asia and the Middle East. SFPE education and distance learning programs have been expanded to facilitate the transfer of fire safety research to engineering practice.

Dr. Evans is a registered professional engineer in the District of Columbia.

Publications of David D. Evans

1970-1979

Evans, D. D.; Breden, L. H.
Numerical Technique to Correct Heat Release Rate Calorimetry Data for Apparatus Time Delay. Final Report.
National Bureau of Standards, Gaithersburg, MD
NBSIR 77-1302; 25 p. November 1977.
Available from National Technical Information Service

Evans, D. D.
Density of Wood Charcoal.
Union Carbide Corp., South Charleston, WV
National Science Foundation, Washington, DC
Home Fire Proj. Tech. Rpt. 14; 11 p. 1976.

Evans, D. D.; Emmons, H. W.
Combustion of Wood Charcoal.
National Bureau of Standards, Gaithersburg, MD
National Science Foundation, Washington, DC
Harvard Univ., Cambridge, MA
Fire Research, Vol. 1, 57-66, March 1977.
Home Fire Proj. Tech. Rpt. 13; 35 p. 1975.

Evans, D. D.; Breden, L. H.
Time Delay Correction for Heat Release Rate Data.
National Bureau of Standards, Gaithersburg, MD
Fire Technology, Vol. 14, No. 2, 85-96, May 1978.

Rogers, G. J.; Evans, D. D.
Characterization of Electrical Ignition Sources Within Television Receivers. Final Report.
National Bureau of Standards, Gaithersburg, MD
Consumer Product Safety Commission, Washington, DC
NBS TN 1109; 60 p. October 1979.
Available from National Technical Information Service
PB80-103450

1980-1985

Evans, D. D.; Stroup, D. W.
Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings.
National Bureau of Standards, Gaithersburg, MD
Nuclear Regulatory Commission, Washington, DC
Fire Technology, Vol. 22, No. 1, 54-65, February 1986.
NBSIR 85-3167; 49 p. July 1985.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov
PB86-105996

Evans, D. D.; Pfenning, D. B.
Water Sprays Suppress Gas-Well Blowout Fires.
National Bureau of Standards, Gaithersburg, MD
Energy Analysts Inc., Norman, OK
Oil and Gas Journal, Vol. 83, No. 17, 80-86, April 29, 1985.
NIST SP 995; Volume 2; March 2003.

Evans, D. D.
Calculating Sprinkler Actuation Time in Compartments.
National Bureau of Standards, Gaithersburg, MD
Fire Safety Journal, Vol. 9, No. 2, 147-155, 1985.
CIB W14/85/14 (USA);
Society of Fire Protection Engineers. Computer Applications in Fire Protection: Analysis, Modeling and Design. March 19-21, 1984, Leesburg, VA, 29 pp, 1984.

Evans, D. D.
Extinguishment of Blowout Fires With Water Sprays.
National Bureau of Standards, Gaithersburg, MD
Minerals Management Service. Technology Assessment and Research Program for Offshore Operations. Annual Information Transfer Meeting, 6th. Session IIA. October 22, 1985, Reston, VA, 17-19 pp, 1985.

Evans, D. D.
Thermal Actuation of Extinguishing Systems.
National Bureau of Standards, Gaithersburg, MD
Combustion Science and Technology, Vol. 40, 79-92, 1984.
NBSIR 83-2807; 28 p. March 1984.
National Bureau of Standards/Center for Fire Research. Fire Science for Fire Safety. August 23-25, 1983, Gaithersburg, MD, Levine, R. S.; Pagni, P. J., Editors, 1984.
Available from National Technical Information Service
PB84-177146

Evans, D. D.
Calculating Fire Plume Characteristics in a Two Layer Environment.
National Bureau of Standards, Gaithersburg, MD
Fire Technology, Vol. 20, No. 3, 39-63, August 1984.
NBSIR 83-2670; 47 p. September 1983.
Available from National Technical Information Service
PB84-114 578

Evans, D. D.; Davis, S.
Technical Support for the Consumer Product Safety Commission 1979 Interim Standards for Cellulose Insulation.
National Bureau of Standards, Gaithersburg, MD
Consumer Product Safety Commission, Bethesda, MD
NBSIR 81-2213; 51 p. March 1981.
Available from National Technical Information Service
PB81-196396

Evans, D. D.; Madrzykowski, D.
Characterizing the Thermal Response of Fusible-Link Sprinklers. Final Report.
National Bureau of Standards, Gaithersburg, MD
NBSIR 81-2329; 39 p. August 1981.
Available from National Technical Information Service
PB82-107020

Evans, D. D.
Analysis of Data from Room Fire Test of Parsons Tables and Comparison with Laboratory Test Methods for Flame Spread and Smoke Generation. Volume 1 and Volume 2.
National Bureau of Standards, Gaithersburg, MD
NBSIR 81-2400; 102 p. November 1981.
Available from National Technical Information Service
PB82-185307

Evans, D. D.
Modeling for Determination of Temperatures of Electrical Cables Within Thermally Insulated Walls. Interim Report.
National Bureau of Standards, Gaithersburg, MD
Department of Energy, Washington, DC
NBSIR 80-2129; 28 p. October 1980.
Available from National Technical Information Service
PB81-113847

Evans, D. D.
Calculated Operating Temperatures of Thermally Insulated Electric Cables. Final Report.
National Bureau of Standards, Gaithersburg, MD
Consumer Product Safety Commission, Washington, DC
NBS TN 1133; 41 p. January 1981.
Available from Government Printing Office
Available from National Technical Information Service
SN003-003-02279-9
PB81-145781

Evans, D. D.
Progress in Fire Growth and Prediction, 1984.
National Bureau of Standards, Gaithersburg, MD
UJNR Panel on Fire Research and Safety. 8th Joint Panel Meeting. May 13-21, 1985., Tsukuba, Japan, 228-242 pp, 1985.

Evans, D. D.
Framework for the Study of Fire Extinguishment.
National Bureau of Standards, Gaithersburg, MD
UJNR Panel on Fire Research and Safety. 8th Joint Panel Meeting. May 13-21, 1985., Tsukuba, Japan, 813-824 pp, 1985.

Evans, D. D.
Control of Blowout Fires With Water Sprays.
National Bureau of Standards, Gaithersburg, MD
OCS Report MMS 84-0001;
U.S. Department of the Interior Minerals Management Service. Technology Assessment and Research Program for Offshore Minerals Operations. March 28-29, 1984, Reston, VA, 89-95 pp, 1984.

Evans, D. D.
Plume Flow in a Two-Layer Environment.
National Bureau of Standards, Gaithersburg, MD
American Society of Mechanical Engineers. Fire Dynamics and Heat Transfer. National Heat Transfer Conference, 21st. July 24-28, 1983., Seattle, WA, American Society of Mechanical Engineers, New York, Quintiere, J. G., Alpert, R. L. and Altenkirch, R. A., Editor, 89-96 pp, 1983.

Milke, J. A.; Evans, D. D.; Hayes, W. D., Jr.
Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment. Part 1 of 2. Report of Test.
National Bureau of Standards, Gaithersburg, MD
Federal Emergency Management Agency, Washington, DC
FR 3956; Work Unit 6121A; Task Order 4A; 54 p. January 1985.

Milke, J. A.; Evans, D. D.; Hayes, W. D., Jr.
Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment. Part 2 of 2. Report of Test.
National Bureau of Standards, Gaithersburg, MD
Federal Emergency Management Agency, Washington, DC
FR 3956; Work Unit 6121A; Task Order 4A; 399 p. January 1985.

Pfenning, D.; Evans, D. D.
Suppression of Gas Well Blowout Fire Using Water Sprays; Large and Small Scale Studies.
Energy Analysts, Inc., Norman, OK
National Bureau of Standards, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
American Petroleum Institute, Committee on Fire and Safety Protection, Production Session, Hyatt Regency, September 11-13, 1984, San Antonio, TX, 1-29 pp, 1984.

Trehan, A. K.; diMarzo, M.; Evans, D. D.
Transient Cooling of a Hot Surface by Droplet Evaporation.
Maryland Univ., College Park, MD
National Bureau of Standards, Gaithersburg, MD
National Bureau of Standards, Gaithersburg, MD
NBS GCR 86-516; 132 p. July 1986.
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. Fall Technical Meeting, 1985. November 4-6, 1985, Philadelphia, PA, 61/1-61/4 pp, 1985.
Available from National Technical Information Service
PB87-145421

1986-1989

Arai, M.; Saito, K.; Altenkirch, R. A.; Evans, D. D.
Study of the Boilover Phenomenon for Liquid Fuel Supported on Water.
Kentucky Univ., Lexington
National Bureau of Standards, Gaithersburg, MD
National Bureau of Standards, Gaithersburg, MD
Paper 2;
National Bureau of Standards. Final Report. Volume 1. Papers Presented at Conferences and Submitted for Publication. Volume 2. Experimental Developments in the Combustion of Crude Oils. August 1, 1987-December 15, 1988, Saito, K. Editor(s), 186 pp, 1988. and Combustion Institute/Central States Section. May 2-3, 1988, Indianapolis, IN, 1-6 pp, 1988 IL, 1-6 pp, 1988., 1988

Budnick, E. K.; Evans, D. D.
Hand Calculations for Enclosure Fires.
National Bureau of Standards, Gaithersburg, MD
NFPA FPH 1686;
Fire Protection Handbook. 16th Edition. Section 21. Chapter 3, National Fire Protection Assoc., Quincy, MA, Cote, A. E. and Linville, J. L., Editor(s), 21/19-24 p., 1986.

diMarzo, M.; Evans, D. D.
Evaporation of a Water Droplet Deposited on a Hot High Thermal Conductivity Solid Surface.
Maryland Univ., College Park
National Bureau of Standards, Gaithersburg, MD
NBSIR 86-3384; 33 p. August 1986.
Available from National Technical Information Service
PB86-247871

diMarzo, M.; Evans, D. D.
Dropwise Evaporative Cooling of High Thermal Conductivity Materials.
Maryland Univ., College Park
National Bureau of Standards, Gaithersburg, MD
National Bureau of Standards, Gaithersburg, MD
Heat and Technology, Vol. 5, No. 1-2, 126-136, 1987.

diMarzo, M.; Trehan, A. K.; Evans, D. D.
Cooling Effect of a Single Evaporating Droplet on a Hot Semi-Infinite Metal Body.
National Bureau of Standards, Gaithersburg, MD
Maryland Univ., College Park
NBSIR 87-3517; 29 p. April 1987.
Available from National Technical Information Service
PB87-201802

diMarzo, M.; Evans, D. D.
Evaporation of a Water Droplet Deposited on a Hot High Thermal Conductivity Surface.
National Institute of Standards and Technology, Gaithersburg, MD
Journal of Heat Transfer, Vol. 111, No. 1, 210-213, February 1989.

Evans, D. D.; Stroup, D. W.
Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings.
National Bureau of Standards, Gaithersburg, MD
Nuclear Regulatory Commission, Washington, DC
Fire Technology, Vol. 22, No. 1, 54-65, February 1986.
NBSIR 85-3167; 49 p. July 1985.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov
PB86-105996

Evans, D. D.; McCaffrey, B. J.; Mulholland, G. W.; Harkleroad, M. F.; Manders, W. F.
Oil Spills on Water. MMS Title: Burning of Oil Spills on Water. This Work is Slightly Shortened Version of NBSIR 86-3420.
National Bureau of Standards, Gaithersburg, MD
Minerals Management Service, Reston, VA
Conservation and Protection, Environment, Canada
; 48 p. 1986.
Conservation and Protection, Enironment, Canada. Arctic and Marine Oil Spill Program Technical Seminar. 9th Proceedings. June 10-12, 1986, Edmonton, Alberta, 301-336 pp, 1986.

Evans, D. D.; Walton, W. D.; McCaffrey, B. J.
Progress in Modeling Sprinkler Performance.
National Bureau of Standards, Gaithersburg, MD
NBSIR 88-3753;
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 9th Joint Panel Meeting of the UJNR Panel. May 4-8, 1987, Norwood, MA, 1-11 pp, 1987.
Available from National Technical Information Service
PB88-215926

Evans, D. D.; Morehart, J.
Investigation of the Effects of a Stratified Two Layer Environment on Fire Plume Temperatures.
National Bureau of Standards, Gaithersburg, MD
California Institute of Technology, Pasadena, CA
American Society of Mechanical Engineers and Japan Society of Mechanical Engineers. Proceedings of the 1987 ASME-JSME Thermal Engineering Joint Conference. Volume 1. March 22-27, 1987, Honolulu, HI, American Society of Mechanical Engineers, New York, Marto, P. J.; Tanasawa, I., Editors, 381-386 pp, 1987.

Evans, D. D.; Baum, H. R.; McCaffrey, B. J.; Mulholland, G. W.; Harkleroad, M. F.; Manders, W. F.
Combustion of Oil on Water.
National Bureau of Standards, Gaithersburg, MD
Department of the Interior, Reston, VA
NBSIR 86-3420; NIST SP 995; Volume 2; 55 p. November 1987.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB89-185581
http://fire.nist.gov/bfrlpubs/fire03/PDF/f03156.pdf

Evans, D. D.
In-Situ Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 762; NIST SP 995; Volume 2; April 1989.
Minerals Management Service, U.S. Department of Interior. Alaska Arctic Offshore Oil Spill Response Technology. Workshop Proceedings. November 29-December 1, 1988, Anchorage, AK, Jason, N. H., Editor, 47-95 pp, 1989.
Available from Government Printing Office

Evans, D. D.; Mulholland, G. W.; Gross, D.; Baum, H. R.; Saito, K.
Environment Effects of Oil Spill Combustion.
National Institute of Standards and Technology, Gaithersburg, MD
Department of the Interior, Reston, VA
Minerals Management Service, Reston, VA
NISTIR 88-3822; 51 p. September 1988.
Available from National Technical Information Service
PB89-107726

Evans, D. D.
Overview of Fire Suppression With Water.
National Institute of Standards and Technology, Gaithersburg, MD
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 1988 Technical Meeting. December 5-7, 1988, Clearwater Beach, FL, D/1-6 pp, 1988.

Evans, D. D.
Ceiling Jet Flows.
National Bureau of Standards, Gaithersburg, MD
NFPA SFPE 88;
SFPE Handbook of Fire Protection Engineering. 1st Edition. Section 1. Chapter 9, National Fire Protection Assoc., Quincy, MA, 1/138-145 p., 1988.

Evans, D. D.; Baum, H. R.; Mulholland, G. W.; Bryner, N. P.; Forney, G. P.
Smoke Plumes From Crude Oil Burns.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 12th. June 7-9, 1989, Calgary, Canada, 1-22 pp, 1989.

Evans, D. D.; Mulholland, G. W.; Gross, D.; Baum, H. R.; Walton, W. D.; Saito, K.
Burning, Smoke Production, and Smoke Dispersion From Oil Spill Combustion.
National Institute of Standards and Technology, Gaithersburg, MD
Kentucky Univ., Lexington
Minerals Management Service, Reston, VA
NISTIR 89-4091; 57 p. October 1989.
Available from National Technical Information Service
PB90-146374

Evans, D. D.; Mulholland, G. W.; Gross, D.; Baum, H. R.; Saito, K.
Generation and Dispersal of Smoke From Oil Spill Combustion.
National Institute of Standards and Technology, Gaithersburg, MD
Kentucky Univ., Lexington
American Petroleum Institute, Environmental Protection Agency and U.S. Coast Guard. Oil Spill Conference: Prevention, Behavior, Control, Cleanup, 1989. February 13-16, 1989, San Antonio, TX, 181-186 pp, 1989.

Gore, J. P.; Faeth, G. M.; Evans, D. D.; Pfenning, D. B.
Structure and Radiation Properties of Large-Scale Natural Gas/Air Diffusion Flames.
Michigan Univ., Ann Arbor, MI
National Bureau of Standards, Gaithersburg, MD
Energy Analysts, Inc., Norman, OK
National Bureau of Standards, Gaithersburg, MD
Fire and Materials, Vol. 10, No. 3&4, 161-169, September/December 1986.

Gore, J. P.; Evans, D. D.; McCaffrey, B. J.
Temperature and Radiation of Large Methane/Air Jet Flames With Water Suppression.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
Maryland Univ., Baltimore
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 1988 Technical Meeting. December 5-7, 1988, Clearwater Beach, FL, 60/1-4 pp, 1988.

Gore, J. P.; Skinner, S. M.; Stroup, D. W.; Madrzykowski, D.; Evans, D. D.
Structure and Radiation Properties of Large Two-Phase Flames.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
HTD-Vol. 122;
American Society of Mechanical Engineers (ASME). Heat Transfer in Combustion Systems. Winter Annual Meeting. HTD-Vol. 122. December 10-15, 1989, San Francisco, CA, Ashgriz, N.; Quintiere, J. G.; Semerjian, H. G.; Slezak, S. E., Editors, 77-86 pp, 1989.

Kavoosi, F.; diMarzo, M.; Baum, H. R.; Evans, D. D.
Application of Boundary Element Methods to a Transient Axisymmetric Heat Conduction Problem.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
HTD-Vol. 110;
American Society of Mechanical Engineers. Numerical Heat Transfer With Personal Computers and Supercomputing. National Heat Transfer Conference, 1989. HTD-Vol. 110. August 6-9, 1989, Philadelphia, PA, ASME, New York, Shah, R. K., Editor, 79-85 pp, 1989.

Lawson, J. R.; Walton, W. D.; Evans, D. D.
Measurement of Droplet Size in Sprinkler Sprays.
National Bureau of Standards, Gaithersburg, MD
Swedish Fire Research Board, Stockholm, Sweden
General Services Admin., Washington, DC
NBSIR 88-3715; 51 p. April 1988.
Available from National Technical Information Service
PB88-215454

McCaffrey, B. J.; Evans, D. D.
Very Large Methane Jet Diffusion Flames.
National Bureau of Standards, Gaithersburg, MD
Combustion Institute, Symposium (International) on Combustion, 21st. August 3-8, 1986, Munich, West Germany, Combustion Inst., Pittsburgh, PA, 25-32 pp, 1986.

Meng, W. H.; Wang, Z. Y.; diMarzo, M.; Evans, D. D.
Single and Multi Droplet Evaporative Cooling.
Maryland Univ., College Park, MD
National Bureau of Standards, Gaithersburg, MD
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 20th Fall Technical Meeting. and National Bureau of Standards/Center for Fire Research. Annual Conference on Fire Research. Combined Technical Meetings. Abstracts. November 2-5, 1987., Gaithersburg, MD, 42/1-4 pp, 1987.

Milke, J. A.; Evans, D. D.; Hayes, W. D., Jr.
Water Spray Suppression of Fully-Developed Wood Crib Fires in a Compartment.
National Bureau of Standards, Gaithersburg, MD
Federal Emergency Management Agency, Washington, DC
NBSIR 88-3745; 66 p. June 1988.
Available from National Technical Information Service
PB88-232871

Sato, K.; Evans, D. D.
Comparison Between Field Model and Zone Model for Ceiling Jet.
Tokyo Univ., Japan
National Bureau of Standards, Gaithersburg, MD
Japanese Association of Fire Science and Engineering Meeting. May 19-20, 1987, 39-42 pp, 1987.

Satoh, K.; Evans, D. D.
Comparative Predictions of Fire Generated Ceiling-Jet Gas Temperatures in an Enclosure Using Both a Field Equation Model and a Three Layer Zone Model.
Fire Research Inst. of Japan, Tokyo
National Bureau of Standards, Gaithersburg, MD
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. 20th Fall Technical Meeting. and National Bureau of Standards/Center for Fire Research. Annual Conference on Fire Research. Combined Technical Meetings. Abstracts. November 2-5, 1987., Gaithersburg, MD, 105/1-4 pp, 1987.

Stroup, D. W.; Evans, D. D.; Martin, P. M.
Evaluating Thermal Fire Detection Systems (English Units). Final Report.
National Bureau of Standards, Gaithersburg, MD
NBS SP 712; 557 p. April 1986.
AVAILABLE FROM: National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov
PB86-206570

Stroup, D. W.; Evans, D. D.; Martin, P. M.
Evaluating Thermal Fire Detection Systems (SI Units). Final Report.
National Bureau of Standards, Gaithersburg, MD
NBS SP 713; 557 p. April 1986.
Available from Government Printing Office, Washington, DC
003-003-02741-3

Stroup, D. W.; Evans, D. D.
Use of Computer Fire Models for Analyzing Thermal Detector Spacing.
National Bureau of Standards, Gaithersburg, MD
Fire Safety Journal, Vol. 14, 33-45, 1988.

Tokura, I.; Saito, K.; Altenkirch, R. A.; Evans, D. D.
Study of Crude Oil Combustion: Thermal Conductivity of the Condensed Phase.
Kentucky Univ., Lexington
National Bureau of Standards, Gaithersburg, MD
National Bureau of Standards, Gaithersburg, MD
Paper 1;
National Bureau of Standards. Final Report. Volume 1. Papers Presented at Conferences and Submitted for Publication. Volume 2. Experimental Developments in the Combustion of Crude Oils. August 1, 1987-December 15, 1988, Saito, K. Editor(s), 186 pp, 1988. and Combustion Institute/Central States Section. May 11-12, 1987, Argonne, IL, 1-6 pp, 1988., 1988.

1990-1995

Benner, B. A., Jr.; Bryner, N. P.; Wise, S. A.; Mulholland, G. W.; Evans, D. D.; Fingas, M. F.; Li, K.
Emissions of Polycyclic Aromatic Hydrocarbons From the Combustion of Crude Oil on Water.
National Institute of Standards and Technology, Gaithersburg, MD
Environment Canada, Ottawa
Spill Technology Newsletter, Vol. 16, No. 1, 1-16, March 1991.

diMarzo, M.; Liao, Y.; Tartarini, P.; Evans, D. D.; Baum, H. R.
Dropwise Evaporative Cooling of a Low Thermal Conductivity Solid.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
International Association for Fire Safety Science. Fire Safety Science. Proceedings. 3rd International Symposium. July 8-12, 1991, Edinburgh, Scotland, Elsevier Applied Science, New York, Cox, G.; Langford, B., Editors, 987-996 pp, 1991.

diMarzo, M.; Tartarini, P.; Liao, Y.; Baum, H. R.; Evans, D. D.
Coupled Solid-Liquid Model for Dropwise Evaporative Cooling.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
Session B-4;
Combustion Institute/Eastern States Section. Chemical and Physical Processes in Combustion. Fall Technical Meeting, 1990. December 3-5, 1990, Orlando, FL, 82/1-4 pp, 1990.

diMarzo, M.; Tartarini, P.; Liao, Y.; Evans, D. D.; Baum, H. R.
Evaporative Cooling Due to a Gently Deposited Droplet.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
International Journal of Heat and Mass Transfer, Vol. 36, No. 17, 4133-4139, 1993.
NIST GCR 96-687; Paper 7; June 1996.
Available from National Technical Information Service
PB96-202304

Evans, D. D.; Walton, W. D.; Baum, H. R.; Lawson, J. R.; Rehm, R. G.; Harris, R. H., Jr.; Ghoniem, A.; Holland, J.
Measurement of Large Scale Oil Spill Burns.
National Institute of Standards and Technology, Gaithersburg, MD
Massachusetts Institute of Technology, Cambridge
Consultant, Wheaton, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 13th. June 6-8, 1990, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 1-38 pp, 1990.

Evans, D. D.; Walton, W. D.
Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 4449;
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 11th Joint Panel Meeting. October 19-24, 1989, Berkeley, CA, Jason, N. H.; Cramer, D. M., Editors, 217-222 pp, 1990.
Available from National Technical Information Service

Evans, D. D.; Walton, W. D.; Baum, H. R.; Mulholland, G. W.; Lawson, J. R.; Koseki, H.; Ghoniem, A.
Smoke Emission From Burning Crude Oil.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Massachusetts Institute of Technology, Cambridge
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oilspill Program Technical Seminar, 14th. June 12-14, 1991, Vancouver, B.C., Environment Canada, Ottawa, Ontario, 421-449 pp, 1991.

Evans, D. D.; Tennyson, E. J.
In-Situ Burning: A Promising Oil Spill Response Strategy.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Herndon, VA
Coastal and Ocean Management, 7th Symposium. July 8-12, 1991, Long Beach, CA, 1-18 pp, 1991.

Evans, D. D.; Mulholland, G. W.; Lawson, J. R.; Tennyson, E. J.; Tebeau, P. A.; Fingas, M. F.; Gould, J. R.
Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Materials Management Service, Herndon, VA
Coast Guard Research and Development Branch, Groton, CT
Environment Canada, Ottawa, Ontario
American Petroleum Institute, Washington, DC
U.S. Coast Guard, American Petroleum Institute, and U.S. Environmental Protection Agency.
International Oil Spill Conference: Prevention, Behavior, Control, Cleanup, 1991 Proceedings. March 4-7, 1991, San Diego, CA, 677-680 pp, 1991.

Evans, D. D.
Burning Oil Spills. BFRL Video Seminar.
National Institute of Standards and Technology, Gaithersburg, MD
Video; June 25, 1991.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Notarianni, K. A.; Lawson, J. R.; Tang, H. C.; Keydel, K. R.; Rehm, R. G.; Madrzykowski, D.; Zile, R. H.; Koseki, H.; Tennyson, E. J.
In-Situ Burning of Oil Spills: Mesoscale Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oilspill Program Technical Seminar, 15th. June 10-12, 1992, Edmonton, Canada, Environment Canada, Ottawa, Ontario, 593-657 pp, 1992.

Evans, D. D.
In Situ Burning as an Oil Spill Response Technology.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service. Technology Assessment and Research Program for Offshore Minerals Operations. OCS Study MMS 91-0057. 1991 Report. Biennial Report of the Technology Assessment and Research Program, 7th. 1991, Reston, VA, Gregory, J. B.; Smith, C. E.; Tennyson, E. J., Editors, 195-200 pp, 1991.

Evans, D. D.
Suppression Research: Strategies.
National Institute of Standards and Technology, Gaithersburg, MD
Swedish Fire Research Board and National Institute of Standards and Technology. Fire Suppression Research, 1st International Conference. May 5-8, 1992, Stockholm, Sweden, Sjolin, V.; Evans, D. D.; Jason, N. H., Editors, 21-35 pp, 1992.

Evans, D. D.; Walton, W. D.; Notarianni, K. A.; Baum, H. R.; Tennyson, E. J.
Burning of Large Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Reston, VA
Department of the Interior, Washington, DC
American Petroleum Institute, Washington, DC
Coast Guard, Washington, DC
Department of Transportation, Washington, DC
Society of Fire Protection Engineers. Large Fires: Causes and Consequences. Extended Abstracts. SFPE Engineering Seminars. November 16-18, 1992, Dallas, TX, Society of Fire Protection Engineers, Boston, MA, 34-39 pp, 1992.

Evans, D. D.
Sprinkler Fire Suppression Algorithm for HAZARD.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 5254; 21 p. August 1993.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 114-120 pp, 1992.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB94-103678

Evans, D. D.
Progress Report on Suppression and Detection Research in the U.S.
National Institute of Standards and Technology, Gaithersburg, MD
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 76-80 pp, 1992.

Evans, D. D.; Walton, W. D.; Notarianni, K. A.; Baum, H. R.; Koseki, H.
Large Fires: Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Reston, VA
Department of the Interior, Washington, DC
American Petroleum Institute, Washington, DC
Coast Guard, Washington, DC
Department of Transportation, Washington, DC
NIST SP 995; Volume 2; March 2003.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 365-371 pp, 1992.

Evans, D. D.
In Situ Burning of Oil Spills: Smoke Production and Plume Behavior.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 867; August 1994.
National Institute of Standards and Technology **and** Minerals Management Service. In Situ Burning Oil Spill. Proceedings. January 26-28, 1994, Orlando, FL, Jason, N. H., Editor, 29-37 pp, 1994.
Available from Government Printing Office
Available from National Technical Information Service
PB95-104907

Evans, D. D.; Madrzykowski, D.; Haynes, G. A.
Flame Heights and Heat Release Rates of 1991 Kuwait Oil Field Fires.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
International Association for Fire Safety Science. Fire Safety Science. Proceedings. 4th International Symposium. July 13-17, 1994, Ottawa, Ontario, Canada, Intl. Assoc. for Fire Safety Science, Boston, MA, Kashiwagi, T., Editor, 1279-1289 pp, 1994.

Evans, D. D.
Ceiling Jet Flows.
National Institute of Standards and Technology, Gaithersburg, MD
NFPA SFPE 95; LC Card Number 95-68247;
SFPE Handbook of Fire Protection Engineering. 2nd Edition. Section 2. Chapter 4, National Fire Protection Assoc., Quincy, MA, DiNenno, P. J.; Beyler, C. L.; Custer, R. L. P.; Walton, W. D., Editor(s)(s), 2/32-39 p., 1995.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Notarianni, K. A.; Tennyson, E. J.; Tebeau, P. A.
Mesoscale Experiments Help to Evaluate In-Situ Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Herndon, VA
Coast Guard Research and Development Branch, Groton, CT
NIST SP 995; Volume 2; API Publication No. 4580; March 2003.
Oil Spill Conference, 1993 Proceedings. 1993, Washington, DC, American Petroleum Institute, Washington, DC, 755-760 pp, 2003.

Gore, J. P.; Evans, D. D.; McCaffrey, B. J.
Temperature and Radiation of Diffusion Flames With Suppression.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
Maryland Univ., Catonsville, MD
Combustion Science and Technology, Vol. 77, No. 4-6, 189-202, 1991.

Gore, J. P.; Evans, D. D.
Development of Hazard Assessment and Suppression Technology for Oil and Gas Well Blowout and Diverter Fires.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service. Technology Assessment and Research Program for Offshore Minerals Operations. OCS Study MMS 91-0057. 1991 Report. Biennial Report of the Technology Assessment and Research Program, 7th. 1991, Reston, VA, Gregory, J. B.; Smith, C. E.; Tennyson, E. J., Editors, 27-32 pp, 1991.

Madrzykowski, D.; Evans, D. D.; Haynes, G. A.
Engineering Analysis of the Kuwait Oil Fires.
National Institute of Standards and Technology, Gaithersburg, MD
Maryland Univ., College Park
Society of Fire Protection Engineers. Large Fires: Causes and Consequences. Extended Abstracts. SFPE Engineering Seminars. November 16-18, 1992, Dallas, TX, Society of Fire Protection Engineers, Boston, MA, 40-47 pp, 1992.

Madrzykowski, D.; Evans, D. D.
Large Fires: Kuwait.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 357-364 pp, 1992.

McGrattan, K. B.; Putorti, A. D., Jr.; Twilley, W. H.; Evans, D. D.
Smoke Plume Trajectory From In Situ Burning of Crude Oil in Alaska.
National Institute of Standards and Technology, Gaithersburg, MD
Alaska Department of Environmental Conservation, Juneau, AK
NISTIR 5273; NIST SP 995; Volume 2; 70 p. October 1993.
Available from National Technical Information Service
PB94-114519

McGrattan, K. B.; Walton, W. D.; Putorti, A. D., Jr.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.
Smoke Plume Trajectory From In Situ Burning of Crude Oil in Alaska: Field Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
Alaska Department of Environmental Conservation, Juneau, AK
NISTIR 5764; NIST SP 995; Volume 2; 40 p. November 1995.
Available from National Technical Information Service
PB96-131560

McGrattan, K. B.; Walton, W. D.; Putorti, A. D., Jr.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.
Smoke Plume Trajectory From In Situ burning of Crude Oil in Alaska: Field Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Arctic and Marine Oilspill Program (AMOP) Technical Seminar 18th. Volume 2. Proceedings. June 14-16, 1995, Ontario, Canada, 901-913 pp, 2003.

Mulholland, G. W.; Benner, B. A., Jr.; Fletcher, R. A.; Steel, E.; Wise, S. A.; May, W. E.; Madrzykowski, D.; Evans, D. D.
Analysis of Smoke Samples From Oil Well Fires in Kuwait. Report of Test FR 3985.
National Institute of Standards and Technology, Gaithersburg, MD
National Oceanic and Atmospheric Admin., Washington, DC
Report of Test FR 3985; FR 3985; Report ofTest 3985; 15 p. June 20, 1991.
http://fire.nist.gov/bfrlpubs/fire91/PDF/f91023.pdf

Notarianni, K. A.; Evans, D. D.; Walton, W. D.
Smoke Production From Large Oil Pool Fires.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers. **Interflam 1993. (Interflam '93).** Fire Safety. International Fire Conference, 6th. March 30-April 1, 1993, Oxford, England, Interscience Communications Ltd., London, England, Franks, C. A., Editor, 111-119 pp, 1993.

Putorti, A. D., Jr.; Evans, D. D.; Tennyson, E. J.
Ignition of Weathered and Emulsified Oils.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 17th Proceedings. Volume 1. June 8-10, 1994, Vancouver, British Columbia, Environment Canada, Ottawa, Ontario, 657-667 pp, 1994.

Saito, K.; Inamura, T.; Ito, A.; Ling, S.; Tagavi, K.; Evans, D. D.
Study of Crude Oil Combustion Supported on Water. Part 1. Study of Boilover in Liquid Pool Fires Supported on Water: Effects of In-Depth Absorption. Part 2. Holographic Interferometry Temperature Measurements in Liquids for Pool Fires. Final Report.
Kentucky Univ., Lexington
National Institute of Standards and Technology, Gaithersburg, MD
National Institute of Standards and Technology, Gaithersburg, MD
Combustion Science and Technology, Vol. 86, 105-119, 1992.
Final Report; 62 p. October 28, 1990.

Sjolin, V.; Evans, D. D.; Jason, N. H.
First International Conference on Fire Suppression Research: Summary.
BRANDFORSK, Stockholm, Sweden
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 4946; 47 p. October 1992.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB93-124964

Steckler, K. D.; Evans, D. D.; Snell, J. E.
Preliminary Study of the 1991 Oakland Hills Fire and Its Relevance to Wood-Frame, Multi-Family Building Construction.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 4724; 53 p. November 1991.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB92-132992

Stroup, D. W.; Evans, D. D.
Suppression of Post-Flashover Compartment Fires Using Manually Applied Water Sprays.
National Institute of Standards and Technology, Gaithersburg, MD
Brandforsk, Stockholm, Sweden
General Services Administration, Washington, DC
NISTIR 4625; 40 p. July 1991.
Available from National Technical Information Service
PB91-240770

Walton, W. D.; Evans, D. D.; McGrattan, K. B.; Baum, H. R.; Twilley, W. H.; Madrzykowski, D.; Putorti, A. D., Jr.; Rehm, R. G.; Koseki, H.; Tennyson, E. J.
In Situ Burning of Oil Spills: Mesoscale Experiments and Analysis.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 16th. Volume 2. June 7-9, 1993, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 679-734 pp, 1993.

Walton, W. D.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.; Tennyson, E. J.
Smoke Measurements Using a Tethered Miniblimp at the Newfoundland Offshore Oil Burn Experiment.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 17th Proceedings. Volume 2. June 8-10, 1994, Vancouver, British Columbia, Environment Canada, Ottawa, Ontario, 1083-1098 pp, 1994.

1996-1999

Budnick, E. K.; Evans, D. D.; Nelson, H. E.
Simplified Fire Growth Calculations.
Hughes Associates, Inc., Baltimore, MD
National Institute of Standards and Technology, Gaithersburg, MD
NPFA FPH 1897; Section 11; Chapter 10;
Fire Protection Handbook, 18th Edition. National Fire Protection Association. 1997, NFPA, Quincy, MA, Cote, A. E.; Linville, J. L.; Appy, M. K.; Benedetti, R. P., Editor(s)(s), 11/97-107 p., 1997.

diMarzo, M.; Tartarini, P.; Liao, Y.; Evans, D. D.; Baum, H. R.
Evaporative Cooling Due to a Gently Deposited Droplet.
Maryland Univ., College Park
National Institute of Standards and Technology, Gaithersburg, MD
International Journal of Heat and Mass Transfer, Vol. 36, No. 17, 4133-4139, 1993.
NIST GCR 96-687; Paper 7; June 1996.
Available from National Technical Information Service
PB96-202304

Evans, D. D.
Large Fire Experiments for Fire Model Evaluation.
National Institute of Standards and Technology, Gaithersburg, MD
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers; Swedish National Testing and Research Institute. Interflam '96. International Interflam Conference, 7th Proceedings. March 26-28, 1996, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, 329-334 pp, 1996.

Evans, D. D.; Walton, W. D.; Mowrer, F. W.
Progress Report on Fires Following the Northridge Earthquake.
National Institute of Standards and Technology, Gaithersburg, MD
Maryland Univ., College Park
NISTIR 6030; June 1997.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 13th Joint Panel Meeting. Volume 2. March 13-20, 1996, Gaithersburg, MD, Beall, K. A., Editor, 273-281 pp, 1997.
Available from National Technical Information Service
PB97-184204

Evans, D. D.; Stroup, D. W.
Sidewall Sprinkler System Design Alternatives for the Rooms in the Library of Congress.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research and Engineering, Second (2nd) International Conference. (ICFRE2). Proceedings. **ABSTRACTS ONLY**. National Institute of Standards and Technology and Society of Fire Protection Engineers. August 10-15, 1997, Gaithersburg, MD, Slaughter, K. C., Editor, 18-18 pp, 1997.

Evans, D. D.
Fire Safety Performance Evaluation. BFRL Major Product Seminar. January 20, 1998. VHS Video.
National Institute of Standards and Technology, Gaithersburg, MD
BFRL Major Product Seminar; January 20, 1998.

Evans, D. D.
U.S. Overview of Fires Following Earthquakes.
National Institute of Standards and Technology, Gaithersburg, MD
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 14th Joint Panel Meeting. Proceedings. May 28-June 3, 1998, Tsukuba, Japan, 138-141 pp, 1998.

McGrattan, K. B.; Hamins, A.; Evans, D. D.
Sprinklers, Vent, and Draft Curtain Interaction: Modeling and Experiment.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Suppression and Detection Research Application Symposium. Research and Practice: Bridging the Gap. Proceedings. National Fire Protection Research Foundation. February 25-27, 1998, Orlando, FL, 98-106 pp, 1998.
http://fire.nist.gov/bfrlpubs/fire99/PDF/f99134.pdf
http://fire.nist.gov/bfrlpubs/fire98/PDF/f98187.pdf

McGrattan, K. B.; Evans, D. D.
Modeling the Performance of Sprinklers, Draft Curtains and Roof Vents in Large Storage Facility Fires.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Detection, Fire Extinguishment and Fire Safety Engineering. NRIFD 50th Anniversary Symposium. Proceedings. Fire Fighting Future 50th Session (FFF50th). Organized by National Research Institute of Fire and Disaster (NRIFD) and Fire and Disaster Management Agency (FDMA) and Sponsored by Fire Protection Equipment and Safety Center. June 1, 1998, Tokyo, Japan, 49-56 pp, 1998.
http://fire.nist.gov/bfrlpubs/fire99/PDF/f99049.pdf

McGrattan, K. B.; Walton, W. D.; Evans, D. D.
Smoke Plumes From In-Situ Burning of Crude Oil.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; API Publication No. 4651; March 2003.
Oil Spill Conference, 1997 Proceedings. 1997, Washington, DC, American Petroleum Institute, Washington, DC, 137-147 pp, 2003.

2000 -2007

Brassell, L. D.; Evans, D. D.
Trends in Firefighter Fatalities Due to Structural Collapse, 1979-2002.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 7069; 37 p. November 2003.
AVAILABLE FROM: National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov

http://fire.nist.gov/bfrlpubs/fire03/PDF/f03024.pdf

Davis, W. D.; Evans, D. D.
Interoperable Dynamic Tactical Information for Public Safety Officials.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Suppression and Detection Research Application, 8th Annual Symposium. Society of Fire Protection Engineers. Proceedings. January 21-23, 2004, Orlando, FL, 1-9 pp, 2004.

http://fire.nist.gov/bfrlpubs/fire04/PDF/f04021.pdf

Evans, D. D.; Pfenning, D. B.
Water Sprays Suppress Gas-Well Blowout Fires.
National Bureau of Standards, Gaithersburg, MD
Energy Analysts Inc., Norman, OK
Oil and Gas Journal, Vol. 83, No. 17, 80-86, April 29, 1985.
NIST SP 995; Volume 2; March 2003.

Evans, D. D.; Baum, H. R.; McCaffrey, B. J.; Mulholland, G. W.; Harkleroad, M. F.; Manders, W. F.
Combustion of Oil on Water.
National Bureau of Standards, Gaithersburg, MD
Department of the Interior, Reston, VA
NBSIR 86-3420; NIST SP 995; Volume 2; 55 p. November 1987.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900. Website: http://www.ntis.gov
PB89-185581
http://fire.nist.gov/bfrlpubs/fire03/PDF/f03156.pdf

Evans, D. D.
In-Situ Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 762; NIST SP 995; Volume 2; April 1989.
Minerals Management Service, U.S. Department of Interior. Alaska Arctic Offshore Oil Spill Response Technology. Workshop Proceedings. November 29-December 1, 1988, Anchorage, AK, Jason, N. H., Editor, 47-95 pp, 1989.
Available from Government Printing Office

Evans, D. D.; Baum, H. R.; Mulholland, G. W.; Bryner, N. P.; Forney, G. P.
Smoke Plumes From Crude Oil Burns.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 12th. June 7-9, 1989, Calgary, Canada, 1-22 pp, 1989.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Lawson, J. R.; Rehm, R. G.; Harris, R. H., Jr.; Ghoniem, A.; Holland, J.
Measurement of Large Scale Oil Spill Burns.
National Institute of Standards and Technology, Gaithersburg, MD
Massachusetts Institute of Technology, Cambridge
Consultant, Wheaton, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 13th. June 6-8, 1990, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 1-38 pp, 1990.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Mulholland, G. W.; Lawson, J. R.; Koseki, H.; Ghoniem, A.
Smoke Emission From Burning Crude Oil.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Massachusetts Institute of Technology, Cambridge
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oilspill Program Technical Seminar, 14th. June 12-14, 1991, Vancouver, B.C., Environment Canada, Ottawa, Ontario, 421-449 pp, 1991.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Notarianni, K. A.; Lawson, J. R.; Tang, H. C.; Keydel, K. R.; Rehm, R. G.; Madrzykowski, D.; Zile, R. H.; Koseki, H.; Tennyson, E. J.
In-Situ Burning of Oil Spills: Mesoscale Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oilspill Program Technical Seminar, 15th. June 10-12, 1992, Edmonton, Canada, Environment Canada, Ottawa, Ontario, 593-657 pp, 1992.

Evans, D. D.; Walton, W. D.; Notarianni, K. A.; Baum, H. R.; Koseki, H.
Large Fires: Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Reston, VA
Department of the Interior, Washington, DC
American Petroleum Institute, Washington, DC
Coast Guard, Washington, DC
Department of Transportation, Washington, DC
NIST SP 995; Volume 2; March 2003.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 365-371 pp, 1992.

Evans, D. D.; Madrzykowski, D.; Haynes, G. A.
Flame Heights and Heat Release Rates of 1991 Kuwait Oil Field Fires.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
International Association for Fire Safety Science. Fire Safety Science. Proceedings. 4th International Symposium. July 13-17, 1994, Ottawa, Ontario, Canada, Intl. Assoc. for Fire Safety Science, Boston, MA, Kashiwagi, T., Editor, 1279-1289 pp, 1994.

Evans, D. D.
Use of Fire Simulation in Fire Safety Engineering and Fire Investigation.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6588; November 2000.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 15th Joint Panel Meeting. Volume 2. Proceedings. March 1-7, 2000, San Antonio, TX, Bryner, S. L., Editor, 441-448 pp, 2000.
AVAILABLE FROM National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov
PB2001-101517

Evans, D. D.; Mulholland, G. W.; Baum, H. R.; Walton, W. D.; McGrattan, K. B.
In Situ Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Journal of Research of the National Institute of Standards and Technology, Vol. 106, No. 1, 231-278, January/February 2001.
For more information contact: Website: http://www.nist.gov/jres

Evans, D. D.; Mulholland, G. W.; Gross, D.; Baum, H. R.
Environmental Effects of Oil Spill Combustion.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Arctic and Marine Oilspill Program (AMOP) Technical Seminar 10th. Proceedings. June 9-11, 1987, Ontario, Canada, 91-130 pp, 2003.

Evans, D. D.; Mulholland, G. W.; Gross, D.; Baum, H. R.; Saito, K.
Burning, Smoke Production and Smoke Dispersion From Oil Spill Combustion.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Arctic and Marine Oilspill Program (AMOP) Technical Seminar 11th. Proceedings. June 7-9, 1988, Ontario, Canada, 41-87 pp, 2003.

Evans, D. D.; Walton, W. D.; Baum, H. R.; Notarianni, K. A.; Tennyson, E. J.; Tebeau, P. A.
Mesoscale Experiments Help to Evaluate In-Situ Burning of Oil Spills.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Herndon, VA
Coast Guard Research and Development Branch, Groton, CT
NIST SP 995; Volume 2; API Publication No. 4580; March 2003.
Oil Spill Conference, 1993 Proceedings. 1993, Washington, DC, American Petroleum Institute, Washington, DC, 755-760 pp, 2003.

Evans, D. D.
Fire Safety Science. Seventh (7th) International Symposium. Proceedings. June 16-21, 2003.
Fire Safety Science. Proceedings. Seventh (7th) International Symposium. International Association for Fire Safety Science (IAFSS). June 16-21, 2003, Worcester, MA, Intl. Assoc. for Fire Safety Science, Boston, MA, Evans, D. D., Editor, 1263 pp, 2003.

Evans, D. D.; Rehm, R. G.; McPherson, E. G.
Physics-Based Modeling of Wildland-Urban Intermix Fires.
National Institute of Standards and Technology, Gaithersburg, MD
USDA Forest Service, Davis, CA
Wildland Fire Conference, 3rd International. Proceedings. October 3-6, 2003, Sydney, Australia, 2003.

Evans, D. D.
First Responders: Problems and Solutions: Tactical Information.
National Institute of Standards and Technology, Gaithersburg, MD
Technology in Society, Vol. 25, 523-528, 2003.

Evans, D. D.; Rehm, R. G.; Baker, E. S.; McPherson, E. G.; Wallace, J. B.
Physics-Based Modeling of Community Fires.
National Institute of Standards and Technology, Gaithersburg, MD
Pacific Southwest Forest Service Research Station
University of Nevada-Reno
Volume 2;
Interflam 2004. (Interflam '04). International Interflam Conference, 10th Proceedings. Volume 2. July 5-7, 2004. Organised by Interscience Communications Ltd. in association with National Institute of Standards and Technology, Building Research Establishment; National Fire Protection Association; Society of Fire Protection Engineers; and Swedish National Testing and Research Institute, Edinburgh, Scotland, Interscience Communications Ltd., London, England, 1065-1076 pp, 2004.
http://fire.nist.gov/bfrlpubs/fire04/PDF/f04033.pdf

Evans, D. D.; Rehm, R. G.; Baker, E. S.
Physics-Based Modeling for WUI Fire Spread: Simplified Model Algorithm for Ignition of Structures by Burning Vegetation.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 7179; 36 p. October 2004.
http://fire.nist.gov/bfrlpubs/fire04/PDF/f04045.pdf

Evans, D. D.; Peacock, R. D.; Kuligowski, E. D.; Dols, W. S.; Grosshandler, W. L.
Active Fire Protection Systems. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-4; 138 p. September 2005.
http://fire.nist.gov/bfrlpubs/fire05/PDF/f05125.pdf
http://wtc.nist.gov/NISTNCSTAR1-4.pdf
http://wtc.nist.gov/oct05NCSTAR1-4index.htm
http://wtc.nist.gov/reports_october05.htm

Kuligowski, E. D.; Evans, D. D.; Peacock, R. D.
Post-Construction Fires Prior to September 11, 2001. Federal Building and Fire Safety Investigation of the World Trade Center Disaster.
National Institute of Standards and Technology, Gaithersburg, MD
NIST NCSTAR 1-4A; 140 p. September 2005.
http://fire.nist.gov/bfrlpubs/fire05/PDF/f05148.pdf
http://wtc.nist.gov/NISTNCSTAR1-4A.pdf
http://wtc.nist.gov/oct05NCSTAR1-4index.htm
http://wtc.nist.gov/reports_october05.htm

Madrzykowski, D.; Evans, D. D.
Large Fires: Kuwait.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
U.S./Japan Government Cooperative Program on Natural Resources (UJNR). Fire Research and Safety. 12th Joint Panel Meeting. October 27-November 2, 1992, Tsukuba, Japan, Building Research Inst., Ibaraki, Japan Fire Research Inst., Tokyo, Japan, 357-364 pp, 1992.

McGrattan, K. B.; Putorti, A. D., Jr.; Twilley, W. H.; Evans, D. D.
Smoke Plume Trajectory From In Situ Burning of Crude Oil in Alaska.
National Institute of Standards and Technology, Gaithersburg, MD
Alaska Department of Environmental Conservation, Juneau, AK
NISTIR 5273; NIST SP 995; Volume 2; 70 p. October 1993.
Available from National Technical Information Service
PB94-114519

McGrattan, K. B.; Walton, W. D.; Putorti, A. D., Jr.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.
Smoke Plume Trajectory From In Situ Burning of Crude Oil in Alaska: Field Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
Alaska Department of Environmental Conservation, Juneau, AK
NISTIR 5764; NIST SP 995; Volume 2; 40 p. November 1995.
Available from National Technical Information Service
PB96-131560

McGrattan, K. B.; Walton, W. D.; Putorti, A. D., Jr.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.
Smoke Plume Trajectory From In Situ burning of Crude Oil in Alaska: Field Experiments.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Arctic and Marine Oilspill Program (AMOP) Technical Seminar 18th. Volume 2. Proceedings. June 14-16, 1995, Ontario, Canada, 901-913 pp, 2003.

McGrattan, K. B.; Walton, W. D.; Evans, D. D.
Smoke Plumes From In-Situ Burning of Crude Oil.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; API Publication No. 4651; March 2003.
Oil Spill Conference, 1997 Proceedings. 1997, Washington, DC, American Petroleum Institute, Washington, DC, 137-147 pp, 2003.

Notarianni, K. A.; Evans, D. D.; Walton, W. D.
Smoke Production From Large Oil Pool Fires.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Interscience Communications Ltd.; National Institute of Standards and Technology; Building Research Establishment; and Society of Fire Protection Engineers. **Interflam 1993. (Interflam '93).** Fire Safety. International Fire Conference, 6th. March 30-April 1, 1993, Oxford, England, Interscience Communications Ltd., London, England, Franks, C. A., Editor, 111-119 pp, 1993.

Pfenning, D.; Evans, D. D.
Suppression of Gas Well Blowout Fire Using Water Sprays; Large and Small Scale Studies.
Energy Analysts, Inc., Norman, OK
National Bureau of Standards, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
American Petroleum Institute, Committee on Fire and Safety Protection, Production Session, Hyatt Regency, September 11-13, 1984, San Antonio, TX, 1-29 pp, 1984.

Putorti, A. D., Jr.; Evans, D. D.; Tennyson, E. J.
Ignition of Weathered and Emulsified Oils.
National Institute of Standards and Technology, Gaithersburg, MD
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 17th Proceedings. Volume 1. June 8-10, 1994, Vancouver, British Columbia, Environment Canada, Ottawa, Ontario, 657-667 pp, 1994.

Rehm, R. G.; Pitts, W. M.; Baum, H. R.; Evans, D. D.; Prasad, K. R.; McGrattan, K. B.; Forney, G. P.
Initial Model for Fires in the World Trade Center Towers.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6879; 18 p. May 2002.
Fire Safety Science. Proceedings. Seventh (7th) International Symposium. International Association for Fire Safety Science (IAFSS). June 16-21, 2003, Boston, MA, Evans, D. D., Editor, 25-40 pp, 2003.
AVAILABLE FROM: National Technical Information Service (NTIS), Technology Administration, U.S. Department of Commerce, Springfield, VA 22161. Telephone: 1-800-553-6847 or 703-605-6000; Fax: 703-605-6900; Rush Service (Telephone Orders Only) 800-553-6847; Website: http://www.ntis.gov
PB2002-106895

Rehm, R. G.; Hamins, A.; Baum, H. R.; McGrattan, K. B.; Evans, D. D.
Community-Scale Fire Spread.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 6891; 16 p. July 2002.
PB2002-107932

Rehm, R. G.; Pitts, W. M.; Baum, H. R.; Prasad, K. R.; Evans, D. D.; McGrattan, K. B.; Forney, G. P.
Modeling Fires in the World Trade Center Towers.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Risk and Hazard Assessment Research Application Symposium. Research and Practice: Bridging the Gap. Proceedings. Fire Protection Research Foundation. July 24-26, 2002, Baltimore, MD, 100-110 pp, 2002.

Rehm, R. G.; Evans, D. D.; Mell, W. E.; Hostikka, S.; McGrattan, K. B.; Forney, G. P.; Bouldin, C.; Baker, E.
Neighborhood-Scale Fire Spread.
National Institute of Standards and Technology, Gaithersburg, MD
J6.7;
Fire and Forest Meteorology, 5th Symposium. Joint With 2nd International Wildland Fire Ecology and Fire Management Congress. Proceedings. November 16-20, 2003, Orlando, FL, 2003.

Seck, M. D.; Evans, D. D.
Major U.S. Cities Using National Standard Fire Hydrants, One Century After the Great Baltimore Fire.
National Institute of Standards and Technology, Gaithersburg, MD
NISTIR 7158; 14 p. August 2004.
http://fire.nist.gov/bfrlpubs/fire04/PDF/f04095.pdf

Walton, W. D.; Evans, D. D.; McGrattan, K. B.; Baum, H. R.; Twilley, W. H.; Madrzykowski, D.; Putorti, A. D., Jr.; Rehm, R. G.; Koseki, H.; Tennyson, E. J.
In Situ Burning of Oil Spills: Mesoscale Experiments and Analysis.
National Institute of Standards and Technology, Gaithersburg, MD
Fire Research Institute, Tokyo, Japan
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program Technical Seminar, 16th. Volume 2. June 7-9, 1993, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 679-734 pp, 1993.

Walton, W. D.; Twilley, W. H.; McElroy, J. A.; Evans, D. D.; Tennyson, E. J.
Smoke Measurements Using a Tethered Miniblimp at the Newfoundland Offshore Oil Burn Experiment.
National Institute of Standards and Technology, Gaithersburg, MD
Minerals Management Service, Herndon, VA
NIST SP 995; Volume 2; March 2003.
Environment Canada. Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 17th Proceedings. Volume 2. June 8-10, 1994, Vancouver, British Columbia, Environment Canada, Ottawa, Ontario, 1083-1098 pp, 1994.

BRIAN W. MELLY, P.E.

TRIAD FIRE PROTECTION ENGINEERING CORPORATION
150 Saxer Avenue • Springfield, PA 19064 • Telephone: 610-328-3020 • Fax: 610-328-2339 • E-Mail: Triad182@aol.com

EDUCATION

UNIVERSITY OF MARYLAND
Bachelor of Science, Fire Protection Engineering, 1978

UNIVERSITY OF MARYLAND
Masters of Engineering, Fire Protection Engineering, 2005

UNIVERSITY OF KANSAS
M.B.A., Graduate Courses, 1980-1981

NATIONAL BUREAU OF STANDARDS
Fire Modeling Courses

SOCIETY OF FIRE PROTECTION ENGINEERS
Fire Hazards Analysis Courses

PROFESSIONAL & HONOR AFFILIATIONS

REGISTERED PROFESSIONAL ENGINEER -- DELAWARE & PENNSYLVANIA
Registered in the Discipline of Fire Protection Engineering

SOCIETY OF FIRE PROTECTION ENGINEERS
Professional Registration Committee, Computer Committee "Hats Off" Award Winner 1987, Member Grade, National

STATE OF PENNSYLVANIA
Professional Engineering Exam Grader in the Discipline of Fire Protection Engineering

UNIVERSITY OF MARYLAND
Member of Salamander Fire Protection Engineering Honor Society & Omicron Delta Kappa Leadership Honor Society.

PROFESSIONAL EXPERIENCE

TRIAD FIRE PROTECTION ENGINEERING CORPORATION, SPRINGFIELD, PA
V.P. ENGINEERING/PRINCIPAL ENGINEER
1994 TO PRESENT

PECO ENERGY, PHILADELPHIA, PA
SENIOR ENGINEER, 1989 - 1994
FIRE PROTECTION PROGRAM MANAGER - FOUR NUCLEAR UNITS

PROFESSIONAL LOSS CONTROL, PHILADELPHIA, PA
Senior Fire Protection Engineer, 1984 - 1989
Project Manager

BLACK & VEATCH CONSULTING ENGINEERS, KANSAS CITY, KS
Fire Protection Design Engineer, 1978 - 1984
Power Division 1979 – 1981
Special Projects Division 1981 - 1984

PROFESSIONAL EXPERIENCE (CONT.)

MR. MELLY HAS 28 YEARS OF EXPERIENCE IN THE DISCIPLINE OF FIRE PROTECTION ENGINEERING. HE HAS SPECIALIZED IN FOSSIL, INDUSTRIAL AND NUCLEAR FIRE PROTECTION ENGINEERING AND HAS CONSIDERABLE EXPERTISE IN THE DEVELOPMENT OF FIRE HAZARDS ANALYSES, DESIGN AND EVALUATION OF FIRE SUPPRESSION SYSTEMS, FIRE PROTECTION INSPECTIONS AND AUDITS, CODE ANALYSES & INTERPRETATIONS, COMPUTER FIRE RE-CREATION ANALYSIS & HYDRAULIC MODELING OF WATER SUPPLY SYSTEMS. MR. MELLY HAS EXPERIENCE IN DESIGNING AND OVERSEEING FOSSIL AND NUCLEAR FIRE PROTECTION SYSTEMS. MR. MELLY IS CURRENTLY INVOLVED IN THE TESTING OF BUILDING SMOKE MANAGEMENT SYSTEMS, FIRE WRAP UPGRADES AND CO2 SYSTEM CONVERSIONS.

MR. MELLY HAS PERFORMED STRUCTURAL STEEL SURVIVABILITY ANALYSES FOR SEVERAL UTILITIES TO PREDICT THE PERFORMANCE OF THE FIRE BARRIER SUPPORT STEEL IN A FIRE. MR. MELLY HAS RECENTLY INTEGRATED THE EFFECTS OF THERMO-LAG 330-1 MATERIAL BURNING INTO THE STRUCTURAL STEEL SURVIVABILITY METHODOLOGY.

MR. MELLY HAS BEEN INVOLVED IN THE IDENTIFICATION AND RESOLUTION OF THE THERMO-LAG FIRE BARRIER ISSUE FOR SEVERAL UTILITIES. HIS EFFORTS INCLUDED THE FORMULATION AND IMPLEMENTATION OF A COMPREHENSIVE RESOLUTION STRATEGY DESIGNED TO ACHIEVE REGULATORY COMPLIANCE WITHOUT WHOLESALE REPLACEMENT OF EXISTING BARRIERS. PRIOR TO HIS INVOLVEMENT IN THE THERMO-LAG ISSUE, MR. MELLY WAS ACTIVE IN THE DEVELOPMENT OF METHODOLOGIES FOR THE ANALYSIS OF COMPLEX WATER SUPPLY NETWORKS. HE PARTICIPATED IN THE DEVELOPMENT OF A HYDRAULIC ANALYSIS SOFTWARE PROGRAM THAT SIMPLIFIES THE ANALYSIS OF WATER SUPPLY SYSTEMS.

MR. MELLY'S OTHER EXPERIENCE INCLUDES COMPUTER FIRE MODELING TO PREDICT AND MODEL THE GROWTH OF FIRE AND IT'S EFFECT IN BUILDINGS. IN ADDITION, MR. MELLY HAS REVIEWED AND EVALUATED ALL CURRENTLY AVAILABLE FIRE PROTECTION HYDRAULIC SOFTWARE FOR THE SOCIETY OF FIRE PROTECTION ENGINEERS. HE HAS PRESENTED HIS REVIEW NATIONWIDE AND HAS BEEN PUBLISHED BY THE SOCIETY OF FIRE PROTECTION ENGINEERS AND NATIONAL FIRE PROTECTION ASSOCIATION.

MR. MELLY IS CURRENTLY ENROLLED IN THE UNIVERSITY FIRE PROTECTION ENGINEERING MASTERS PROGRAM WITH AN EMPHASIS ON FIRE MODELING AND ADVANCED SUPPRESSION DESIGN.

SKILLS

- X DESIGN & EVALUATION OF SPRINKLER AND CO_2 FIRE SUPPRESSION & DETECTION SYSTEMS
- X DESIGN & EVALUATION OF UNDERGROUND & ABOVEGROUND FIRE WATER DISTRIBUTION SYSTEMS
- X INSTALLATION SUPERVISION & ACCEPTANCE TESTING OF FIRE SUPPRESSION, FIRE DETECTION AND FIRE WATER DISTRIBUTION SYSTEMS
- X SYSTEM ANALYSES, SYSTEM DESIGN SPECIFICATIONS & PURCHASE SPECIFICATION DEVELOPMENT FOR FIRE SUPPRESSION SYSTEMS
- X EXPERIENCED IN CFAST, FDS, CONTAM, EXIT89, FIREST3
- X FIRE PROTECTION INSPECTIONS & AUDITS
- X PENETRATION SEAL PROGRAM EVALUATIONS
- X MODEL BUILDING CODE & FIRE CODE ANALYSIS & INTERPRETATION
- X COMPUTER AIDED FIRE MODELING
- X COMPUTER AIDED NETWORK HYDRAULIC MODELING
- X IPEEE FIVE METHODOLOGY EVALUATIONS
- X THERMO-LAG, DARMATT, E-MAT, FS-195, MECATISS FIRE BARRIER EVALUATIONS
- X DESIGN BASIS DOCUMENTS (DBD), PROGRAM, SYSTEM & TOPICAL DEVELOPMENT
- X FIRE PROTECTION PROGRAM REVIEWS

Resume For:

Mr. Steven P. Nowlen

Current Employment:

Employer:	Sandia National Laboratories Risk and Reliability Department 6761
Title/Position:	Distinguished Member of the Technical Staff
Employed Since:	October 17, 1983
Mailing Address:	Mail Stop 0748 PO Box 5800 Albuquerque, New Mexico 87185-0748
Phone:	(505) 845-9850
Facsimile:	(505) 844-2829
E-Mail Address:	spnowle@sandia.gov

Education and Honors:

Appointment as a Distinguished Member of the Technical Staff at Sandia National Laboratories, October 2001.

Master of Science, Mechanical Engineering, Michigan State University, East Lansing Michigan, Degree Awarded March 1984.

Bachelor of Science with High Honor, Mechanical Engineering, Michigan State University, East Lansing Michigan, Degree Awarded December 1980.

Inducted into the Phi Beta Kappa Honor Society for outstanding graduates upon completion of undergraduate degree, 1980.

DuPont Research Fellow in the Department of Mechanical Engineering, Michigan State University, 1981-1983.

Patents:

"Automatic insulation resistance testing apparatus," Patent Number: 06907363

Educational Background and Professional Experience:

I have completed formal education through the Master's Degree level in the field of Mechanical Engineering with a focus on heat transfer, thermodynamics and computer programming. Since joining Sandia National Laboratories in 1983, I have been active in both experimental and analytical fire safety and fire risk research. Since 1987 I have acted as key personnel, technical lead and project manager for several fire research programs. The most important application of my research has been in the development and application of quantitative tools and data for the assessment of fire risk for nuclear power plant safety and operations.

My current role is as the technical lead and program area manager for the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) sponsored fire research programs at Sandia. Ongoing programs include experimental studies of fire phenomena, the development and application of quantitative risk analysis methods, tools and data, and implementation of risk-informed regulatory applications. I was a member of the Senior Review Board for the review and evaluation of NRC licensee submittals under the Individual Plant Evaluation of External Events Program (work completed in 2001). As technical lead for the RES team on a collaborative effort between RES and the Electric Power Research Institute (EPRI), I was co-principal author on the jointly published fire PRA methodology document (NUREG/CR-6850). I was also a member of the core writing team for the recently published American Nuclear Society Standard on fire PRA methodology (ANSI/ANS-58.23-2007). I have also testified as an expert witness in nuclear power plant fire safety in federal criminal district court.

I have published, as author or co-author, approximately 70 formal reports, journal articles, and conference papers, most on the subject of fire safety. A publication list is attached. I have also prepared many unpublished letter reports for our sponsors at the U.S. Nuclear Regulatory Commission (USNRC). A list of these reports is available on request.

My experimental work has included the planning, execution, evaluation and reporting of various types of experiments generally exploring harsh environments and the functionality of equipment in those environments. Specifically, I have experience in the testing of fire growth behavior, large-scale room fire tests, testing to assess enclosure ventilation and smoke purging effects, the evaluation of cable and electrical equipment fire-induced damage, smoke particulate characterization, fire barrier testing, the assessment of smoke damage effects on digital equipment, and cable ampacity and ampacity derating assessments.

As a secondary aspect of my experimental experience, I have participated in Equipment Qualification tests assessing the performance of electrical equipment in the harsh steam and radiation environments associated with nuclear power plant severe accidents. This includes both accelerated thermal and radiation aging of electrical cables, and the actual evaluation of cable performance during harsh environmental exposures.

Related analytical efforts in the area of fire safety have also been a significant part of my work responsibilities. This has included the application, evaluation and validation of computer fire simulation models, reviews of past fire events in nuclear power plants, fire risk assessment methods development, application and support work, and the development and evaluation of analytical methods for cable ampacity and fire barrier ampacity derating assessments.

List of Publications for Steven P. Nowlen:

Journal Articles and Handbook Contributions:

1. "A Review of Research at Sandia National Laboratories Associated with the Problem of Smoke Corrosivity," SAND87-2484J, *Fire Safety Journal*, Vol. 15 No. 5, 1989, ISSN: 0379-7112 (Author).
2. "Fire Models for Assessment of Nuclear Power Plant Fires," SAND89-1651J, *Nuclear Engineering and Design*, 125 (1991) (Co-Author).
3. "A Discussion of Fire Suppression Induced Equipment Damage and Systems Impact through an Examination of Spurious Fire Suppression System Actuation Incidents," SAND89-1956J, *Nuclear Engineering and Design*, 125 (1991) (Principal Author).
4. "Nuclear Power Plants, A Unique Challenge to Fire Safety," SAND89-2924J, *Fire Safety Journal*, V19, pgs 3-18, 1992 (Author).
5. "Fire Risk Analysis: A Discussion on Uncertainties and Limitations," *Upgrading of fire safety in nuclear power plants*, IAEA-TECDOC-1014, April 1998 (Co-Author).
6. "An Update of Preliminary Perspectives Gained from Individual Plan Examination of External Events (IPEEE) Submittal Reviews," *Nuclear Engineering and Design*, V194 (1999), pp.225-250 (Co-Author).
7. "Impact of Smoke Exposure on Digital Instrumentation and Control," Nuclear Technology, ANS, V143, pp. 152-160, Aug. 2003 (Co-Author).
8. "The RES/EPRI Consensus Fire Probabilistic Risk Assessment Method," Invited Contribution to *Kerntechnik*, Bundesamt für Strahlenschutz, Oberschleissheim, Germany, publication pending, 2007 (Author).
9. "Fire Risk Assessment for Nuclear Power Plants", Section 5, Chapter 14 of *The SFPE Handbook of Fire Protection Engineering*, Society of Fire Protection Engineers, Bethesda, MD, 4th Edition, publication pending, 2008 (Co-Author).

Formal Reports:

10. *Non-Equilibrium Thermodynamic Modeling and Parameter Estimation of Phenomenological Coefficients Describing Coupled Transport Across a Membrane*, Masters Degree Thesis, Department of Mechanical Engineering, Michigan State University, December 1983 (Author).
11. *Heat and Mass Release Rates for Some Transient Fuel Source Fires, A Test Report*, SAND86-0312, NUREG/CR-4680, USNRC, October 1986 (Author).
12. *Quantitative Data on the Fire Behavior of Combustible Material Found in Nuclear Power Plants, A Literature Review*, SAND86-0311, NUREG/CR-4679, USNRC, February 1987 (Author).
13. *Enclosure Environment Characterization Testing for Base Line Validation of Computer Fire Simulation Codes*, SAND86-1296, NUREG/CR-4681, USNRC, March 1987 (Author).
14. *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Cabinets, Part II - Room Effects Tests*, SAND86-0336, NUREG/CR-4527/V2, USNRC, October 1988 (Co-Author).

15. *Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues*, SAND88-0177, NUREG/CR-5088, USNRC, December

1988 (Co-Principal Author).

16. *A Summary of the USNRC Fire Protection Research Program at Sandia National Laboratories; 1975-1987*, SAND89-1359, NUREG/CR-5384, USNRC, December 1989 (Author).
17. *The Impact of Thermal Aging on the Flammability of Electric Cables*, SAND90-2121, NUREG/CR-5619, USNRC, March 1991, (Author).
18. *An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables*, SAND90-0696, NUREG/CR-5546, USNRC, May 1991, (Author).
19. *Fire Safety Lessons Learned from the Design and Operation of Commercial Nuclear Reactor Facilities*, SAND90-1827, SNL, February 1993, (Author).
20. *Prioritization of Reactor Control Components Susceptible to Fire Damage as a Consequence of Aging*, SAND93-7107, NUREG/CR-6103, USNRC, January 1994, (Co-Author).
21. *An Evaluation of the Fire Barrier System Thermo-Lag 330-1*, SAND94-0146, SNL, September 1994, (Principal Author).
22. *An Assessment of Fire Vulnerability for Aged Electrical Relays*, SAND94-0769, NUREG/CR-6220, USNRC, March 1995, (Co-Author).
23. *Aging Assessment for Active Fire Protection Systems*, SAND95-1361, SNL, June 1995, (Co-Author).
24. *A Summary of the Fire Testing Program at the German HDR Test Facility*, SAND94-1795, NUREG/CR-6173, USNRC, November 1995, (Author).
25. *Circuit Bridging of Components by Smoke*, SAND96-2633, NUREG/CR-6476, USNRC, October 1996, (Co-Author).
26. *LDRD Report: Smoke Effects on Electrical Equipment*, SAND2000-0599, SNL, March, 2000 (Co-Author).
27. *Ampacity Derating and Cable Functionality for Raceway Fire Barriers*, SAND2000-1825, NUREG/CR-6681, USNRC, August 2000 (Author).
28. *Results and Insights on the Impact of Smoke on Digital Instrumentation and Controls*, SAND99-1320, NUREG/CR-6597, USNRC, January 2001 (Co-Author).
29. *Risk Methods Insights Gained From Fire Incidents*, SAND2001-1676P, NUREG/CR-6378, USNRC, September 2001 (Principal Author).
30. *Perspectives Gained From the Individual Plant Examination of External Events (IPEEE) Program*, NUREG-1742, USNRC, Apr. 2002 (Principal Contributing Author).
31. *Cable Insulation Resistance Measurements Made During Cable Fire Tests*, SAND2002-0447P, NUREG/CR-6776, USNRC, June 2002 (Co-Author).
32. *Circuit Analysis - Failure Mode and Likelihood Analysis*, SAND2002-1942P, NUREG/CR-6834, USNRC, Sept. 2003 (Co-Author).
33. *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities*, a joint publication of EPRI and the U.S. Nuclear Regulatory Commission, EPRI TR-1011989, NUREG/CR-6850, September, 2005 (a report in 2 volumes) (Co-Principal Author).
34. *CAROLFIRE Test Report - Volume 1: General Test Descriptions and the Analysis of Circuit Response Data*, <u>and</u> *Volume 2: Cable Fire Response Data for Fire Model Improvement*, NUREG/CR-6931, U.S. NRC, Draft for public comment issued May 2007 (Principal Author).

<u>Invited Conference Papers:</u>

35. "Investigation of Smoke Corrosivity in Nuclear Power Plant Equipment," SAND87-

2484C, *International Conference on the Corrosive Effects of Combustion Products*, London England, October 13-14, 1987 (Author).

36. "Unaddressed Issues in Fire Modeling and Risk Assessments," *International Symposium on Fire Protection and Fire Fighting in Nuclear Installations*, IAEA, Vienna, Austria, Feb. 27 - Mar. 3, 1989 (Principal Author).
37. "Fire Risk Analysis: A Discussion on Uncertainties and Limitations," *International Symposium on Upgrading the Fire Safety of Operating Nuclear Power Plants*, IAEA, Vienna, Austria, November 18-21, 1997, (Co-Author).
38. "Results of Experimental Fire Research," *OECD/CSNI International Workshop on Fire Risk Assessment*, Helsinki, Finland, June 29 - July 1, 1999 (Author).
39. "CAROLFIRE - Cable Response to Live Fire," to be presented at the SMiRT-19 Post-Conference Seminar on Fire Safety in Nuclear Power Plants and Installations, Toronto, Canada, August 2007 (Co-Author).

Other Conference Papers:

40. "Large-Scale Tests to Evaluate Enclosure Fire Environments," SAND86-0805C, Conference Proceedings of the International ANS/ENS Topical Meeting on the Operability of Nuclear Power Plant Equipment in Normal and Adverse Environments, September 1986 (Author).
41. "Investigation of Smoke Corrosivity in Nuclear Power Plant Equipment," SAND87-2484C, International Conference on the Corrosive Effects of Combustion Products, London England, October 1987 (Author).
42. "The Effects of Aging on the Fire Vulnerability of Nuclear Power Plant Component," SAND88-2969C, Conference Proceedings of the Sixteenth Water Reactor Safety Meeting, USNRC, NUREG/CP-0097, October 1988 (Author).
43. "Fire Protection and Fire Fighting in Nuclear Installations," Proceedings of an International Symposium on Fire Protection and Fire Fighting in Nuclear Installations International Atomic Energy Agency, IAEA-SM-305/2, Vienna, Austria, February 1989 (Principal Author).
44. "An Overview of the Fire Risk Scoping Study," SAND89-0029C, Conference Proceedings of the EPRI Workshop on Nuclear Power Plant Fire Safety, Electric Power Research Institute, February 1989 (Principal Author).
45. "An Overview of the Fire Risk Scoping Study, Objectives, Approach, Findings, and Follow-On Efforts," SAND88-3353C, Conference Proceedings of the ANS/ENS International Topical Meeting on Probability, Reliability and Safety Assessment, April 1989 (Principal Author).
46. "The Impact of Updated Information and Modeling Techniques on Four Previously Completed Commercial Nuclear Power Plant Fire Probabilistic Risk Assessments," SAND88-3355C, Conference Proceedings of the ANS/ENS International Topical Meeting on Probability, Reliability and Safety Assessment, April 1989 (Co-Author).

47. "Observations Concerning the COMPBRN III Fire Growth Code," SAND88-2160C, *Conference Proceedings of the ANS/ENS International Topical Meeting on Probability, Reliability and Safety Assessment*, April 1989 (Co-Author).
48. "Fire Models for Assessment of Nuclear Power Plant Fires," SAND89-1651C, *Conference Proceedings of the Structural Mechanics in Reactor Technology Post Conference Seminar #6 on Fire Safety in Nuclear Power Plants*, August 1989 (Co-

Author).

49. "A Discussion of Fire Suppression Induced Equipment Damage and Systems Impact Through an Examination of Spurious Fire Suppression Actuation Incidents", SAND89-1956C, *Conference Proceedings of the Structural Mechanics in Reactor Technology Post Conference Seminar #6 on Fire Safety in Nuclear Power Plants*, August 1989 (Principal Author).
50. "A Critical Look at Nuclear Qualified Electrical Cable Insulation Ignition and Damage Thresholds", SAND88-2161C, *Conference Proceedings of the ANS/ENS Topical Meeting on the Operability of Nuclear Systems in Normal and Adverse Environments*, September 1989 (Co-Author).
51. "The Fire Performance of Aged Electrical Cables," SAND91-0963C, Presented at the 15th Biennial Reactor Operations Division Topical Meeting on Reactor Operating Experience "Nuclear Power Plant Operations - Ready for 2000", American Nuclear Society, *Conference Proceedings*, August 11-14, 1991, (Author).
52. "The Estimation of Electrical Cable Fire-Induced Damage Limits," SAND92-1404C, *Fire and Materials* 1st International Conference and Exhibition, Sept. 24-25, 1992, Washington DC, (Principal Author).
53. "Perspective Gained from Individual Plant Examination of External Events (IPEEE) Fire Review," *Conference Proceedings of the International Topical Meeting on Probabilistic Safety Assessment*, ANS, Park City, UT, Sept. 29-Oct. 3, 1996, (Co-Author).
54. "Recent Activities in Nuclear Power Plant Fire Safety Research at Sandia National Laboratories," *Conference Proceedings* of the Structural Mechanics in Reactor Technology (SMIRT'97) Post-Conference Seminar No. 6, Fire Safety in Nuclear Power Plants and Installations, Lyon, France, August 25-29, 1997, SAND96-2969, (Principal Author).
55. "An Update of Preliminary Perspectives Gained from Individual Plant Examination of External Events (IPEEE) Submittal Reviews," *Conference Proceedings of the 25th Water Reactor Safety Information Meeting*, October 1997, USNRC, (Co-Author).
56. "Preliminary Perspectives from NRC's Review of Utilities' Individual Plant Examination of External Events (IPEEE) Submittals", *Conference Proceedings* of the 6th International Conference on Nuclear Engineering, ICONE-6, May 10-15, 1998, ASME, (Co-Author).
57. "Methodological and Applications Issues in Fire Risk Assessment," *Conference Proceedings of the 26th Water Reactor Safety Information Meeting*, October 1998, USNRC, (Principal Author).
58. "Risk Insights Gained from Fire Incidents," *International Topical Meeting on Probabilistic Safety Assessment: Risk-Informed Performance-Based Regulation in the New Millennium*, PSA-99, Washington DC, August 22-26, 1999, ANS (Principal Author).

59. “Cable Hot Shorts and Circuit Analysis in Fire Risk Assessment,” *International Topical Meeting on Probabilistic Safety Assessment: Risk-Informed Performance-Based Regulation in the New Millennium*, PSA-99, Washington DC, August 22-26, 1999, ANS (Co-Author).
60. “Risk Insights Gained from Fire Incidents,” SAND99-1463C, published in *International Topical Meeting on Probabilistic Safety Assessment: Risk-Informed Performance-Based Regulation in the New Millennium*, PSA-99, Washington DC, August 22-26, 1999, ANS (Co-Author).
61. “The U.S. Nuclear Regulatory Commission’s Fire Risk Research Program: Status and Results,” *Int. Conf. on Probabilistic Risk Assessment and Management* (PSAM 5), Osaka, Japan, Nov. 27 - Dec. 1, 2000 (Co-Author).
62. “Perspectives from the U.S. Nuclear Regulatory Commission’s Reviews of Individual Plant Examination of External Event (IPEEE) Submittals: Fire Analyses,” *Int. Conf. on Probabilistic Risk Assessment and Management* (PSAM 5), Osaka, Japan, Nov. 27 - Dec. 1, 2000 (Co-Author).
63. “Fire PRA Methodological Issues and the USNRC Fire Methods Research Program,” *Fire and Safety 2001*, London, U.K., February 12-14, 2001 (Principal Author).
64. “Fire Risk Insights from Nuclear Power Plant Fire Incidents,” *Fire and Safety 2001*, London, U.K., February 12-14, 2001 (Principal Author).
65. “Fire-Induced Cable Failure Modes and Effects Testing,” *Structural Mechanics in Reactor Technology (SMiRT 16) Post Conference Seminar No. 1 - Fire Safety in Nuclear Power Plants and Installations*, Waterford, CT, USA, August 20-23, 2001 (Principal Author).
66. “Perspectives from the U.S. Nuclear Regulatory Commission’s Reviews of Individual Plant Examination of External Events (IPEEE) Submittals: Fire Analyses,” *Structural Mechanics in Reactor Technology (SMiRT 16) Post Conference Seminar No. 1 - Fire Safety in Nuclear Power Plants and Installations*, Waterford, CT, USA, August 20-23, 2001 (Co-Author).
67. “Fire Detection and Suppression: PRA Modeling and Data Analysis,” SAND2002-2586C, Proceedings - 6th Intern. Conf. On Probabilistic Safety Assessment and Management (PSAM6), Elsevier Science Ltd., San Juan, PR, June 23-28, 2002 (Principal Author).
68. “Cable Failure Modes and Effects Risk Analysis Perspectives”, SAND2003-2771C, Conference Proceedings: Structural Mechanics in Reactor Technology (SMiRT) Post Conference Seminar 21-Fire Safety in Nuclear Plants and Installations held August 25-28, 2003 in Piestany, Slovakia (Author).
69. “Methods Advances in the EPRI/USNRC Fire Risk Requantification Study”, SAND2003-3009C, Conference Proceedings: Structural Mechanics in Reactor Technology (SMiRT) Post Conference Seminar 21-Fire Safety in Nuclear Plants and Installations held August 25-28, 2003 in Piestany, Slovakia (Principal Author).
70. “Cable Failure Modes and Effects Risk Analysis Perspectives”, SAND2003-4253C, Conference Proceedings: ANS Pacific Basin Nuclear Conference, March 21-25, 2004 in Honolulu, HI (Author).

71. “Methods Advances in the EPRI/USNRC Fire Risk Requantification Study - Fire Modeling,” SAND2004-0537C, Conference Proceedings: Probabilistic Safety Assessment and Management (PSAM) 7, Berlin Germany, June 13-18, 2004 (Principal Author).
72. “Expanding the Use of Operating Experience in Fire PRA,” SAND2004-4617C, Conference Proceedings, American Nuclear Society (ANS) Topical Meeting on Operating Nuclear Facility Safety, Baltimore, MD, November 14-18, 2004 (Author).
73. “Events Operating Experience: The Initial U.S. Contribution to the OECD Database,” SAND2005-2919C, presented at the OECD Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI), Working Group on Risk Assessment (WGRisk), International Workshop on Fire Probabilistic Safety Assessment, Puerto Vallarta, Mexico, May 23-26, 2005 (Principal Author).
74. “Current Limitations of Fire PRA Methodology and Potential Areas for Future Research Activities,” Conference Proceedings of the International Conference on Probabilistic Safety Assessment and Management (PSAM 8), New Orleans, LA, May 13-19, 2006 (Principal Author).
75. “Integrating Insights from the Fire PRA Methodology for Nuclear Power Facilities Into the Fire Protection SDP”, Conference Proceedings of the International Conference on Probabilistic Safety Assessment and Management (PSAM 8), New Orleans, LA, May 13-19, 2006 (Co-Author).

Resume For:

Ms. Laurence Rigollet

Current Employment:

Employer: Institut de Radioprotection et de Sûreté Nucléaire

Title/position : Head of the Fire Research and Development of Uncertainty and Simulation Methods Laboratory

Employed Since: August 1994

Mailing Address: Centre d'Etude de Cadarache BP 3
13115 Saint Paul Lez Durance Cedex – France

Phone : 33 (0)4 42 19 96 75
Facsimile: 33 (0)4 42 19 91 67
E-mail address: Laurence.rigollet@irsn.fr

Education:

Engineer of the Ecole Supérieur d'Ingénieurs de Poitiers (France), 1993

Professional experience:

1994-1997: In charge of the development and the validation of zone fire codes:

- FEUMIX, zone code which simulates sodium jet fire,
- FLAMME-S, zone code which simulates hydrocarbon pool fire.

1998-2004: In charge of the fire experiments:

- Characterise gloves boxes materials, as PMMA and LEXAN;
- Study electrical cabinet fires; first step was an analytical approach with experiments carrying out PMMA in a steal box; this first approach had allowed us to understand the main phenomena of such fires; the second phase was to perform experiments with actual electrical cabinets; based on these experiments, a model has been established and is now introduced in the IRSN zone model SYLVIA.

2004-2005: Performed fire safety analyses.

Since 2005: Head of the Laboratory where fire codes are developed: the CFD code ISIS, and the zone code SYLVIA. As well as the scientific manager of the OECD project PRISME with objectives to study heat and mass transfers induced by a fire in a multi-room configuration.

List of publications in congress:

1. **L. Rigollet**, L. Audouin, J-M. Such, « Thermal plumes of upward fire spread on vertical PMMA plates: comparison between one side and two sides wall fires », Third International Seminar on Fire and Explosion Hazards, 2000, United Kingdom

2. **L. Rigollet** & S. Mélis**,** « Heat Release Rate of vertical combustible inside a confinement : an analytical approach to the fire of electrical cabinets », INTERFLAM Congress 2004
3. L. Audouin, J. Torero, O. Mangs & **L. Rigollet,** « An Example of the Use of Standard Flammability Criteria for Performance Analysis of Materials: Polycarbonate and PMMA », 8th International Symposium on Fire Safety Science, 2005
4. S. Mélis & **L. Rigollet,** « Fires of electrical cabinets », NURETH-11 (Nuclear Reactor Thermal Hydraulics), 2005
5. R. Gonzalez, M. Faury**, L. Rigollet**, C. Casselman, J-M. Such, « Status and prospects of IRSN research related to fire safety in nuclear plants », European Nuclear Conference, 2005
6. S. Suard, L. Audouin, F. Babik, **L. Rigollet**, J-C. Latché, « Verification and Validation of the ISIS CFD Code for Fire Simulation », Workshop on Assessment of Calculation Methods in FSE, 2006, USA
7. S. Suard, S. Mélis, F. Babik, P. Querre, C. Lapuerta, L. Audouin**, L. Rigollet,** « Status of IRSN Fire Codes Development and Validation », SMiRT - 19 Post Conference Seminar on Fire Safety in Nuclear Power Plants and Installations, 2007, Canada

José L. Torero

BRE Trust/RAEng Professor of Fire Safety Engineering
Director, BRE Centre for Fire Safety Engineering
The University of Edinburgh

School of Engineering and Electronics
King's Buildings
Edinburgh, EH8 9PP
United Kingdom

Education & Professional Accreditation

Chartered Engineer, Engineering Council Division, UK		(2002)
Ph.D.	University of California, Berkeley	(1992)
M.Sc.	University of California, Berkeley	(1991)
B.Sc.	Pontificia Universidad Catolica del Peru	(1988)

Academic Contributions

Co-Authorship of a book in computational methods for fire safety engineering, 8 book chapters in diverse subjects of fire safety and more than 300 technical publications and reports in a broad array of subjects associated to fire safety engineering.

Awards

Awarded a Research Professorship by the Royal Academy of Engineering. Diverse scientific awards such as the NASA-Certificate of Recognition for Outstanding Contributions to Space Shuttle Mission and the Faculty Achievement Award, from the Office of the President of the University of Maryland. Recognised for service to the profession with honorary membership to the Salamander Fire Protection Engineering Honour Society and with the Faculty Service Award, A. J. Clark School of Engineering (University of Maryland). Acknowledged for oral communication with the William M. Carey Award for the Best Paper Presented at the Fire Suppression and Detection Research Application Symposium and for written communication and for written communication twice with the Harry C. Bigglestone Award for the Best Paper Published in Fire Technology. Awarded the FM-Global and Bdycotte-Warrington Best Paper Awards for 2007. Teaching contributions have been recognised with the Lilly-Center for Teaching Excellence Fellowship, the Outstanding Mentor of the Year Award, the E. Robert Kent Outstanding Teaching Award for Junior Faculty and the Outstanding Teacher Award all at the University of Maryland.

Academic Experience

Upon completion of doctoral studies and a brief Post Doctoral appointment at NASA Lewis Research Centre (1992), joined the Laboratoire de Chimie et Physique de la Combustion (Poitiers, France) as a European Space Agency Post Doctoral researcher (1993) followed by an appointment as a CNRS Research Scientist at the Laboratoire de Combustion et Detonique (Poitiers, France) until 1995. Directed research programmes in spacecraft fire safety, polyurethane foam fires, compartment fires and tunnel fire spread and smoke control.

Joined the Department of Fire Protection Engineering at the University of Maryland (1995-2001) where held the titles of Assistant and Associate Professor and remains as Adjunct Professor. Served also as Affiliate Associate Professor in the Department of Aerospace Engineering. Taught all general and specialty classes in Fire Protection Engineering, continued research in spacecraft fire safety and compartment fires and extended experience to the areas of material flammability, fire suppression, smoke detection and oil spill control.

Appointed Reader in Fire Dynamics (2001) and later BRE Trust/ RAEng Professor of Fire Safety Engineering and Director of the BRE Centre for Fire Safety Engineering at the University of Edinburgh (2004). Organized the BRE Centre for Fire Safety Engineering and state of the art laboratory facilities. Developed a new undergraduate curriculum in Structural Fire Safety Engineering and developed research work in the areas of tunnel fire safety, structural behaviour in fire, material flammability, post fire remediation and sensor driven emergency response.

Appointed to the Advisory Boards of WPI and Glasgow Caledonian University and Adjunct Professor at the University of Cantabria, Spain. Held short time appointments as Visiting professor at the University of Texas at Austin, the University of California, Berkeley and San Diego, the University of Bremen (ZARM), Germany, the Catholic University of Santiago, Chile, the Instituto Nacional de Tecnica Aeroespacial (INTA), Spain and the Universities of Poitiers, Bourges, ENSTIB, Ecole de Mines de Saint Etienne, Ecole Polytechnique and Aix-Marseille in France.

Developed numerous short courses taught around the world to professionals in fire investigation, fire safety engineering design, building control and the fire service.

Professional Involvement & Affiliations

Active membership in The Institution of Fire Engineers (IFE), American Society of Mechanical Engineers (ASME), American Institute of Aeronautics and Astronautics (AIAA), Combustion Institute, International Association for Fire Safety Science (IAFSS), Society of Fire Protection Engineers (SFPE) and the National Fire Protection Association (NFPA).

Associate Editor of Combustion Science and Technology and member of the Editorial Boards of Fire Technology Journal, Fire Safety Journal, Fire Science and Technology and Progress in Energy and Combustion Science. Colloquium Chair for the 30th and 31st Combustion Symposium and member of the Program Committee for the 8th International Symposium on Fire Safety Science. Advisor to the National Association for State Fire Marshals (USA), the Scottish Chief Fire Officers Forum, the Office of the Deputy Prime Minister and a member of the International Association for Fire Safety Science (IAFSS) International Committee. Member of the Forum of Chief Fire Officers of Scotland (SDAF) and of the CFOA Training Needs Analysis Gateway Review Group. Member of the Society of Fire Protection Engineers, International Standards Development Committee, Underwriters Laboratory STP-162 Foams Fire Suppression Systems Committee, the American Institute of Aeronautics and Astronautics (AIAA) Micro-Gravity and Space Processes Technical Committee, the Committee of the British Section of the Combustion Institute and the American Society of Mechanical Engineers, K-11 Committee on Fire and Combustion.

Experience as a Consultant

Conducted work on prescriptive and performance based design, forensic fire investigation and product development. Conducted detailed structural response to fire, fire resistance evaluation, material selection, life safety analysis, smoke evacuation, detection and alarm design as well as standard and advanced fire suppression systems. Developed projects on transportation centres, hangars, trains and aircraft, industrial facilities, tunnels, high rise buildings, public assembly facilities and historic buildings. Used different codes and standards as well as a comprehensive array of analytical and numerical tools. Conducted third party reviews and supported fire service and building control in the approval process.

Lecture Invitations

Invited Conference Lectures

1. J. L. Torero, “Laminar Diffusion Flames Established over a Flat Plate Burner under Micro-Gravity Conditions,” *International Workshop on Short Term Experiments under Strongly Reduced Gravity Conditions*, Bremen, Germany, July 1994.
2. J. L. Torero, “Diffusion Flames in Micro-Gravity,” *Meeting of the ESA Physical Sciences Working Group*, Berlin, Germany, April, 1995.
3. J. L. Torero, “Numerical Simulation of Flat Plate Ethane-Air Diffusion Flames and Experimental Validation at Different Gravity Levels,” *9th European Symposium on Gravity Dependent Phenomena in Physical Sciences*, Berlin, May 1995.
4. J. L. Torero, “The Emmons Problem: Experimental Results and Progress Leading to a MiniTexus Experiment,” *ESA-Sounding Rocket Experiments Workshop*, ESTEC, Noordwijk, The Netherlands, September 1998.
5. J. L. Torero, “Material Flammability and Fire Safety,” *Society of Fire Protection Engineers*, Chesapeake Chapter, Maryland, September, 1998.
6. J. L. Torero, “La Formation de l’Ingenieur Incendie-Programmes Developpes aux Etats Unis et dans d’Autres Pays,” *SFPE Chapitre Francaise*, Les Salons du Grand Louvre, October 1998.
7. J. L. Torero, “Educación en Ingeniería de Protección Contra Incendios,” *Primer Foro Regional NFPA*, Lima ’99, Lima, Peru, October, 1999.
8. J.L. Torero, “Challenges and Needs in Fire Protection Engineering Research and Education,” *European Seminar on Environmental Risks*, Niort, France, October 2000.
9. J.L. Torero, “Cooperation and Student Exchange Between the University of Maryland and French Higher Education Institutions,” *Global E3 Annual Meeting*, Lake George, New York, June 2001.
10. J.L. Torero, “The Mass Transfer Number as a Criterion for Spacecraft Material Flammability,” *Workshop on Research Needs in Fire Safety for the Human Exploration and Utilization of Space*, NASA Glenn Research Center, Cleveland, Ohio, June 2001.
11. J.L. Torero, “The Role of Fire Science in Fire Investigation,” *Fire Safety and Rescue Asia Conference*, Singapore, November, 2001.
12. Torero, J. L., J. G. Quintiere and T. Steinhaus, “Fire Safety in High-rise Buildings: Lessons Learned from the WTC,” 51st *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Dresden, Germany, 2002.
13. J.L. Torero, “Fire and the Environment,” *International Workshop on Environmental Risk Assessment*, Damascus, Syria, October, 2002.
14. J.L. Torero, “Scaling of Micro-gravity Combustion Systems, Implications to Spacecraft Fire Safety” *European Workshop on Micro-gravity Combustion*, Poitiers, France, October 2002.
15. J.L. Torero, “Desarrollo de una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios,” *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002.
16. J.L. Torero, “Conclusiones para una Reglamentacion Adecuada en Materia de Seguridad Contra Incendios,” *Conference on Fire Safety organized by the Vice-President of the Republic*, Lima, Peru, November 2002.
17. J.L. Torero, “Fire Safety Science in Support of Performance Based Design: Innovation or Just Filling the Gaps?,” *The Graduate Lecture*, The Institution of Fire Engineers, Preston, Lancashire, April 2003.
18. J.L. Torero, “Fire Modeling and Fire Performance,” *The Rasbash Lecture and ECD Conference*, Ministry of Defence, Whitehall, London, UK, June 2003.
19. J.L. Torero, “La Experiencia del World Trade Center,” *Seminario Donde Hubo Fuego, Que Hacemos con las Cenizas*, Santiago, Chile, June 2003.
20. J.L. Torero, “L’Approche des Risques en Europe et aux Etats-Unis,” *Colloque Les risques Industriels & Technologiques, Enjeux Internes et Effets Externes, Bourges*, France, October 2003.

21. J.L. Torero and D.D. Drysdale, "Ignition and Flame Spread Studies as they Relate to Material Flammability," *Joint Meeting of the Fire Engineering Research Network (FERN) and the Fire Chemistry Network (FCHEM)*, March, 2004.

22. J.L. Torero, "FireGrid: Data Base Needs," *Digital Library Workshop*, National Institute of Standards and Technology (NIST), Maryland, USA, April 2004.

23. J.L. Torero, "Structures in Fire: An Overview of the Boundary Condition," *Fire And Structures: The Implications of the World Trade Center Disaster Conference*, The Royal Society of Edinburgh, Edinburgh, April, 2004.

24. J.L. Torero, "The Use and Misuse of Fire Modelling" *Society of Fire Protection Engineers*, California Chapter Spring Meeting, Luncheon Speaker, May, 2004.

25. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," *NATO-Russia Workshop on the Protection of Civil Infrastructure from Acts of Terrorism*, Russian Academy of Sciences, May 2004.

26. J.L. Torero, and T. Steinhaus, "Applications of Computer Modelling to Fire Safety Design," 53rd *Jahresfachtagung der Vereingung zur Forderrung des Deutschen Brandschutzez e. V.*, Essen, Germany, June, 2004.

27. J. L. Torero, "Lecciones Aprendidas Durante el Colapso de las Torres Gemelas en N.Y.," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004.

28. J.L.Torero, "Introducción al Diseño Basado en el Desempeño de la Ingeniería Contra Incendios," *Primer Congreso Nacional de Seguridad Contra Incendios, NFPA 2004*, Mexico City, November, 2004.

29. J.L.Torero, "L'évolution du métier Préventeur – Fire Risk Manager" *Salon POLLUTEC*, Lyon, France, November 2004.

30. J.L. Torero, "What is Fire Engineering? Where has it come from and where is it going?" *Developing the Role of Fire Engineering,* Cavendish Conference Centre, London, New Civil Engineering, April 2005.

31. J.L. Torero, "Structural Fire Engineering and Conjugate Heat Transfer," *Fire Bridges*, Belfast, Northern Ireland, May 2005.

32. J.L. Torero, "How can Fire Models Support Fire Reconstruction?" *The Rasbash Lecture and ECD Conference*, Ministry of Defense, Whitehall, London, UK, June 2005.

33. B. Lane, J.L. Torero, A. Usmani, S. Lamont, A. Jowsey, G. Flint, "Structural Fire Response and Collapse Analysis of WTC 1 & 2," *Technical Conference on the Federal Building and Fire Safety Investigation of the World Trade Center (WTC) Disaster*, National Institute of Standards and Technology, Gaithersburg, Maryland, September, 2005.

34. J.L. Torero, "Forensic Fire Investigation," *Fire Risk Management Networking Meeting*, IOSH, Edinburgh, September 2005.

35. J.L. Torero, "Fire-Arguably the Most Destructive Risk a Business Faces-Do We Understand this Risk? Are We Protected Adequately?" *AEOLUS*, Edinburgh, October, 2005.

36. J.L. Torero, "Heat and Mass Transfer in Fires: Scaling Laws and their Application" *12emes, Journees Internationales de Thermique*, Tangiers, Morocco, November 2005.

37. J.L. Torero, "Structures and Fire – Modern Techniques in Building Design," *Institution of Engineers of Brazil,* Sao Paulo, Brazil , November 2005.

38. J.L. Torero. "Smoke and Fire Detection," *Meeting of the GDR Feux*, ENSMA, Poitiers, January, 2006.

39. J.L. Torero "La Seguridad Contra Incendios en las Edificaciones: ¿Responsabilidad de Ingenieros o de Arquitectos? *International Conference to Celebrate the 10th Anniversary of the Polytechnic University of Puerto Rico*, Overcoming Fire: Architecture and Engineering Solutions, Puerto Rico, February 2006.

40. J.L. Torero "The NIST Report: What are the Future Design Implication for High Rise Buildings," *Designing for Fires in the UK: Can we learn from the NIST Report?*, Institution of Civil Engineers, London, March 2006.

41. J.L. Torero "High Power Computing Solutions for Fire," National Science Foundation, *NSF Workshop on Cyber-based Combustion Science*, Washington D.C., USA, April 2006.

42. J.L. Torero "Questions Liées à la Formation et à l'Entraînement des Personnes Avant, Pendant et Après la Crise," *Stop Feux*, Marseille, May 2006.

43. J.L. Torero, “Post-Flashover Numerical Modelling,” *FDS Global Seminar*, Ove Arup and Partners, London, May 2006.

44. J.L. Torero, “Métodos de Protección Pasiva, Análisis Critico y Tendencias,” *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios*, Santiago de Chile, July, 2006.

45. J.L. Torero, “Emergency Response for Fires: Sensors, Fire Fighters or Both,” *Royal Academy of Engineering Research Forum*, September 2006.

46. J.L. Torero, “Te Risk Imposed by Fire to Tall Buildings, What is the State of the Art?,” *International Conference on Fire Safety in Tall Buildings*, Santander, October 2006.

47. J.L. Torero, “Sensor Driven Emergency Response for Fires, FireGrid,” *Distinguish Lecture Series in Mechanical Engineering, University of Texas at Austin*, October 2006.

48. J.L.Torero, “Fire Safety Engineering: Science or Regulation?” *IRSN Conference on Fire Research and Applications*, Lyon, France, December 2006.

49. J. L.Torero, “Industrial Needs, New Regulation, Existing Knowledge and Available Training in Structural Fire Safety Engineering: Harmony or Chaos?” *IStructE-Seminars*, Royal Society of Edinburgh, Edinburgh, January 2007.

Publications

Books

1. Alvear, D. Capote, J.A., M. Lazaro, Abreu, O.V., Rein, G. and Torero, J.L. "Modelado y Simulación Computacional en la Edificación," Díaz de Santos Eds., pp. 336, (in press) 2007.

Chapters in Books

1. H.Y. Wang, J.L. Torero, L. Bonneau and P. Joulain, "Numerical Simulation of Ethane-Air Diffusion Flames Established over a Flat Plate Burner: Comparison with Different Gravity Experiments," *Transport Phenomena in Combustion*, S.H. Chan Editor, **2**, Taylor and Francis Publishers, 1141-1152, 1996.
2. J. L. Torero, H. Y. Wang, P. Joulain and J. M. Most "Flat Plate Diffusion Flames: Numerical Simulation and Experimental Validation for Different Gravity Levels," *Lecture Notes in Physics*, Ratke, L. Walter, H. and Feuerbacher, Eds., Springer-Verlag, **464**, 401-408, 1996.*(Invited & Refereed)*
3. J. T'ien, H-Y. Shih, C-B. Jiang, H.D. Ross, F.J. Miller, A.C. Fernandez-Pello, J.L. Torero and D. C. Walther, "Mechanisms of Flame Spread and Smolder Wave propagation," Fire in Free Fall: Micro-Gravity Combustion, H. Ross, Editor, Academic Press Chapter 5, pp.299-418, 2001.
4. J.L. Torero, "The Risk Imposed by Fire to Buildings and how to Address it," The Protection of Civil Infrastructure from Acts of Terrorism, NATO Advanced Science Institute series, Kluwer Academic Publishers, Frolov and Becker Eds. Pp. 37-56, 2006.
5. C. Lautenberger, J.L. Torero and A.C. Fernandez-Pello, "Considerations for Material Flammability," Chapter 2, *Flammability Testing of Materials in Building, Construction, Transport and Mining Sectors*, Apte Editor (in press) 2005.
6. A. Jowsey, S. Welch and J.L. Torero, "Heat and Mass Transfer for Modeling of Structures in Fire," Transport Phenomena in Fire, B. Sunden and M. Faghri Editors, WIT Press, UK (in press) 2006.

Articles in Refereed Journals

1. J. L. Torero, M. Kitano and A. C. Fernandez-Pello, "Opposed Flow Smoldering of Polyurethane Foam," *Combustion Science and Technology*, **91** (1-3), 95-117, 1993.
2. J. L. Torero, A. C. Fernandez-Pello and D. Urban "Experimental Observations of the Effect of gravity Changes on Smoldering Combustion, " *AIAA Journal*, **31** (5), 991-996, 1994.
3. J.L. Torero, L.Bonneau, J.M.Most and P.Joulain "The Effect of Gravity on a Laminar Diffusion Flame established over a Horizontal Flat Plate," *Proceedings of the Combustion Institute*, **25**, 1701-1709, 1994.
4. J. L. Torero, A.C.Fernandez-Pello and M.Kitano "Downward Smolder of Polyurethane Foam," *Fourth International Symposium on Fire Safety Science*, 409-420, 1994.
5. X. Zhou, J. L. Torero, J. C. Goudeau and B. Bregeon "On the Ignition and Propagation of a Reaction Front Through a Porous Fuel: Application to Mixtures Characteristic of Urban Waste," *Combustion Science and Technology*, **110-111** (1-6), 123-146, 1995.
6. J. L. Torero and A. C. Fernandez-Pello "Natural Convection Smolder of Polyurethane Foam, Upward Propagation," *Fire Safety Journal*, **24** (1), 35-52, 1995.
7. L. Audouin, G. Kolb, J. L. Torero and J. M. Most "Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings," *Fire Safety Journal*, **24** (2), 167-187, 1995.
8. J. L. Torero, L. Bonneau, J. M. Most and P. Joulain "On the Geometry of Laminar Diffusion Flames Established over a Flat Plate Burner," *Advances in Space Research*, **16** (7), 149-152, 1995.
9. L. Audouin, G. Kolb, J.L. Torero and J.M. Most "Response to the Letter by D.Milov Commenting the Paper Entitled: "Average Centerline Temperatures of a Buoyant Pool Fire Obtained by Image Processing of Video Recordings" (F.S.J., 24, 2, 1995)," *Fire Safety Journal*, **24** (4), 361-363, 1995.

10. D. P. Stocker, S. L. Olson, D. Urban, J.L. Torero, D. Walther and A.C. Fernandez-Pello,"Small Scale Smoldering Combustion Experiments in Microgravity," *Proceedings of the Combustion Institute*, **26**, 1361-1368, 1996.

11. N. Wu, M. Baker, G. Kolb and J. L. Torero "Ignition, Flame Spread and Mass Burning Characteristics of Liquid Fuels on a Water Bed," *Spill Science and Technology Bulletin*, **3** (4), 209-213, 1996.

12. J. L. Torero and A. C. Fernandez-Pello "Forward Smoldering of Polyurethane Foam in a Forced Air Flow," *Combustion and Flame*, **106** (1-2), 89-109, 1996.

13. L. Brahmi, T. Vietoris, P. Joulain and J. L. Torero, "Experimental Study on the Stability of a Diffusion Flame Established in a Laminar Boundary Layer," *Microgravity Abstracts*, **5**, 80-87, 1998. *(in Japanese)*

14. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Determination par camera Infrarouge des distributions de Temperature sur l'Enveloppe d'une Flamme de Diffusion Etablie sur un Bruleur Poreux Plan en Microgravite," *Enthropie*, **215**, 69-73**,** 1998. *(in French)*

15. N. Wu, G. Kolb and J. L. Torero, "Piloted Ignition of a Slick of Oil on a Water Sublayer: The Effect of Weathering," *Proceedings of the Combustion Institute*, **27**, 2783-2790, 1998.

16. T. Vietoris, J. L. Torero and P. Joulain, "Experimental Characterization of a Laminar Diffusion Flame in Micro-Gravity," *Journal de Chimie Physique*, **96**, 1022-1030, 1999.

17. J. P. Garo, J. P. Vantelon, S. Gandhi and J. L. Torero "Determination of the Thermal Efficiency Pre-boilover Burning of a Slick of Oil on Water," *Spill Science and Technology Bulletin*, **5** (2), 141-151, 1999.

18. L. Brahmi, T. Vietoris, J. L. Torero and P. Joulain, "Estimation of Boundary Layer Diffusion Flame Temperatures by Means of an Infra-Red Camera under Micro-Gravity Conditions," *Measurement Science and Technology*, **10**, 859-865, 1999.

19. R. T. Long, J. L. Torero, J. G. Quintiere and A. C. Fernandez-Pello, "Scale and Transport Considerations on Piloted Ignition of PMMA," *Sixth International Symposium on Fire Safety Science*, 567-578, 1999.

20. H. Y. Wang, J. L. Torero and P. Joulain, "Calculation of Vertical Parallel Wall Fires with Buoyancy Induced Flow," *Sixth International Symposium on Fire Safety Science*, 671-678, 1999.

21. T. Vietoris, P. Joulain and J. L. Torero "Experimental Observations on the Geometry and Stability of a Laminar Diffusion Flame in Micro-Gravity," *Sixth International Symposium on Fire Safety Science,* 373-386, 1999.

22. S. Leach, G. Rein, J. Ellzey, O. A. Ezekoye and J. L. Torero, "Kinetic and Fuel Property Effects on Forward Smoldering Combustion," *Combustion and Flame*, **120**, 3, 2000.

23. M. K. Anderson, R. T. Sleight and J. L. Torero, "Ignition Signatures of a Downward Smolder Reaction," *Experimental Thermal and Fluid Science*, **21**,1-3, 33-40, 2000.

24. M. Anderson, R. Sleight and J. L. Torero "Downward Smolder of Polyurethane Foam: Ignition Signatures," *Fire Safety Journal*, **35**, 131-148, 2000.

25. Fernandez-Pello, A.C., Walther, D.C., Cordova, J.L., Steinhaus, T., Quintiere, J.G., Torero, J.L., and Ross, H., "Test Method for Ranking Materials Flammability in Reduced Gravity," *Space Forum,* **6**, 237-243, 2000.

26. T. Vietoris, J. L. Ellzey, P.Joulain, S.N. Mehta and J.L. Torero, "Laminar Diffusion Flame in Micro-Gravity: The Results of the Mini-Texus 6 Sounding Rocket Experiment, *Proceedings of the Combustion Institute,* **28**, 2000.

27. N. Wu, G. Kolb and J. L. Torero, "The Effect of Weathering on the Flammability of a Slick of Crude Oil on a Water Bed," *Combustion Science and Technology*, **161**, 269-308, 2000.

28. M. Roslon, S. Olenick, D. Walther, J.L. Torero, A.C. Fernandez-Pello and H. Ross, "Micro-Gravity Ignition Delay of Solid Fuels," *AIAA-Journal*,**.39**, No.12, pp. 2336-2342, Dec. 2001.

29. J.L. Cordova, D. C. Walther, J. L. Torero and A.C. Fernandez-Pello, "Oxidizer Flow Effects on the Flammability of Solid Combustibles," *Combustion Science and Technology,* **164**, N0. 1-6, pp. 253-278, 2001.

30. T. Vietoris , P. Joulain and J. L. Torero, "Gas-Gas and Gas-Solid Laminar Flat Plate Diffusion Flames in Micro-Gravity: Structure and Stability," *Micro-Gravity Science and Technology,* **XIII**, 1, 3-7, 2001.

31. C. Worrell, G. Gaines, R. Roby, L. Streit and J.L. Torero, "Enhanced Deposition, Acoustic Agglomeration and Chladni Figures in Smoke Detectors," *Fire Technology*, Fourth Quarter, **37**, Number 4, pages 343-363, 2001.

32. S.D. Wolin, N.L. Ryder, F. Leprince, J.A. Milke, F.W. Mowrer and J.L. Torero, "Measurements of Smoke Characteristics in HVAC Ducts," *Fire Technology*, Fourth Quarter, **37**, Number 4, pages 363-395, 2001.

33. Torero, J.L., Vietoris, T., Legros, G., Joulain, P. "Evaluation d'un Nombre de Transfert de Masse Réel d'une Flamme Ascendante" *Journal de Physique IV*, **11**, pp. 291-300, 2001. *(in French)*

34. Milke, J.A., Torero, J.L., Mowrer, F. W. and Fuhrmeister, C., "Use of Optical Density-Based Measurements as Metrics for Smoke Detectors," *ASHRAE Transactions*, **8**, pp. 699-711, 2002.

35. Torero, J.L., Vietoris, T., Legros, G., Joulain, P. "Estimation of a Total Mass Transfer Number from Stand-off Distance of a Spreading Flame," *Combustion Science and Technology*, **174** (11-12), pp.187-203 , 2002.

36. Rouvreau, S., Cordeiro, P., Joulain, P., Wang, H.Y. and Torero, J.L., "Numerical Evaluation of the Influence of Fuel Generation on the Geometry of a Diffusion Flame: Implications to Micro-Gravity Fire Safety," *Seventh International Symposium on Fire Safety Science*, 283-295, 2002.

37. Dakka, S.M., Jackson, G. S. and Torero, J.L., "Mechanisms Controlling the Degradation of Poly(methyl methacrylate) Prior to Piloted Ignition" *Proceedings of the Combustion Institute*, **29**, 281-287, 2002.

38. Rouvreau, S., Joulain, P., Wang, H.Y., Cordeiro, P. and Torero, J. L. "Numerical Evaluation of Boundary Layer Assumptions Used for the Prediction of the Stand-off Distance of a Laminar Diffusion Flame" *Proceedings of the Combustion Institute*, **29**, 2527-2534, 2002.

39. Rogaume, T., Jabouille, F., Auzanneau, M., Goudeau, J.C. and Torero, J.L., "The Effects of Different Airflows on the Formation of Pollutants During Waste Incineration," *Fuel*, **81**, 2277-2288, 2002.

40. G. Rein Soto-Yarritu, J.L. Torero and J.L. Ellzey, "Simulacion Numerica de Combustión Latente en Flujo Directo," *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingenieria*, **18**, No. 4, 459-474, December 2002. *(in Spanish)*

41. Zhou, Y.Y., Walther, D.C., Fernandez-Pello, A.C., Torero, J.L., Ross, H.D., "Theoretical Predictions of Micro-Gravity Ignition Delay of Polymeric Fuels in Low Velocity Flows," *Micro-Gravity Science and Technology*, **XIV**, 1, 44-50, 2003.

42. J.L. Torero, S.M. Olenick, J.P. Garo and J.P. Vantelon, "Determination of the Burning Characteristics of a Slick of Oil on Water, Spill Science and Technology Bulletin, **8**, 4, pp.379-390, 2003.

43. T. Rogaume, M. Auzanneau, F. Jabouille, J.C. Goudeau and J.L. Torero, "Computational Model to Investigate the Effects of Different Airflows on the Formation of Pollutants During Waste Incineration," *Combustion Science and Technology*, **175**, 8, 2003.

44. A.S. Usmani, Y.C. Chung and J.L. Torero, "How Did the World Trade Center Collapsed: A New Theory," *Fire Safety Journal*, **38**, Issue 6, Pages 501-591, 2003.

45. C.L. Worrell, J.A. Lynch, G. Jomaas, R.J. Roby, L. Streit and J.L. Torero, "Effect of Smoke Source and Horn Configuration on Enhanced Deposition, Acoustic Agglomeration and Chladni Figures in Smoke Detectors," *Fire Technology*, **39**, 309-346, 2003.

46. T. Rogaume, F. Jabouille, J.L. Torero, "Computational Model to Investigate the Mechanisms of NO_x Formation During Waste Incineration," *Combustion Science and Technology*, **176**, 5-6, 925-943, 2004.

47. T .Ma, S.M. Olenick, M.S.Klassen, R.J. Roby and J.L. Torero, "Burning Rate of Liquid Fuel on Carpet (Porous Media)" *Fire Technology*, **40**,3, 227-246, 2004.

48. G. Legros, P. Joulain, J.-P. Vantelon, C. Breillat and J. L. Torero "Epaisseur Optique d'une couche de suie formee par une flamme de diffusion en micropesanteur," *Journal de Mecanique et Industries*, **5**, September-October, 2004. *(in French)*

49. Bar-Ilan, G. Rein, A.C. Fernandez-Pello, J.L. Torero, D.L. Urban, "Effect of Buoyancy on Forced Forward Soldering," *Experimental Thermal and Fluid Science*, **28**, 743-751, 2004.

50. F. Mowrer, J. Milke and J.L. Torero, "Comparative Driving Forces for Smoke Movement in Buildings," *Journal of Fire Protection Engineering*, **14**, 4, 237-264, 2004.

51. G. Rein, A. Bar-Ilan, A. C. Fernandez-Pello, J. L. Ellzey, J. L. Torero, D. L. Urban, "Modeling of One-Dimensional Smoldering of Polyurethane in Microgravity Conditions," *Proceedings of the Combustion Institute*, **30**, 2, 2327-2334, 2004.

52. A. Bar-Ilan, G. Rein, D.C. Walther, A.C. Fernandez-Pello, J.L. Torero and D.L. Urban, "The effect of Buoyancy on Opposed Smoldering," *Combustion Science and Technology*, **176**, 2027-2055, 2004.

53. S. Rouvreau, J.L. Torero and P. Joulain, "Numerical evaluation of boundary layer assumptions for laminar diffusion flames in micro-gravity" *Combustion Theory and Modelling*, **9**, 137-168, 2005.

54. S. Rouvreau, P.Cordeiro, J.L. Torero and P. Joulain, Influence of g-jitter on a laminar boundary layer type diffusion flame, *Proceedings of the Combustion Institute*, **30**, 1, 519-526, 2005.

55. J.-P. Vantelon, B. Lodeho, S. Pignoux, J. L. Ellzey and J. L. Torero, Experimental Observations on the Thermal Degradation of a Porous Bed of Tires, *Proceedings of the Combustion Institute*, **30**, 2, 2239-2246, 2005.

56. L. Brahmi, T. Vietoris, S. Rouvreau, P. Joulain L. David and J.L. Torero, "Microgravity Laminar Diffusion Flame In A Perpendicular Fuel And Oxidizer Streams Configuration", *AIAA Journal*, **43**, 8, 1725-1733, 2005.

57. P. Joulain, P. Cordeiro, S. Rouvreau, G. Legros, A. Fuentes and J. L. Torero, " Influence of G-Jitter on the Characteristics of a Non-Premixed Flame: Experimental Approach" *Micro-Gravity Science and Technology*, **XVI**, 1, 2005.

58. A. Fuentes, G. Legros, P. Joulain, J.-P. Vantelon and J. L. Torero, "Evaluation of the Extinction Factor in a Laminar Flame Established over a PMMA Plate in Microgravity"," *Micro-gravity Science and Technology*, **17**, 3, 10-14, 2005.

59. S. Olenick, M. Spearpoint, T. Steinhaus and J.L. Torero, "A flammability evaluation of motor vehicle upholstery materials," *Fire and Materials*, **29**, 265-282, 2005.

60. J-L Consalvi, B. Porterie, M. Coutin, L. Audouin, C. Casselman, A. Rangwala, S.G. Buckley and J.L. Torero, "Diffusion Flames Upwardly Propagating over PMMA: Theory, Experiment and Numerical Modeling, *Eighth International Symposium on Fire Safety Science*, 397-409*, 2005*

61. J. L. Torero, O. Mangs, L. Audouin, L. Rigollet, "An Example of the Use of Standard Flammability Criteria for Performance Analysis of Materials: Polycarbonate and PMMA" *Eighth International Symposium on Fire Safety Science*, 493-506, 2005.

62. G. Legros, J. Baillargeat, P. Joulain, J-P Vantelon, P. Ben-Abdallah and J.L. Torero, "Three-Dimensional Recomposition of the Absorption Field Inside an Non-Buoyant Diffusion Flame," *Optics Letters*, **30**, 24, 3311-3313, 2005.

63. Flint, G., Usmani, A., Lamont, S., Torero, J.L. and Lane, B., "Effect of Fire on Composite Long Span Truss Floor Systems," *Journal of Constructional Steel Research*, **62**, 4, 303-315, 2006.

64. Carvel, R. O. and Torero, J. L., "Preliminary results quantifying the contribution of Asphalt road surfaces to fire risk in tunnel fires," *Tunnel Management International*, **9**, 2, 2006.

65. G. Legros, P. Joulain, J.-P. Vantelon, A. Fuentes, D. Berthau and J. L. Torero "Soot Volume Fraction Measurements in a Three Dimensional Laminar Diffusion Flame Established in Microgravity," *Combustion Science and Technology*, **178**, 5, 813-835, 2006.

66. Rogaume, T., Koulidiati, J., Richard, F., Jabouille, F., Torero, J.L., "A Model of the Chemical Pathways Leading to NOx Formation During Combustion of Mixtures of Cellulosic and Plastic Materials," *International Journal of Thermal Sciences*, **49**, 359-366, 2006.

67. G. Rein, C. Lautenberger, A. C. Fernandez-Pello, J. L. Torero, D. L. Urban, "Smoldering Combustion of Polyurethane Foam: Using Genetic Algorithms to Derive its Kinetics," *Combustion and Flame*, **146** (1-2), 95-108, 2006.

68. S. Lamont, B. Lane, A. Jowsey, G. Flint, A. Usmani and J.L. Torero, "Innovative structural Engineering for Tall Buildings in Fire," *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, **16**, 2, pp. 142-147, 2006.

69. G. Legros, A. Fuentes, B. Rollin, P. Joulain, J-P. Vantelon and J.L. Torero, "Extinction Simulation of a Diffusion Flame Established in Microgravity," *Journal of the Energy Institute*, **79**, 4, 207-211, 2006.

70. Rogaume, T., Koulidiati, J., Richard, F., Jabouille, F. and Torero, J.L., **“**Optimization of the oxidizer repartition in order to reduce the no emissions in municipal waste incineration,” *Clean Air*, **7**, 1, 43-58, 2006.

71. A. Fuentes, G. Legros, A. Claverie, P. Joulain, J-P Vantelon and J.L. Torero, “Influence of the Oxidizer Velocities on Sooting Behaviour of a Non-Buoyant Laminar Diffusion Flame,” *Proceedings of the Combustion Institute*, **31**, 2, 2685-2692, 2007.

72. D. Rich, C. Lautenberger, J. L. Torero, J. G. Quintiere, A. C. Fernandez-Pello, “Mass Loss Rate of Combustible Solids at Piloted Ignition,” *Proceedings of the Combustion Institute*, **31**, 2, 2653-2660, 2007.

73. A. S. Rangwala, S. G. Buckley and Jose L. Torero, “Upward Flame Spread on a Vertically-Oriented Fuel Surface: The Effect of Finite Width,” *Proceedings of the Combustion Institute*, **31**, 2, 2607-2615, 2007.

74. A. Fuentes, G. Legros, S. Rouvreau, P. Joulain, J.-P. Vantelon, J. L. Torero and A. C. Fernandez-Pello, “Sooting Behaviour Dynamics of a Non-Buoyant Laminar Diffusion Flame,” *Combustion Science and Technology*, **179**, 1-2, 3-19, 2007.

75. T. Steinhaus, R. Carvel, S. Welch, J.L. Torero, “Large Pool Fires and Post-Crash Aircraft Fires,” Journal of Thermal Sciences, **3**, 2007.

76. I. Fletcher, R. Carvel, S. Welch and J.L. Torero, “Concrete in Fire: A Review,” Journal of Thermal Sciences, **3**, 2007.

77. R.O. Carvel and J.L. Torero, “Clyde Tunnel Refurbishment: modelling the performance of the new lining system and drainage channel in the event of a fire,” *Tunnel Management International*, (in press) 2007.

78. G. Flint, A. Usmani, A. Lamont, J. L. Torero and B. Lane, “Structural Response of Tall Buildings to Multiple Floor Fire: Part 1 - General Response,” *ASCE Journal of Structural Engineering*, (in press), 2007.

79. G. Flint, A. Usmani, A. Lamont, J. L. Torero and B. Lane, “Structural Response of Tall Buildings to Multiple Floor Fire: Part 2 – Parametric Study,” *ASCE Journal of Structural Engineering*, (in press), 2007.

80. A. Fuentes, G. Legros, H. El-Rabii, P. Joulain, J.-P. Vantelon and J. L. Torero, “Laser-Induced Incandescence Calibration in a Three-Dimensional Laminar Diffusion Flame Established in Microgravity,” *Experiments in Fluids* (in press), 2007.

81. J.L. Consalvi, Y. Pizzo, B. Porterie and J.L. Torero, “On the Flame Height Definition for Upward Flame Spread,” *Fire Safety Journal*, (in press) 2007.

Other Journal Publications

1. V. Brannigan and J. L. Torero, “The Expert’s New Clothes: Arson “Science” After Kumho Tire,” *Fire Chief Magazine*, 60-65, July 1999.

2. J.L. Torero and A. Atreya, “Book Review: Modélisation et Théorie des Flammes, by Borghi and Champion,” *Applied Mechanics Reviews*, Book Review, **54**, 5, B93, 2001.

3. *J.D. Rivera, P. Matamala and J.L. Torero “Laboratorio de Ensayo y de Resistencia al Fuego,”* Seventh International Symposium on Fire Safety Science, *111-113, 2002.*

4. J.L. Torero, “Review of the Book: Industrial Fire Protection Engineering by Robert G. Zalosh,” Fire Safety Journal **39**, 6, 528-533, 2004.

5. J.L. Torero, “Review of: Ignition Handbook, Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science by Vytenis Babrauskas, PhD,” Journal of Fire Protection Engineering, **14**, 229-232, 2004.

6. J.L. Torero, “Review of: Ignition Handbook, Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science by Vytenis Babrauskas, PhD,” Fire Protection Engineering, **21**, p.3, 2004.

7. J.L. Torero and B. Lane, “The Changing Face of Structural Design for Fire,” *International Fire Buyers Guide*, August, 2004.

Extension Activities and Professional Courses

1. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 1998.
2. *Control de Riesgos de Incendio* – Pontificia Universidad Catolica de Chile, Santiago, Chile, November 1998.
3. *Feu et Combustion* – Ecole National Superieure de Mecanique et d'Aerothechnique (ENSMA), Universite de Poitiers, France, March 1999.
4. *Seminaire sur le Management des risques d'Incedie,* Univeriste de Poitiers-Site de Niort, France, January, 2000.
5. *Fire Phenomena/Enclosure Fires* – Bureau of Alcohol Tobacco and Firearms, Maryland Fire and Rescue Institute, University of Maryland, August 2000.
6. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, November 2000.
7. *Fire Safety* – Masters of Science Loss Prevention and Risk Management, ENSI-Bourges, Bourges, France, December 2001.
8. *Fire Safety Engineering* – Ecole des Mines St. Etienne, St. Etienne, France, January, 2002.
9. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2002.
10. *Performance Based Design of Fire Safety Systems* – Pontificia Universidad Catolica de Chile, June 2002.
11. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2003.
12. *Fire Science and Fire Investigation* – The University of Edinburgh, March 2003.
13. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, March 2003.
14. *Ingenieria de Proteccion Contra el Fuego* - Pontificia Universidad Catolica de Chile, June 2003.
15. *Fire Science and Fire Investigation* – The University of Edinburgh, March 2004.
16. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2004.
17. *Concrete Structures in Fire* – Pontificia Universidad Catolica de Chile, September, 2004.
18. *Introduction to Fire Safety Engineering,* – Ecole Polytechnique de Marseille, Marseille, France, September, 2004.
19. *Introduction to Fire Safety Engineering,* – Ecole des Mines St. Etienne, St. Etienne, France, February, 2005.
20. *Timber Construction in Fire*– Pontificia Universidad Catolica de Chile, June 2005.
21. *Primer Seminario de Ingenieria de Proteccion Contra Incendios* – Pontificia Universidad Catolica del Peru, November 2005.
22. *Fire Dynamics and Fire Safety Engineering Design* - The University of Edinburgh, April 2006.
23. *Fire Science and Fire Investigation* – The University of Edinburgh, April 2006.
24. *Seminario de Innovación en el Diseño y Protección de Estructuras contra Incendios,* Santiago de Chile, July, 2006.
25. *Introduction to Fire Safety Engineering,* Ecole Polytechnique de Marseille, November 2006.

APPENDIX F: INTRODUCTORY MATERIALS PRESENTED AT FIRST PANEL MEETING

This appendix includes the slides of the presentations that were given to the panel at the start of the PIRT.

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Fire Modeling Phenomena Identification Ranking Table (PIRT)

Opening Remarks PIRT panel
NRC Headquarters, Rockville, MD.
May 22, 2007

Jennifer Uhle, Deputy Director
Division of Fuel, Engineering and Radiological Research

RES Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Overview

- The PIRT process has been successfully used in a number of other NRC activities
  - Thermal Hydraulics Modeling Codes
  - Accident Analysis Modeling Codes
  - Next Generation Reactors
- Apply the process to Fire Modeling
  - Insights to model performance and improvements
  - Insights to future experiments
- Fire Modeling is important in a Risk-Informed, Performance-Based Regulatory Environment (NFPA 805)

RES Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Process

- NRC would like to get a detailed, rigorous, expert evaluation of the fire scenarios that will be presented

- NRC would like to thank our partners supporting this effort
  - Sandia National Laboratories (SNL)
  - National Institute of Standards and Technology (NIST)
  - Electric Power Research Institute (EPRI)

Office of Nuclear Regulatory Research

Nuclear Power Plant Fire Modeling Applications PIRT

Meeting Introduction
Steve Nowlen
Sandia National Laboratories
May 22, 2007

Sandia National Laboratories

What is PIRT?

- PIRT = Phenomena Importance Ranking Table
  - An expert elicitation process
  - Define the PHENOMENA relevant to the defined applications
  - Rank the identified phenomena for importance against the PIRT figure of merit (we will define these in a moment)
  - We also include a state of knowledge assessment for each phenomena
- The output of the PIRT is the ranking table itself
  - Identifies phenomena ranked for both importance and state of knowledge
- This information is used to guide future research
  - e.g., a phenomena that is ranked of high importance but has a poor state of knowledge would be a research priority

Sandia National Laboratories

Let's talk about "Phenomena"

- "Phenomena" does not mean "Parameters"
- Example:
  - Heat transfer to wall surfaces is a phenomena
  - Thermal conductivity and the surface heat transfer coefficient are parameters
- We are identifying and ranking phenomena!
  - If a parameter is "identified" I will ask for the underlying phenomena and that is what will go on the ranking table
- When we get to state of knowledge assessment we will accept input stating that knowledge (or lack) relative to one or more parameters will be the key to ensuring adequate treatment of an identified phenomena

Sandia National Laboratories

Our Metric:

- Nuclear power plant fire modeling applications
- The NRC mission: protect the health and safety of the public
- That means the main concern is plant accidents that could cause an off-site release of radioactive materials
- As a surrogate we use Risk:
  - Accidents leading to core damage
  - Accidents leading to loss of containment integrity

Sandia National Laboratories

Our metric (cont.)

- So the metric is:
  - How important is each phenomena to fire modeling as applied to nuclear power plant analyses…
  - Where these may be associated with:
    - Risk Assessment (by NRC or licensees),
    - Regulatory enforcement (e.g., risk-informed assessments of licensee non-compliance issues),
    - Licensee analyses performed in support of risk-informed compliance applications (e.g., NFPA-805 or an exemption request)
  - Its about Plant Safety and fire as a potential threat to core integrity

Sandia National Laboratories

So what does that mean to you?

- The application drives the importance ranking for identified phenomena
- Example:
  - The panel may identify toxicity effects as a phenomena
  - Ranking this phenomena must consider the metric
  - How important is toxicity relative to fire modeling predictions supporting an assessment of the potential impact of plant fires on public health and safety

Sandia National Laboratories

Process that we will follow:

- Background material presented
- PIRT exercise itself follows a series of steps:
  - We will present you with a fire scenario including:
    - Pre-defined elements/characteristics
    - Specific objectives/goals of the fire modeling analysis
  - First pass: Panel will identify all phenomena relevant to the scenario and the fire modeling objective/goal
  - Second pass: Panel will rank each identified phenomena for importance
  - Third pass: Panel will assess state of knowledge for each phenomena

Sandia National Laboratories

Process (cont)

- We will also be asking you to provide a basis for your judgments on each item
- We will allow for iteration and review as necessary
  - We will likely review to some extent at the beginning of each meeting
  - You will have a chance to update your input
- Interim meeting results will be distributed to panel for comment and review after each meeting
- PIRT results will be published in a NUREG/CR report
  - Each of you will be asked to review that report

Sandia National Laboratories

A word about State of Knowledge

- **We will be ranking state of knowledge based on several factors:**
  - **What is the current status of fire modeling tools relative to each identified phenomenon**
  - **What is the status of relevant input data needed for treatment of the phenomenon**
  - **What is the potential for development of new input data to support treatment of the phenomenon**
  - **What is the status of data suitable to the validation of fire models relative to the phenomena**

Sandia National Laboratories

Some final comments on process

- **As moderator, I will direct the discussions but the input is *yours***
- **Various knowledge area experts are present**
  - **They are NOT panelists, they are here to support *you* and to answer your questions**
- **We will seek consensus among the panel on rankings, but we may also "agree to disagree"**
  - **I will decide when a debate has gone on long enough**
  - **If I choose to cut off debate, please respect that**
- **We want to hear from *every panel member***
  - **Each panelist will be asked to at least concur on rankings**
  - **You may defer (pass) if you feel that you have no expertise in a particular area, but I will ask you to state that**
  - **If someone is too quiet, expect me to draw you in…**
- **You are all peers – debate is good, but respect each other**

Sandia National Laboratories

PIRT Terms (1)

Figure of Merit	
Top Level	Protecting the health and safety of the public (NRC mission)
Second Tier	Fires at a nuclear power plant leading to off-site release of radioactive materials.
Third Tier	Fires that cause the loss of critical plant systems and equipment leading in turn to reactor control challenges, core damage, and a challenge to containment integrity.
Fourth Tier:	Fire Probabilistic Risk Assessment (FPRA) and other regulatory applications of fire modeling tools to assess plant safety, adequacy of the fire protection program, and findings of non-compliance. NFPA-805 applications.

Sandia National Laboratories

Terms (2)

Phenomena Importance Rankings	
Descriptor:	Definition:
High	First order importance to figure of merit.
Medium	Secondary importance to figure of merit.
Low	Negligible importance to figure of merit. Not necessary to model this parameter for this application.
Uncertain	Potentially important. Importance should be explored through sensitivity study and/or discovery experiments and the PIRT revised accordingly.

Sandia National Laboratories

Terms (3):

Model Adequacy Rankings	
Descriptor	Definition
High	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	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	No significant discovery activities have occurred and model form is still unknown or speculative.
Unknown	The panel is unaware of the existing state of fire modeling tools with respect to this phenomenon.

Sandia National Laboratories

Terms (4):

Data Adequacy Rankings for Existing Input Data and Validation Data	
Descriptor:	Definition:
High	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	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	No existing database or low-resolution database in existence. Assessments cannot be made with even moderate reliability based on existing knowledge.

Sandia National Laboratories

Terms (5):

Data Adequacy Rankings for Potential to Develop New Data	
Descriptor:	Definition:
High	Data needed are readily obtainable based on existing experimental capabilities.
Medium	Data would be obtainable but would require moderate, readily attainable extensions to existing capabilities.
Low	Data are not readily obtainable and/or would require significant development of new capabilities.

Sandia National Laboratories

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Fire Branch Research

A Brief Introduction to: Fire Hazard Analysis (FHA) & Fire Modeling in Commercial Nuclear Power Plant (NPP)

Presentation to Fire Modeling Phenomena Identification Ranking Table (PIRT) panel
NRC Headquarters, Rockville, MD.
May 22, 2007

Mark Henry Salley, P.E.
Chief, Fire Research Branch

RES Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Overview

- Provide a High Level Overview of Fire Hazards Analysis (FHA) as used in the Nuclear Industry
- Provide a High Level Overview of the status of Fire Modeling as used in the Nuclear Industry
- Provide a High Level Overview on major targets such as Electrical Cables and how they effect Reactor Safety

RES Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

General NPP Fire Protection

- Plant-wide Fire Protection
  - Addresses all areas of the Nuclear Power Plant (NPP)
  - Based on Defense-In-Depth (DID)
    - Fire Prevention
    - Early Detection & Rapid Suppression
    - Design Features to protect essential NPP safety functions
  - Requires a Fire Hazard Analysis (FHA)

Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Fire Hazard Analysis

- Considers potential of fire hazards in NPP
  - Transients combustibles
  - In situ combustibles
- Determines the consequences of fire
  - Reactor Safety
  - Release of Radioactivity
- Specifies fire protection measures
  - Fire prevention
  - Fire detection
  - Fire suppression
  - Fire containment

Office of Nuclear Regulatory Research

Post-Fire Safe-Shutdown

- Commonly referred to as “Appendix R”
- Postulated fire anywhere in NPP
  - Provide the ability to achieve & maintain hot-shutdown of the reactor
- Primary questions:
  - What equipment/systems available for safe-shutdown?
  - What equipment/systems lost or damaged?
  - What equipment/systems can spuriously operate/mal-operate and impede safe-shutdown?

Browns Ferry Fire - Lessons Learned

- NUREG-0050
- March 22, 1975, Fire in Cable Spreading Room (CSR)/ Unit 1 (~ 20 x 40 Sq.Ft. area)
- Ignition of temporary penetration seal between CSR and Unit 1
- 1600 electrical cables damaged
- All Unit 1 Emergency Core Cooling Systems (ECCS) lost – Many Unit 2 ECCS lost
- Fire lasts almost 8 hours

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Browns Ferry Fire- Penetration Seal Area

Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Browns Ferry Fire - Cable Trays

Office of Nuclear Regulatory Research


U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment
Browns Ferry Fire – Cable Trays
Office of Nuclear Regulatory Research


U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment
Browns Ferry Fire – Fire Damage
Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Browns Ferry Fire – Post Fire Penetration Seal Testing

Office of Nuclear Regulatory Research

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Browns Ferry Fire – Post Fire Full-Scale Cable Testing

Office of Nuclear Regulatory Research

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Fire Research

Nuclear Power Plant Design Philosophy – Redundancy & Diversity

- Redundancy – Multiple sets of equipment
  - Example – If a 100% pump is needed, two are provided
  - Two or more, "Trains" or "Divisions" of equipment
- Diversity – Separation or Different Supply
  - Example – If one pump is electric motor driven, the second may be steam driven, or the second electric motor driven pump is powered by a different electric supply

Office of Nuclear Regulatory Research

U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION

Protecting People and the Environment

Fire Research

Electrical Cables – The Weak Link

- The majority of fire safety concerns tend to focus on cable and their routing
- There are locations in the NPP where cable routing/separation is extremely difficult to achieve
  - Main Control Room (MCR)
  - Cable Spreading Room (CSR)
  - Cable Tunnels
- There have been issues with cable fire protection Electrical Raceway Fire Barrier Systems (ERFBS)
  - Thermo-Lag, Kaowool, Hemyc

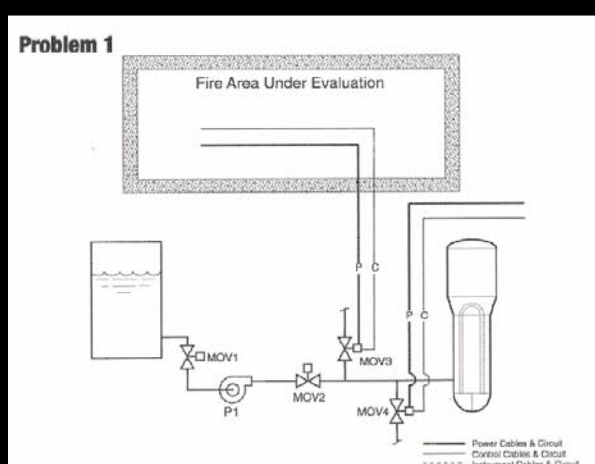
Office of Nuclear Regulatory Research

Electrical Cables – Construction & Function

- Electrical Cable Construction can be broken down into two broad families based on their polymers
  - Thermoplastic which begin to fail in the neighborhood of 400F
  - Thermosets which begin to fail in the neighborhood of 700F
- Electrical Cables are used for 3 different functions
  - Power
  - Control
  - Instrumentation
- Electrical Cables can fail in a number of different modes such as
  - Short to Ground
  - Short within a cable or to another cable
  - Open Circuits

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Electrical Circuit/Fire Interaction



Office of Nuclear Regulatory Research

Fire Dynamics/Modeling State-of-the-Art in NPPS

- NUREG-1805, “Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program.” (2004)
  - Introduction to Fire Dynamics for NRC Inspectors
- NUREG/CR-6850 Fire PRA Methodology for Nuclear Power Facilities (2005)
- NUREG- 1824 “Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications (2007)
- NUREG/CR-XXXX “Fire Model PIRT” (2007/8)
- NUREG-XXXX “Fire Modeling Users Guide” (2008/9)

Final Thoughts

- Office of Nuclear Regulatory Research is looking for this PIRT to assist us in future decisions such as
  - Fire Model Improvements/Enhancements
  - Design of Experiments
- There are a number of additional experts supporting this PIRT as a resource for the panel – Use them if necessary
  - NPP Design/Fire Hazard Background
  - Fire Model Developers
- We are much more interested in thoroughness and rigor of the phenomena discussions rather than the number of scenarios covered
  - Strive for completeness
  - Cover all aspects of the scenario

Thank-you!!!
Questions???

Fire Branch Research

Validating Fire Models for Nuclear Power Plant Applications

Jason Dreisbach, US NRC
Anthony Hamins, NIST
Francisco Joglar, SAIC/EPRI
Kevin McGrattan, NIST
Bijan Najafi, SAIC/EPRI
Richard Peacock, NIST
Mark Salley, US NRC

Verification and Validation

- *Verification:* **tests the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate; only that the equations are being implemented and solved correctly. Is the Math right?**
- *Validation:* **determines the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurements. Is the Model right?**
- **This presentation focuses primarily on validation.**

Models Selected

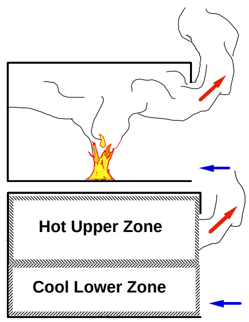
Fire Dynamics Tools (FDTs)	NRC Spreadsheets
FIVE-Rev1	EPRI Spreadsheets
Cons. Fire & Smoke Transport (CFAST)	NIST zone model
MAGIC	Electricite de France zone
Fire Dynamics Simulator (FDS)	NIST CFD Model

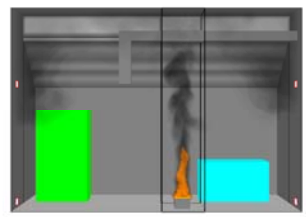
Spreadsheets

Zone Models

Field Models

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D$$



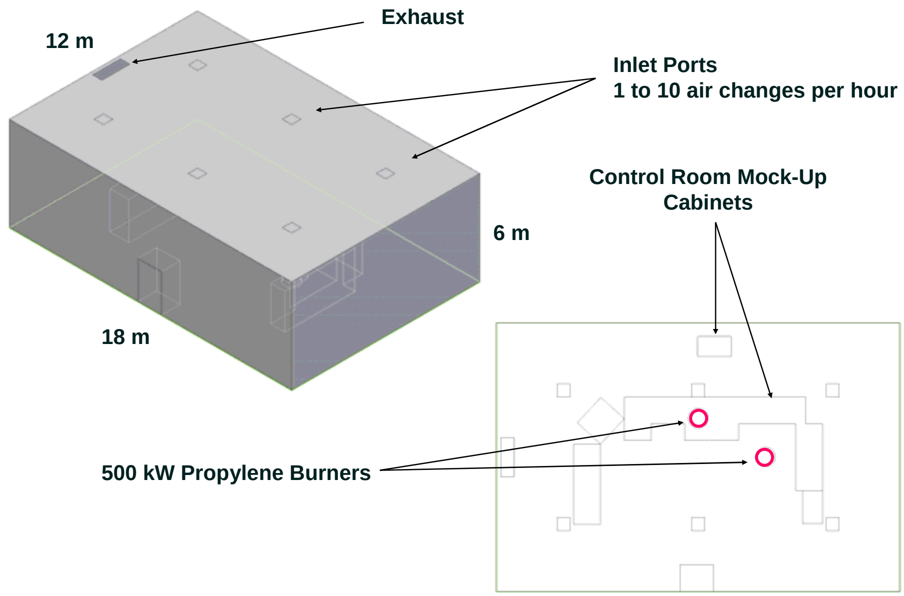


Experiments Selected

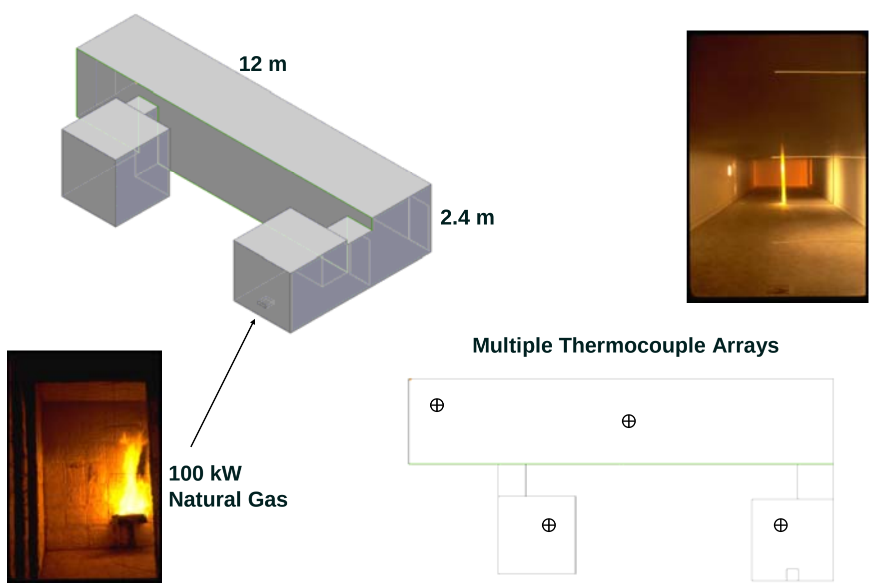
Six sets of experiments selected (26 tests in all)

Series	Number of Tests	Q (kW)	*V* (m^3)	*H* (m)
FM/SNL	3	500	1400	6.1
NBS	3	100	15	2.4
ICFMP BE #2	3	1800-3600	5900	19
ICFMP BE #3	15	400-2300	580	3.8
ICFMP BE #4	1	3500	74	5.7
ICFMP BE #5	1	400	73	5.6

Factory Mutual / Sandia National Labs (1985)

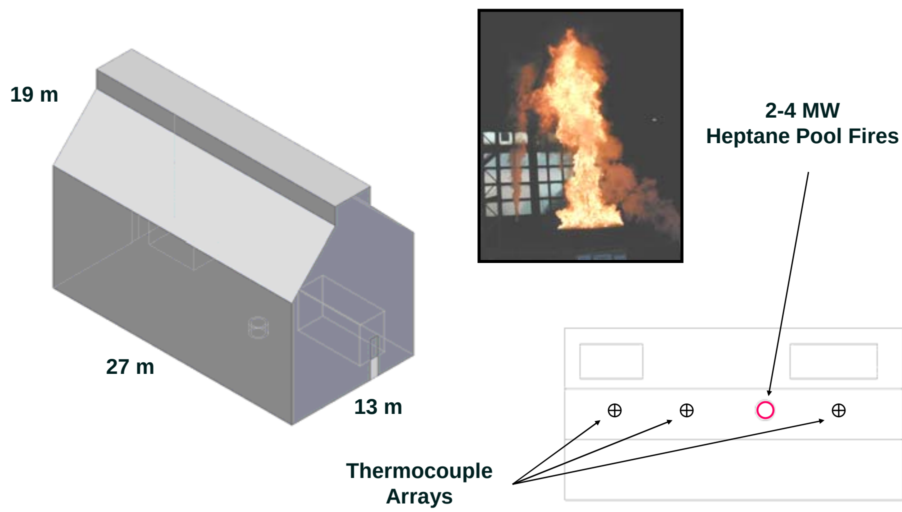


NBS Multi-Room Fire Tests (1985)



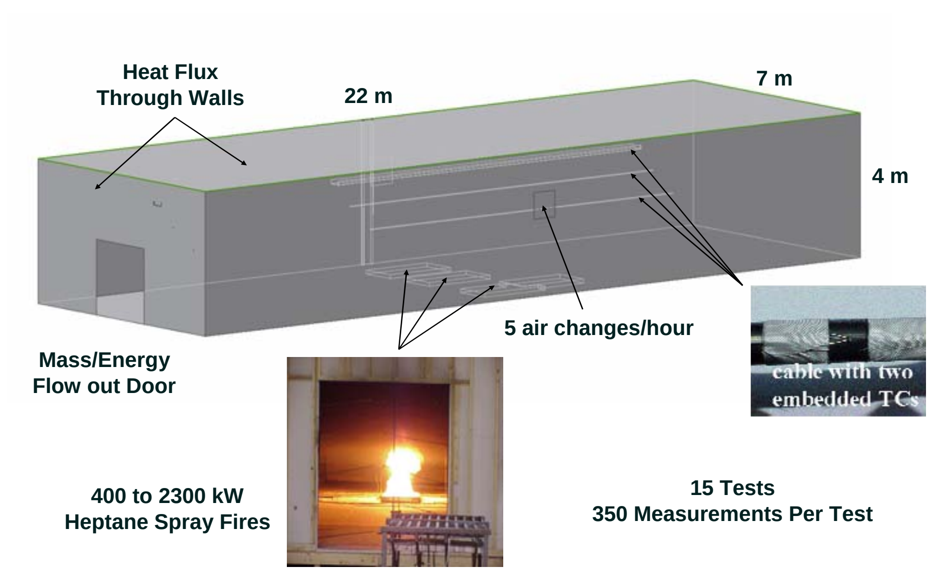
VTT (Finland) Large Hall Fire Tests (1998-1999)

ICFMP Benchmark Exercise #2

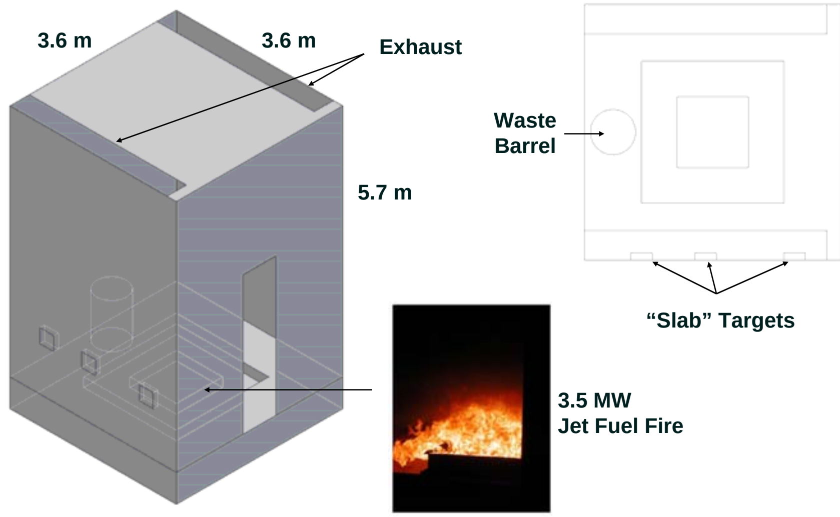


NIST/NRC Fire in a Switch Gear Room (2003)

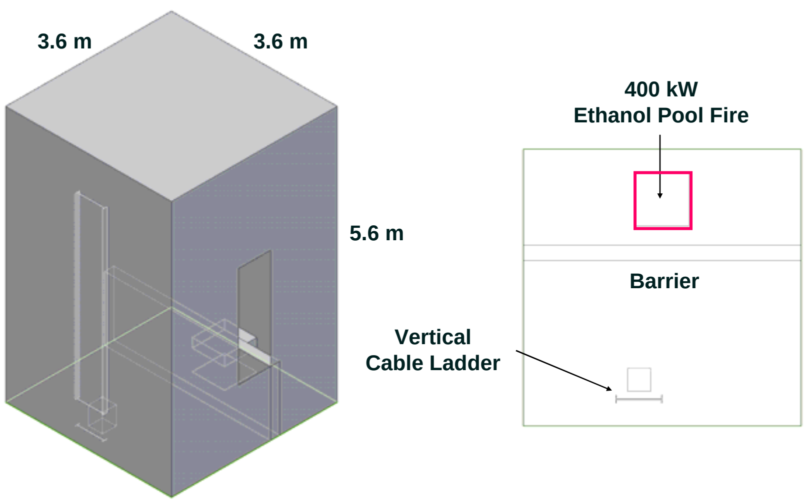
ICFMP Benchmark Exercise #3



Institut für Baustoffe, Massivbau und Brandschutz (iBMB) Germany (2004)
Pool Fire Inside a Compartment
ICFMP Benchmark Exercise (BE) #4



Institut für Baustoffe, Massivbau und Brandschutz (iBMB) Germany (2004)
Flame Spread in Cable Trays
ICFMP Benchmark Exercise #5



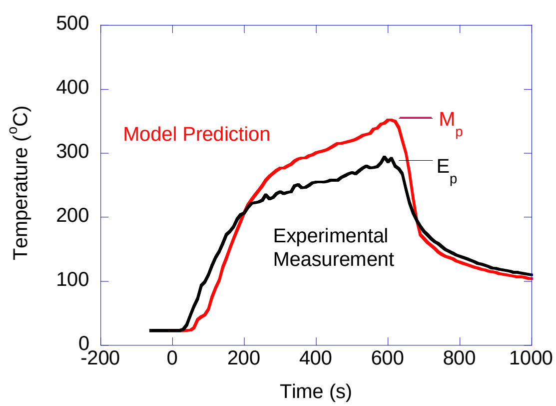
List of quantities

Hot gas layer temperature
Hot gas layer height
Ceiling jet temperature
Plume temperature
Flame height
Oxygen concentration
Smoke concentration
Compartment pressure
Radiated heat flux to target
Total heat flux to target
Target temperature
Total heat flux to walls
Wall temperature

Comparison of Models with Actual Measurements

What is “The degree of accuracy required for each quantity?” NFPA 805 and ASTM E 1355 don’t say.

<u>Big Idea – Use experimental uncertainty as a yardstick.</u>

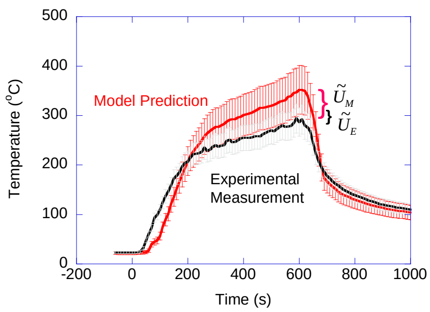


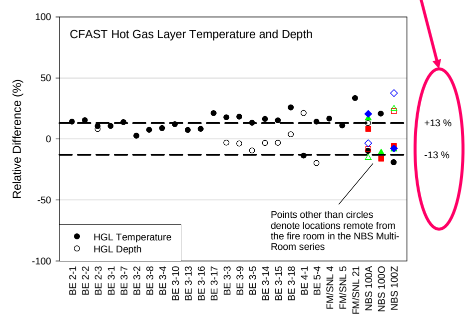
Model Evaluation Approach

$$\varepsilon = \frac{M_p - E_p}{E_p}$$ **Define relative difference**

$$U_C = \left(\tilde{U}_M^2 + \tilde{U}_E^2\right)^{1/2}$$ **Combine measurement and model uncertainty**

$$|\varepsilon| \overset{?}{<} U_C$$ **Assessment**





Model Input Uncertainty

Experimental heat release rate, $\dot{Q}$ drives fire effects, and its uncertainty dominates model uncertainty.

$$\dot{Q} = \chi_a \cdot \dot{m} \cdot H_c$$

$\dot{Q}$ = heat release rate (kW)

$\dot{m}$ = mass burning rate (g / s)

χ_a = combustion efficiency

H_c = heat of combustion (kJ / g)

Example: Hot Gas Layer (HGL) Temperature

According to an empirical correlation substantiated by hundreds of measurements:

$$T_g - T_\infty = 6.85 \left(\frac{\dot{Q}^2}{A_0 \sqrt{H_0}\, h_k A_T} \right)^{1/3} \propto \dot{Q}^{2/3}$$

$$\frac{\delta T}{\mathrm{T}} \propto (2/3) \frac{\delta \dot{Q}}{\dot{Q}}$$

Uncertainty in HRR measurements is roughly 15 %

Uncertainty in the HGL temperature prediction varies by 2/3 x 15 % = 10 %

Combined Uncertainty

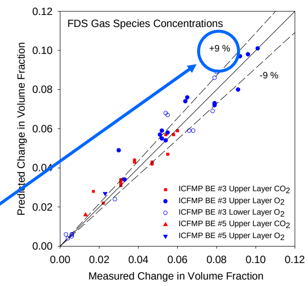
$$U_C = \left(\tilde{U}_M^2 + \tilde{U}_E^2 \right)^{1/2}$$

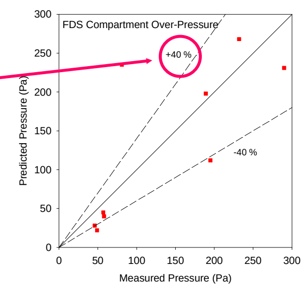
Summary of the Relative Expanded Uncertainties
Associated with the HGL Layer Depth and Temperature Rise

Series	HGL Depth			HGL Temperature Rise		
	$\tilde{U}_E$ (%)	$\tilde{U}_M$ (%)	U_c (%)	$\tilde{U}_E$ (%)	$\tilde{U}_M$ (%)	U_c (%)
NBS	6	2	6	6	10	12
FM/SNL	23	2	23	10	13	16
BE #2	8	2	8	9	10	13
BE #3	6	2	6	6	11	12
BE #4	22	2	22	6	17	18
BE #5	9	2	9	7	10	12

Representative Uncertainties

Parameter	Number of Tests	Weighted Combined Uncertainty (%)
HGL Temperature Rise	26	13
HGL Depth	26	9
Ceiling Jet Temperature	18	16
Plume Temperature	6	14
Gas Concentration	16	9
Smoke Concentration	15	33
Pressure	15	40 (no forced ventilation)
		80 (with forced ventilation)
Heat Flux	17	20
Surface / Target Temperature	17	14





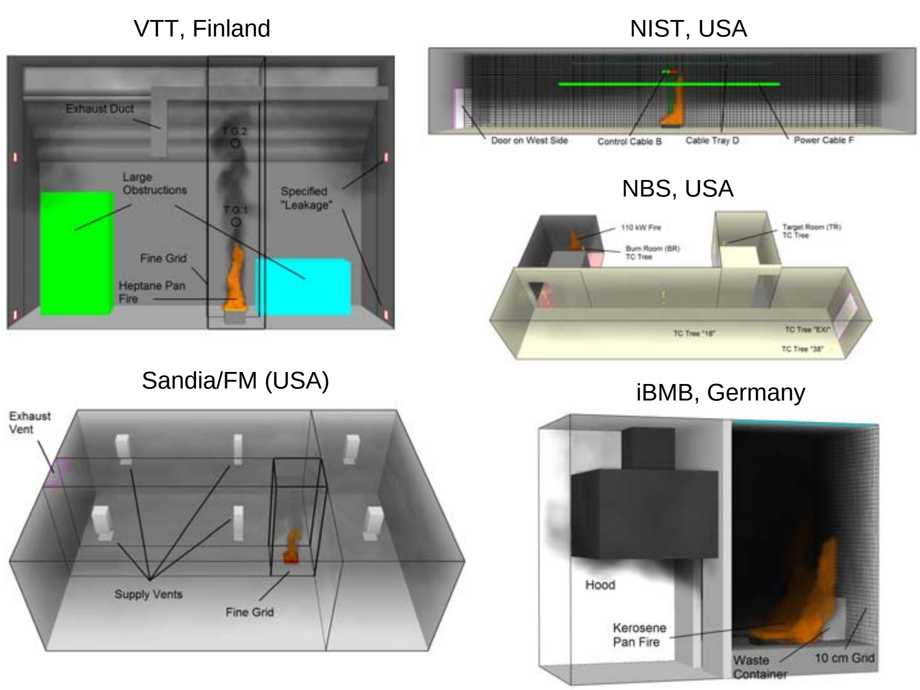
Conclusions

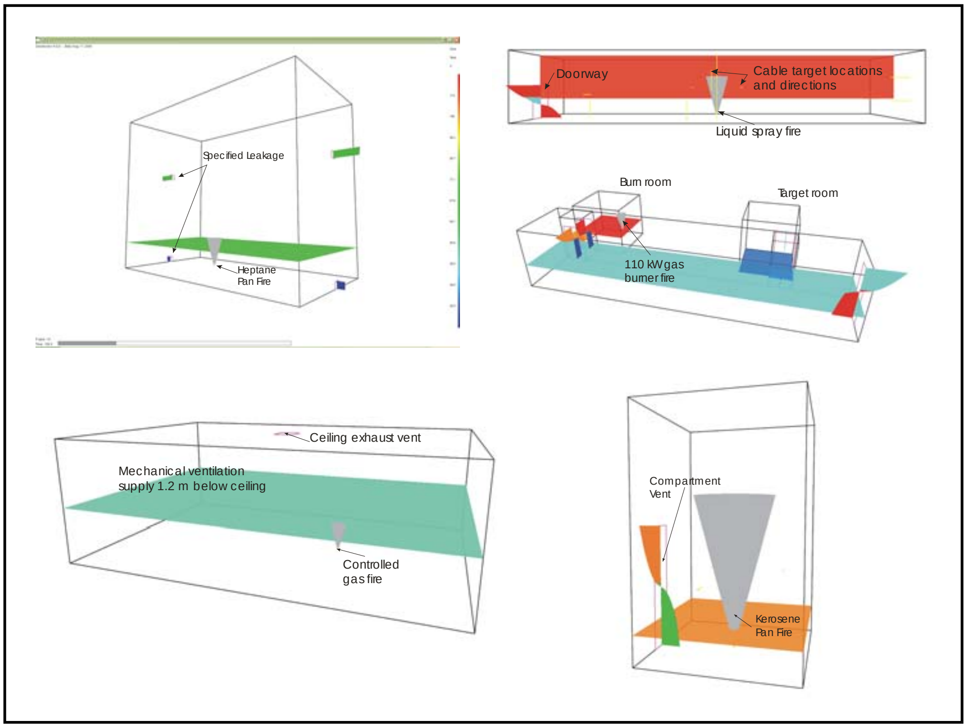
- **Quantified experimental uncertainty used as criteria for validation.**
- **Combined uncertainty represented by sum of experimental uncertainty and model sensitivity.**
- **Experimentalists need to document and reduce measurement uncertainty to advance model validation.**
- **Magnitude of uncertainty can be used to prioritize effort to improve measurement accuracy.**

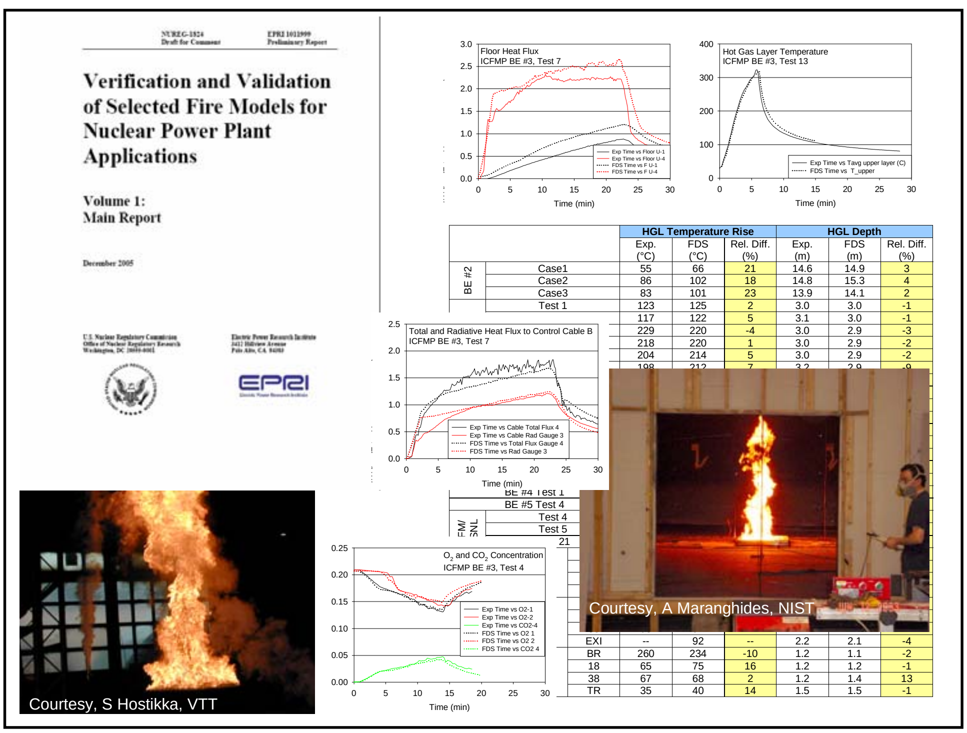
Since 2000, the US Nuclear Regulatory Commission has participated in the <u>International Collaborative Fire Model Project</u> (ICFMP) to evaluate fire models for nuclear power plant applications.

NIST has participated, evaluating FDS and CFAST, along with modelers and experimentalists from:

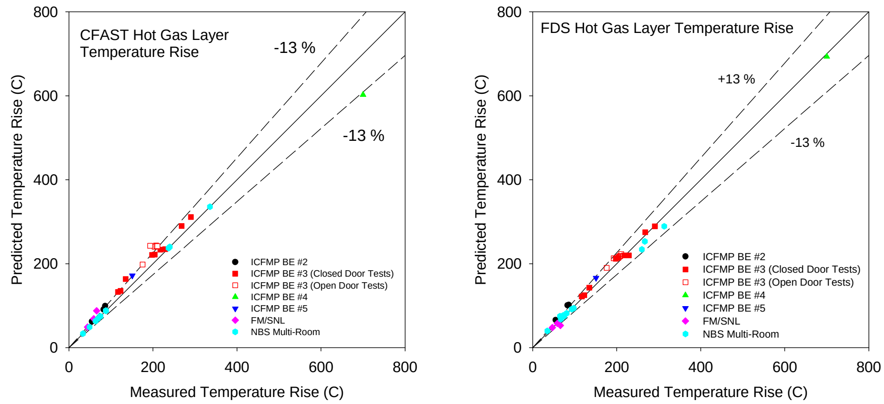
Fire Research Station, UK (JASMINE)
GRS, Germany (COCOSYS, CFX)
iBMB, Germany (Validation Experiments)
Électricité de France (Magic)
IRSN, France (Flamme-S)
VTT, Finland (Validation Experiments)




Specified leakage
Heptane Pan Fire
Doorway
Cable target locations and directions
Liquid spray fire
Burn room
Target room
110 kW gas burner fire
Ceiling exhaust vent
Mechanical ventilation supply 1.2 m below ceiling
Controlled gas fire
Compartment Vent
Kerosene Pan Fire

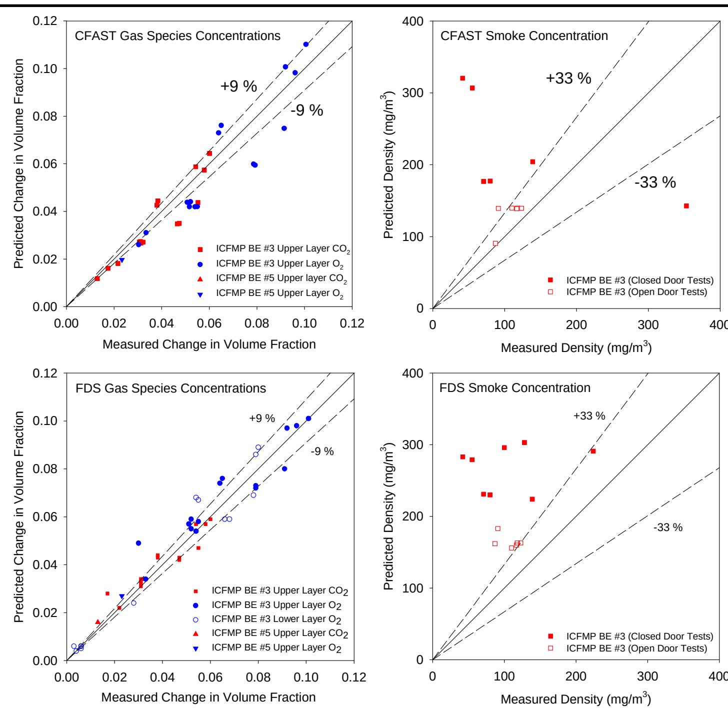

NUREG-1824 Draft for Comment
EPRI 1011999 Preliminary Report
Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications
Volume 1: Main Report
December 2005
Floor Heat Flux ICFMP BE #3, Test 7
Hot Gas Layer Temperature ICFMP BE #3, Test 13
Time (min)
HGL Temperature Rise
HGL Depth
Total and Radiative Heat Flux to Control Cable B ICFMP BE #3, Test 7
O2 and CO2 Concentration ICFMP BE #3, Test 4
Courtesy, A Maranghides, NIST
Courtesy, S Hostikka, VTT

Hot Gas Layer Temperature



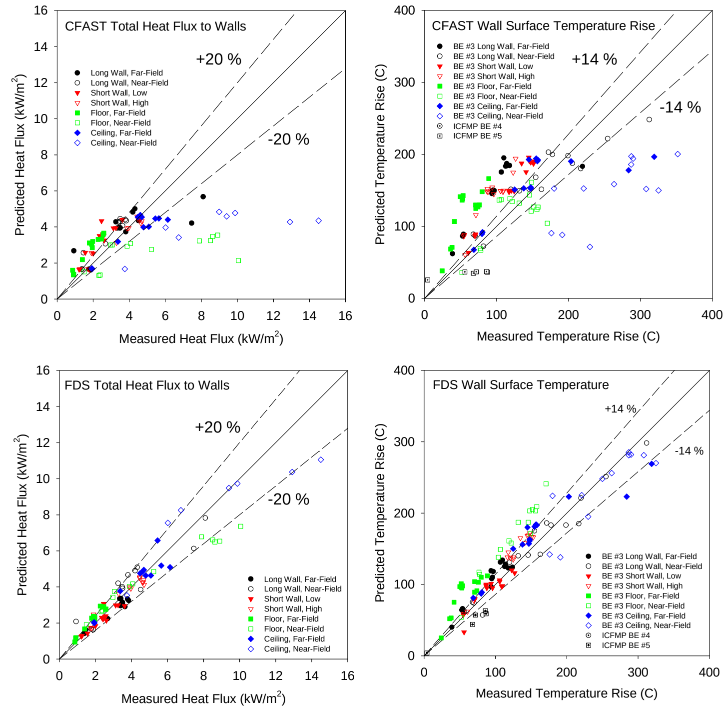
CFAST
Gas Species
and Smoke

FDS
Gas Species
and Smoke



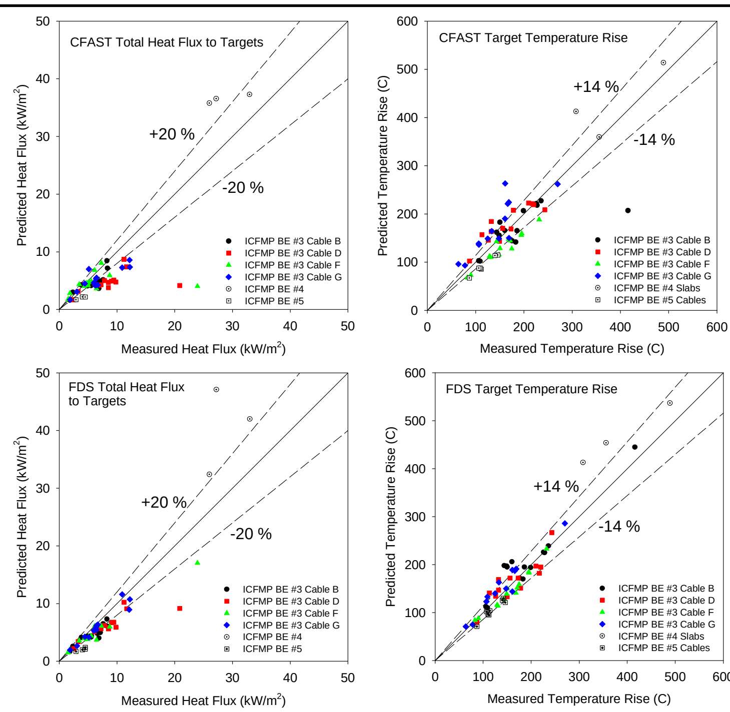
CFAST
Heat Flux and
Wall Temperature

FDS
Heat Flux and
Wall Temperature



CFAST
Heat Flux and
Target Temperature

FDS
Heat Flux and
Target Temperature



General Findings of NUREG 1824

In general, the experiments conformed to the classic 2 layer fire model.

Consequently, CFD model only marginally more accurate, even though it demands about 1000 times the CPU time (minutes vs days).

CFD is very powerful, but may be unnecessary for design fire applications in non-cluttered compartments with flat ceilings.

Obstructions/geometric complexity should impact selection of model type.

Special Topic: Cables

Power, control, and instrument cables are a big part of any fire modeling analysis involving NPPs, and were included in several of the V&V exercises.

How should cables be handled in the fire models? How much complexity do we need to predict (1) electrical failure, and (2) ignition and flame spread?

To address issue (1), modeling has been a part of the recent CAROLFIRE program.

Simple Response Models in Fire

$$\frac{dT_l}{dt} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}(T_g - T_l)$$

Solve for link temperature using velocity **u** and gas temperature from Fire Model. The RTI (Response Time Index) is unique to each sprinkler.
Source: Gunnar Heskestad, Factory Mutual

$$\frac{dY_c}{dt} = \frac{Y_e(t) - Y_c(t)}{L/\mathbf{u}}$$

Solve for smoke chamber concentration using external smoke concentration and velocity **u** from Fire Model. L is a length scale unique to each detector.

Surely, you're joking…

There must be more to sprinklers and smoke detectors than just these simple equations!

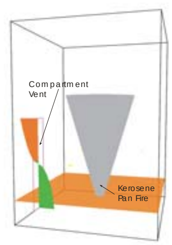
Absolutely, but consider the fire models in which these sub-models are embedded…

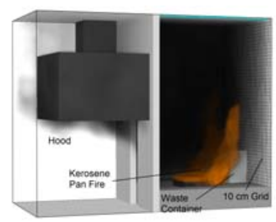
Three Classes of Fire Models

Hand Calculations | Two-Zone Models | CFD

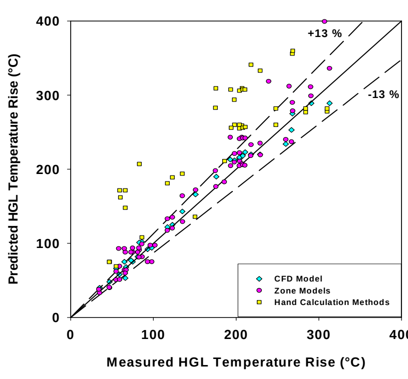
$$T_g - T_\infty = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}\,h_k A_T}\right)^{1/3}$$

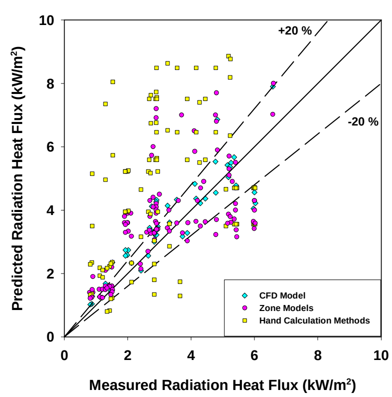
McCaffrey, Quintiere, Harkleroad (MQH)





Results of NRC V&V (NUREG 1824)





Cable Failure Model

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{k_s}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_s}{\partial r}\right)$$

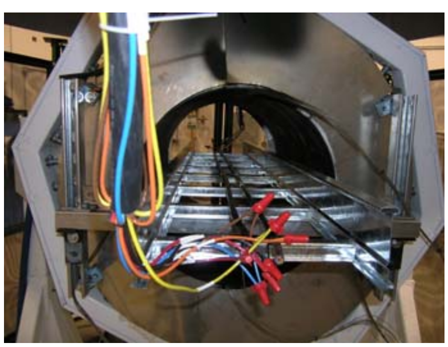
$$-k_s \frac{\partial T_s}{\partial r} = \dot{q}_c'' + \dot{q}_r''$$

1-D heat conduction into homogenous cylinder. Thermal conductivity (k) and specific heat (c) assumed constant for all cables. Density (ρ) obtained from cable diameter and mass per unit length. Failure temperature obtained experimentally.

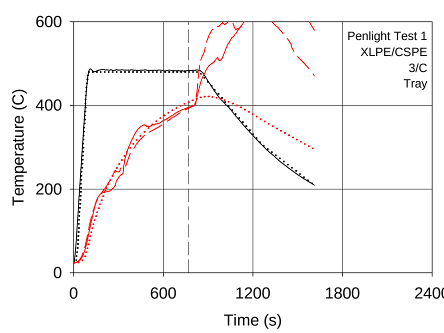
The Fire Model provides the convective and radiative heat flux at the cable surface.

Source: Andersson and Van Hees, SP Fire, Sweden.

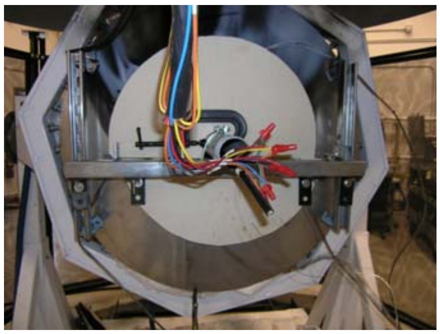
Results

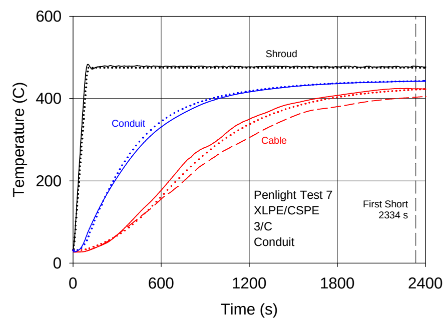


Courtesy Steve Nowlen and Frank Wyant
Sandia National Laboratory



More Results





Courtesy Steve Nowlen and Frank Wyant
Sandia National Laboratory

Summary of Cable Modeling

- Cable model developed in conjunction with CAROLFIRE test program
- Simplicity and accuracy of the model consistent with current generation large-scale fire models

NRC FORM 335 (9-2004) NRCMD 3.7 U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER **(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)** NUREG/CR-6978 SAND2008-3997P
2. TITLE AND SUBTITLE A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications	3. DATE REPORT PUBLISHED MONTH: November YEAR: 2008 4. FIN OR GRANT NUMBER N6374
5. AUTHOR(S) Tara J. Olivier and Steven P. Nowlen	6. TYPE OF REPORT Technical 7. PERIOD COVERED *(Inclusive Dates)* 9/6/2006-6/30/2008

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Sandia National Laboratories
Risk and Reliability Analysis Department 6761 MS-0748
Albuquerque, New Mexico 87185

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

J. Dreisbach and D. Stroup, NRC Project Managers

11. ABSTRACT *(200 words or less)*

This report documents 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 United States Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES). The PIRT exercise is performed via a facilitated expert elicitation process. In this case, the expert panel was comprised of seven international fire science experts. The panel 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 panel is presented with a series of specific fire scenarios, each of which is based on the types of scenarios typically considered in NPP applications. Each scenario includes a figure of merit; that is, a specific goal to be achieved in analyzing the scenario using fire modeling tools. To illustrate, one scenario involved a main control room fire. For this scenario the figure of merit was predicting the time to operator abandonment. Given each scenario, the panel identifies all those related phenomena that are of potential interest to an assessment based on the figure of merit. The phenomena are ranked relative to their importance in predicting the figure of merit. Each phenomenon is then further ranked for the existing state of knowledge and the 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.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	13. AVAILABILITY STATEMENT
Fire modeling, PIRT	unlimited
	14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified
	15. NUMBER OF PAGES
	16. PRICE