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Final Report

EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities

Volume 1: Summary & Overview

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EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities

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Final Report

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ABSTRACT

This report documents state-of-the-art methods, tools, and data for the conduct of a fire Probabilistic Risk Assessment (PRA) for a commercial nuclear power plant (NPP) application. This report is intended to serve the needs of a fire risk analysis team by providing a structured framework for conduct of the overall analysis, as well as specific recommended practices to address each key aspect of the analysis. The methods have been developed under the Fire Risk Requantification Study. This study was conducted as a joint activity between the Electric Power Research Institute (EPRI) and the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) under the terms of an NRC/EPRI Memorandum of Understanding and an accompanying Fire Risk Addendum. Participants from the U.S. Nuclear Power Industry supported demonstration analyses and provided peer review of this methodology. Methodological issues raised in past fire risk analyses, including the Individual Plant Examination of External Events (IPEEE) fire analyses, have been addressed to the extent allowed by the current state-of-the-art and the overall project scope. While the primary objective of the project was to consolidate existing state-of-the-art methods, in many areas, the newly documented methods represent a significant advancement over previously documented methods.

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REPORT SUMMARY

The Fire Risk Requantification Study has resulted in state-of-the-art methods, tools, and data for a fire probabilistic risk assessment (PRA) for commercial nuclear power plant application. This study was conducted jointly by EPRI and the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) under the terms of an NRC/EPRI Memorandum of Understanding and an accompanying Fire Research Addendum. Industry participants supported demonstration analyses and provided peer review of the methods. The documented methods are intended to support future applications of fire PRA, including risk-informed regulatory applications.

Background

This document is written primarily for practitioners conducting a nuclear power plant fire PRA study. A fire PRA requires a team effort because few individuals have the full range of expertise and knowledge necessary to complete the analysis. This report assumes that the fire risk analysis team will include individuals with expertise in four key areas: 1) fire analysis (basic fire behavior, fire modeling, fire protection engineering, and plant fire protection regulatory compliance practices and documentation); 2) general PRA and plant systems analysis (event tree/fault tree analysis, nuclear power plant systems modeling, reliability analysis, PRA practices as applied in the internal events domain, and specific knowledge of the plant under analysis); 3) human reliability analysis (emergency preparedness, plant operations, plant-specific safe shutdown procedures, and operations staff training practices); and 4) electrical analysis (circuit failure modes and effects analysis and post-fire safe shutdown, including plant-specific regulatory compliance strategies and documentation). While some of this expertise is generic, much of it is specific to the plant under analysis.

The methods documented in this report represent the current state-of-the-art in fire PRA practice. Certain aspects of PRA continue to evolve and likely will see additional developments in the near future. Such developments should be easily captured within the overall analysis framework described here. It is important to emphasize that while specific aspects of the analysis process will likely evolve, the overall analysis framework represents a stable and well-proven platform and should not be subject to fundamental changes in the foreseeable future.

Objectives

- To consolidate recent research and development activities into a single state-of-the-art fire PRA methodology.
- To serve the needs of a fire risk analysis team by providing a structured framework for the overall analysis, as well as specific recommended practices to address key aspects of the analysis.

Approach

Developing this fire PRA methodology document involved a consensus process designed to fully debate and build consensus on past methodological issues. Two technical development teams were assembled, one by EPRI and the second by RES. Each team provided a full complement of experts covering all aspects of the analysis. These experts worked together to develop an overall analysis framework and specific instructions for key aspects of the fire PRA.

Technical differences were aired in sometimes-lively discussions. The technical exchange process was designed to seek consensus where possible. However, the process also allowed RES and EPRI to maintain differing technical views in cases where consensus could not be reached. In practice, this did not prove necessary. The documented methods do, in all cases, represent a consensus view of the two technical development teams.

Another key aspect of the project involved participation of the commercial nuclear power industry in review, demonstration, and, to a lesser extent, development of the recommended methods. An industry peer-review panel was formed from the six non-pilot utility participants in this program. Two nuclear power plants participated as pilot plants and supported demonstration studies conducted jointly by the EPRI and RES technical development teams. A third nuclear power plant participated as an independent pilot plant, exercising the proposed methods independently and providing feedback to the technical development teams.

Results

The documented fire PRA method reflects state-of-the-art fire risk analysis approaches. Methodological issues raised in past fire risk analyses, including individual plant examination of external events (IPEEE) fire analyses, have been addressed to the extent allowed by the current state-of-the-art and overall project scope. Methodological debates were resolved through a consensus process between experts representing both EPRI and RES. The consensus process included a provision allowing both EPRI and RES to maintain differing technical positions if consensus could not be reached. No cases were encountered where this provision was invoked. While the primary objective of the project was to consolidate existing state-of-the-art fire PRA methods, in many areas, the newly documented methods represent a significant advance over previously documented methods. In several areas, this project has, in fact, resulted in new methods and approaches. Such advances typically relate to areas of past methodological debate.

EPRI Perspective

This report provides the single most complete and comprehensive methodology for conducting a fire PRA to date. Two aspects of the approaches described here are especially unique. First, the methodology has been developed based on a consensus process involving both EPRI and RES. Second, the methods specifically address and resolve previously identified methodological issues. Clearly, these fire PRA methods should offer a stable basis for proceeding with risk-informed regulatory approaches to fire protection regulatory compliance.

Keywords

Fire
Probabilistic Risk Assessment (PRA)
Nuclear Plant Fire Safety
Fire Risk
Risk Analysis
Risk-Informed Regulation

PREFACE

This report is presented in two volumes. Volume 1, the Executive Summary, provides general background and overview information including both programmatic and technical, and project insights and conclusions.

Volume 2 provides the detailed discussion of the recommended approach, methods, data and tools for conduct of a Fire PRA. This information is structured in 18 chapters that describe each of the project technical tasks as they are shown in Figure 1.

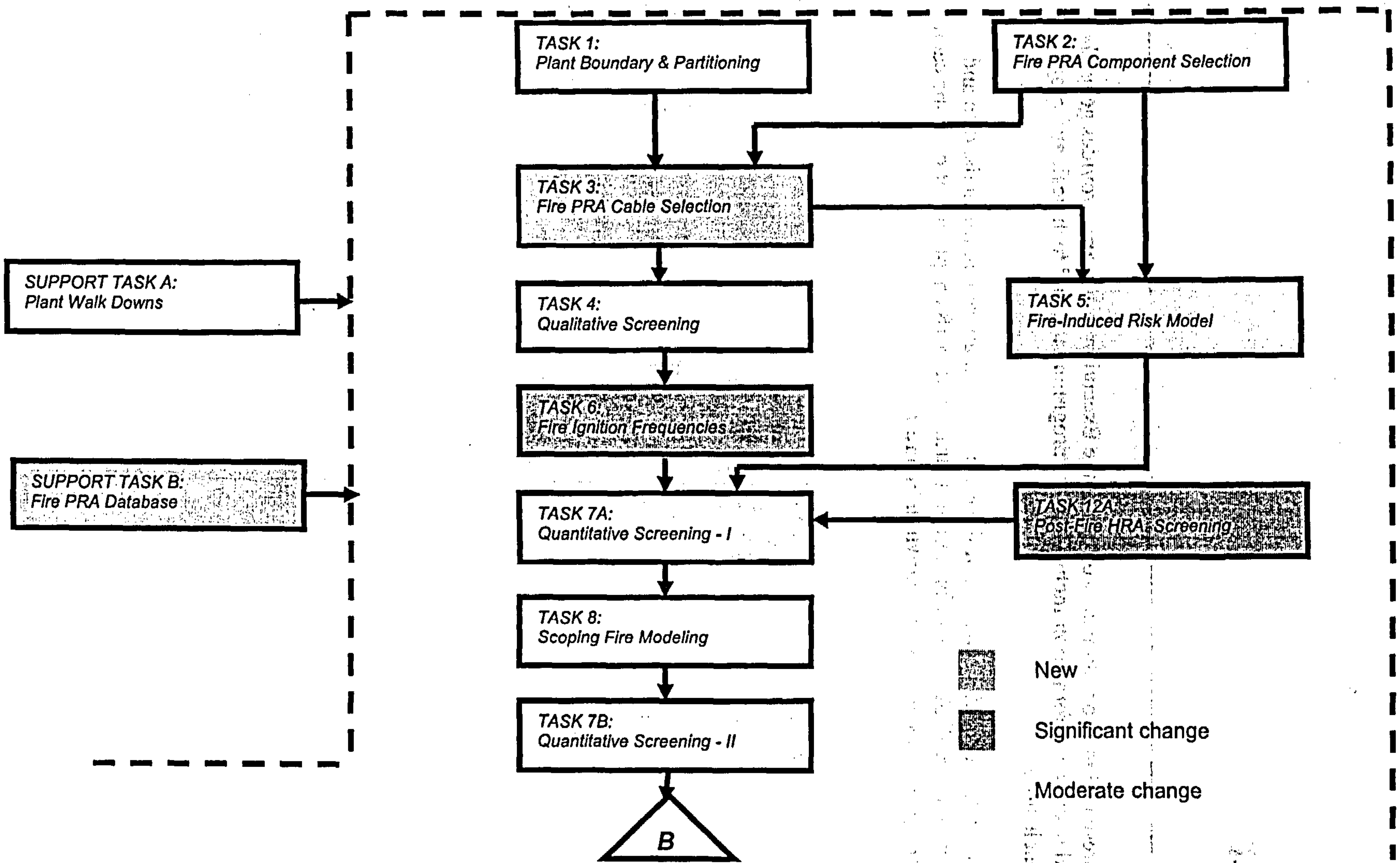

Figure 1
Overview of the Fire PRA Process

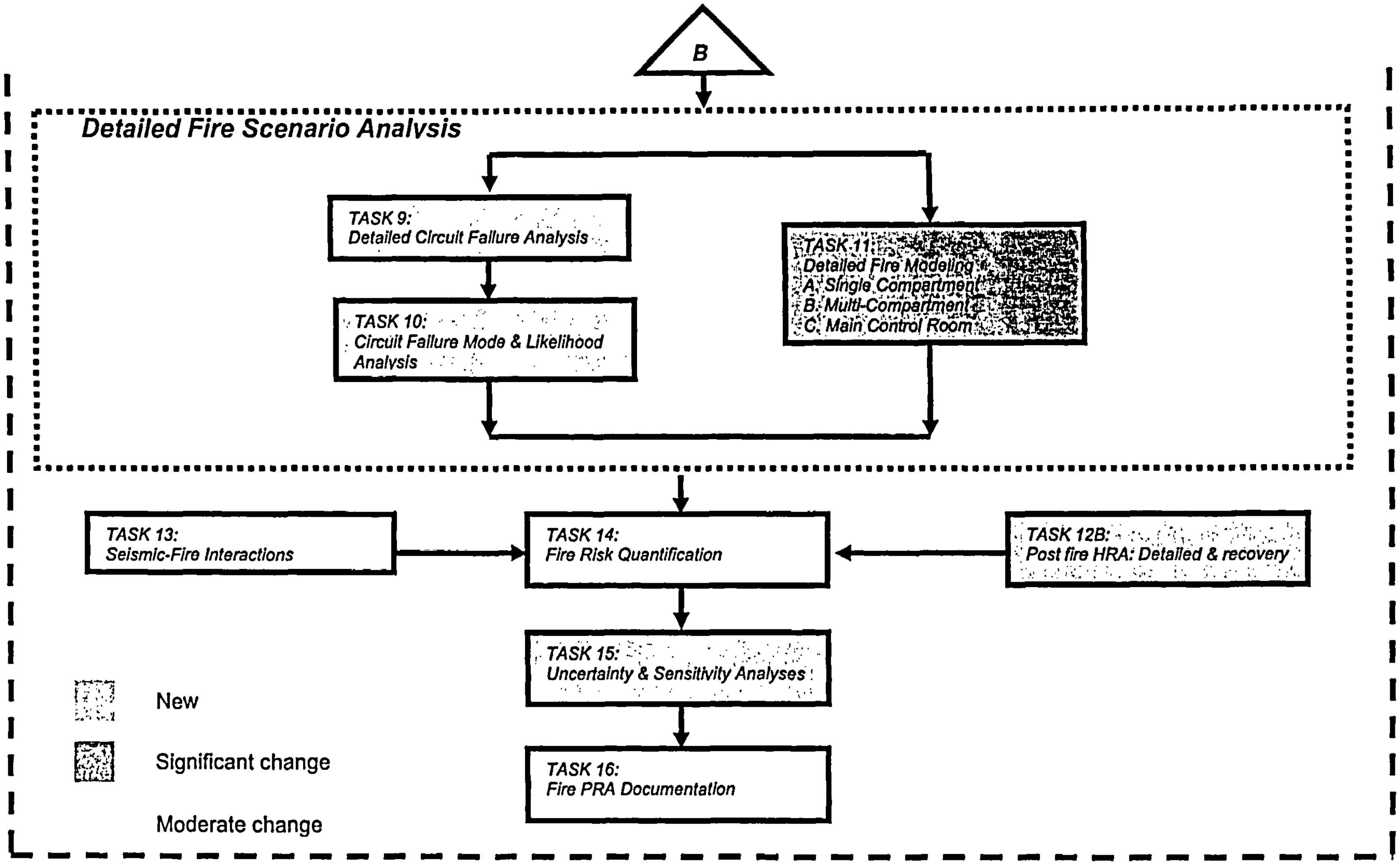

Figure 1
Overview of the Fire PRA Process (Continued)

FOREWORD

Fire probabilistic risk assessment (PRA) methods have been used in the Individual Plant Examinations of External Event (IPEEE) program to facilitate a nuclear power plant examination for vulnerabilities. However, in order to make finer, more realistic decisions for risk-informed regulation, Fire PRA methods needed to be improved. Licensee applications and U.S. Nuclear Regulatory Commission (NRC) review guidance with respect to many regulatory activities such as the risk-informed, performance-based fire protection rulemaking (endorsing National Fire Protection Association Standard 805) will benefit from more robust Fire PRA methods. In order to address the need for improved methods, the NRC Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI) embarked upon a program to develop state-of-art Fire PRA methodology.

Under a joint Memorandum of Understanding, RES and EPRI initiated a collaborative, results-oriented research program, the Fire Risk Requantification Study, with the primary objective to develop improved methodology for conducting Fire PRA for a nuclear power plant.

These studies address the full breadth of Fire PRA technical issues for power operations, and include consideration of large early release frequency. The current scope excludes low power/shutdown operations, spent fuel pool accidents, sabotage, and PRA Level 3 estimates of consequence.

Both RES and EPRI have provided specialists in fire risk analysis, fire modeling, electrical engineering, human reliability analysis, and systems engineering for methods development. These improved methods have been applied at pilot plant Fire PRAs to test their viability and effectiveness. Also, the associated procedures have been assessed for technical basis, practicality, and scope by technical review panels comprised of industry participants.

A formal technical issue resolution process was developed to direct the deliberative process between RES and EPRI. The process ensures that divergent technical views are fully considered, yet encourages consensus at many points during the deliberation. Significantly, the process provides that each party maintain its own point of view if consensus is not reached. Consensus was reached on all technical issues documented in this report.

The methodology documented in this report reflects the current state-of-the-art in Fire PRA. These methods are expected to form a basis for risk-informed analyses related to the plant fire protection program. However, such analyses rely upon an evaluation of the condition of fire protection systems and structures which is beyond this methodology, and may need interpretations of this methodology as well.

This document does not constitute regulatory requirements. RES participation in this study does not constitute or imply regulatory approval of applications based upon this methodology.

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LIST OF ACRONYMS

ACB	Air-cooled Circuit Breaker
ACRS	Advisory Committee on Reactor Safeguard
AEP	Abnormal Event Procedure
AFW	Auxiliary Feedwater
AGS	Assistance General Supervisor
AOP	Abnormal Operating Procedure
ATWS	Anticipated Transient Without Scram
BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
CCDP	Conditional Core Damage Probability
CF	Cable (Configuration) Factors
CCPS	Center for Chemical Process Safety
CCW	Component Cooling Water
CDF	Core Damage Frequency
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CLERP	Conditional Large Early Release Probability
CM	Corrective Maintenance
CR	Control Room
CRS	Cable and Raceway (Database) System

CWP	Circulating Water Pump
EDG	Emergency Diesel Generator
EF	Error Factor
EI	Erroneous Status Indicator
EOP	Emergency Operating Procedure
EPR	Ethylene-Propylene Rubber
EPRI	Electronic Power Research Institute
FEDB	Fire Events Database
FEP	Fire Emergency Procedure
FHA	Fire Hazards Analysis
FIVE	Fire-Induced Vulnerability Evaluation (EPRI TR 100370)
FMRC	Factory Mutual Research Corporation
FPRAIG	Fire PRA Implementation Guide (EPRI TR 105928)
FRSS	Fire Risk Scoping Study
FSAR	*Final Safety Analysis Report*
HEAF	High Energy Arcing Fault
HEP	Human Error Probability
HFE	Human Failure Event
HPI	High Pressure Injection
HPCI	High Pressure Coolant Injection
HRA	Human Reliability Analysis
HRR	Heat Release Rate
HTGR	High Temperature Gas-cooled Reactor
HVAC	Heating, Ventilation, and Air Conditioning
ICDP	Incremental Core Damage Probability

ILERP	Incremental Large Early Release Probability
INPO	Institute for Nuclear Power Operations
IPE	Individual Plant Examination
IPEEE	Individual Plant Examination for External Events
IS	Ignition Source
ISLOCA	Interfacing Systems Loss of Coolant Accident
KS	Key Switch
LCO	Limiting Condition of Operation
LERF	Large Early Release Frequency
LFL	Lower Flammability Limit
LOC	Loss of Control
LOCA	Loss of Coolant Accident
LPG	Liquefied Petroleum Gas
LWGR	Light-Water-cooled Graphite Reactors (Russian design)
MCC	Motor Control Center
MCR	Main Control Room
MG	Motor-Generator
MFW	Main Feedwater
MOV	Motor Operated Valve
MQH	McCaffrey, Quintiere and Harkleroad's Method
MS	Main Steam
NC	No Consequence
NEI	Nuclear Energy Institute
NEIL	Nuclear Electric Insurance Limited
NFPA	National Fire Protection Association

NPP	Nuclear Power Plant
NPSH	Net Positive Suction Head
NQ cable	Non-Qualified (IEEE-383) cable
NRC	Nuclear Regulatory Commission
P&ID	Piping and Instrumentation Diagram
PE	Polyethylene
PM	Preventive Maintenance
PMMA	Polymethyl Methacrylate
PORV	Power Operated Relief Valve
PRA	Probabilistic Risk Assessment
PSF	Performance Shaping Factor
PTS	Pressurized Thermal Shock
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
Q cable	Qualified (IEEE-383) cable
RBMK	Reactor Bolshoy Moshchnosty Kanalny (high-power channel reactor)
RCIC	Reactor Core Isolation Cooling
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RDAT	Computer program for Bayesian analysis
RES	The Office of Nuclear Regulatory Research (at NRC)
RHR	Residual Heat Removal
RI/PB	Risk-Informed / Performance-Based
RPS	Reactor Protection System
RWST	Refueling Water Storage Tank

SCBA	Self-Contained Breathing Apparatus
SDP	Significance Determination Process
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SMA	Seismic Margin Assessment
SO	Spurious Operation
SOV	Solenoid Operated Valve
SRV	Safety Relief Valve
SSD	Safe Shutdown
SSEL	Safe Shutdown Equipment List
SUT	Start-up Transformer
T/G	Turbine/Generator
TGB	Turbine-Generator Building
TSP	Transfer Switch Panel
UAT	Unit Auxiliary Transformer
VCT	Volume Control Tank
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre of Finland)
VVER	The Soviet (and now, Russian Federation) designation for light water pressurized reactor
XLPE	Cross-Linked Polyethylene
ZOI	Zone of Influence

1
INTRODUCTION

1.1 Background

Over the past decade, there has been a considerable movement in the nuclear power industry from prescriptive rules and practices towards broadened use of risk information to supplement decision-making. In the area of fire protection, this movement is evidenced by numerous initiatives by the U.S. Nuclear Regulatory Commission (NRC) and the nuclear community worldwide. In 2001, the National Fire Protection Association (NFPA) completed the development of NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants 2001 Edition" [1.1]. Effective July 16, 2004, the NRC amended its fire protection requirements to permit existing reactor licensees to voluntarily adopt fire protection requirements contained in NFPA 805 as an alternative to the existing deterministic fire protection requirements [1.2]. In addition, there is significant recent emphasis on risk-informed decision-making under the current 10 CFR 50 Appendix R rule [1.3] concerning changes to the plant's fire protection licensing basis, requests for exemption or deviation, and the evaluation of inspection findings.

During the 1990s, both the NRC Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) were active in the development of methods for fire risk analysis. EPRI, in particular, developed methods to support its utility members in the preparation of responses to Generic Letter 88-20, Supplement 4, Individual Plant Examination of External Events (IPEEE). This effort produced the Fire Induced Vulnerability Evaluation (FIVE) Method [1.4] and the Fire PRA Implementation Guide [1.5]. FIVE was reviewed by the NRC and approved (with certain conditions [1.6]) for use in the IPEEE program. The Fire PRA Implementation Guide was reviewed by the NRC during the IPEEE process and, following resolution of several issues, was ultimately accepted by NRC as meeting the IPEEE goals. Virtually every U.S. nuclear utility used one or both of these documents to perform their IPEEE fire analyses. However, in a broader context (i.e., for applications beyond the IPEEE process), a comprehensive effort to resolve comments and concerns was still needed. As a result of NRC's review of licensee submittals and based on their experience with the IPEEE program, the NRC raised a number of technical issues regarding FIVE and the Fire PRA Implementation Guide [1.5]. While the applied methods were deemed acceptable for accomplishing the objectives of the IPEEE, it became clear that they would need upgrades to support future Risk-Informed/Performance-Based (RI/PB) applications in fire protection.

1.2 Programmatic Overview

Under a joint Memorandum of Understanding [1.7], RES and EPRI initiated a collaborative project to document the state-of-the-art for conduct of a Fire PRA. This collaboration, known as the Fire Risk Requantification Study, brings together the wealth of information generated by the fire research programs at EPRI and RES in an environment that promotes deliberation of differing technical views, yet encourages consensus. This report is the result of this collaboration between EPRI and RES.

1.2.1 Program Objectives

The principal objective of the Fire Risk Requantification Study is to develop a technical basis and methodology that will clarify issues affecting application of fire risk methods. The project was designed to culminate in a joint EPRI/RES publication of state-of-the-art Fire PRA methodology. In effect, this document will serve as a revision to the EPRI Fire PRA Implementation Guide [1.5]. This document represents the second full publication of this revision, the first having been published as a draft for public comment in October 2004.

This report is a compendium of methods, data and tools to perform a fire probabilistic risk assessment and develop associated insights. It is expected that this methodology will have broad use across many different types of analysis issues, including those related to permanent changes to the fire protection program and temporary conditions.

Specific objectives of this effort are as follows:

- Develop methodology for conducting a Fire PRA at NPPs. This methodology will provide insights regarding the applicability of results generated using earlier fire risk analysis methods, tools, and data; the Fire PRA technical issues identified in past NPP Fire PRAs; and practical limitations and constraints in the application of the RES and EPRI research results;
- Develop state-of-the-art fire risk estimates that reflect the use of the improved Fire PRA methods, tools, and data developed since publication of the EPRI FIVE and Fire PRA methods;
- Determine the qualitative and quantitative impact on predicted fire risk associated with the use of these improved Fire PRA methods, tools, and data;
- Develop insights on strengths and weaknesses of the Fire PRA models and results;
- Provide specific insights on the elements of a Fire PRA expected to form the basis for RI/PB applications in fire protection; and
- Transfer the technology through workshops and training courses.

Note that this report does *not* address the verification and validation (V&V) process for computational fire models. A separate project is currently underway involving the RES and EPRI to V&V a select set of commonly applied computational fire models[1] in accordance with the requirements described in the ASTM E 1355-04, "Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models". Once completed, a joint EPRI and RES report will be prepared offering the results of this project for review and publication.

The Fire PRA Methodology documented in this report complements, but does not overlap with, the Fire Model V&V project. This document provides instructions for identification and characterization of fire scenarios, including the selection of key fire modeling input parameters. It also describes the types of fire modeling information needed to support the Fire PRA, and provides a framework for the incorporation of fire modeling results. In those cases where computational fire models are currently unable to address the fire behaviors of interest, this report provides empirical rule sets for the development and analysis of fire scenarios. However, with the notable exception of the probabilistic Main Control Board (MCB) approach documented in Appendix L, and the flame spread and cable tray heat release rate models documented in Appendix R, this report does not rely on specific computational fire modeling tools. In fact, this report is not intended as a reference for the selection and/or evaluation of specific computational fire modeling tools. The responsibility for the selection of appropriate computational fire models lies with the PRA analyst, including providing a V&V basis for the selected tools.

Note that the term "fire model" is defined rather broadly in this document to refer to any one of a wide range of tools used to characterize and analyze fire scenarios. The NRC-RES/EPRI fire model V&V project is focused on verification and validation of five commonly used computational fire models.

1.2.2 Program Approach

The Fire Risk Requantification Study involved two Technical Development Teams, one representing EPRI and the second representing RES. Each Technical Development Team includes an overall Technical Program Manager, and four individual Technical Area Experts collectively representing the key technical disciplines: fire analysis, plant systems and PRA systems analysis, electrical circuit failure modes and effects analysis, and human reliability analysis (HRA). The primary responsibility of the Technical Development Teams was to document (and/or develop) state-of-the-art Fire PRA methods, tools, and data and to seek resolution for methodological issues related to their areas of expertise. Although the principal intent was to document the state-of-the-art rather than conduct further research, the Technical Development Teams did advance the state-of-the-art where realism and defensibility could be improved with limited and focused investigations.

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[1] The current compliment of computational fire modeling tools being addressed in the V&V effort are FIVE-Rev 1 developed by EPRI (EPRI 1002981), the Fire Dynamics Tools (FDTs) developed by the NRC (NUREG-1805), the French zone fire model MAGIC developed by Electricite De France, the zone fire model CFAST developed by NIST, and the computational fluid dynamics model Fire Dynamics Simulator (FDS) developed by NIST.

The Technical Development Teams also led the demonstration studies in cooperation with the pilot plants. The pilot plants provided on-site, plant-specific knowledge and support. Technical area experts worked with counterparts among the pilot plant staff to complete the demonstration studies. The demonstration studies provided a vehicle for testing of the proposed procedures against actual plant configurations and situations. Insights gained through the demonstration studies supported further refinements of the methods. In parallel with the EPRI and RES Technical Development Teams' efforts to write procedures and perform demonstration studies, staff from the non-pilot participant utilities acted as an industry peer review team. The peer reviewers commented on working drafts of the proposed procedures. The Technical Area Experts considered comments, and the procedures were modified as deemed necessary and appropriate.

1.2.3 Program Structure and Status

This project is being executed in four phases, of which the first two have been completed. The first phase involved the initial documentation and development of state-of-the-art Fire PRA methods, tools, and data. This included the conduct of demonstration studies at two pilot plants that participated in close cooperation with the EPRI and RES Technical Development Teams. The first phase also included a peer review process supported by the non-pilot participating utilities. The second phase involved publication of this first full version of the EPRI/NRC-RES Fire PRA Methodology. Phase III, which is currently underway, consists of demonstration studies conducted at a third pilot plant with substantial involvement with the EPRI and RES Technical Development Teams, and a fourth independent pilot plant. Phase III will also include the incorporation of insights from these additional pilot studies and publication of a revision to this report in 2005. Phase IV, also not yet completed, will involve technology transfer in the form of workshops and training courses.

1.3 Technical Process Overview

1.3.1 Technical Issue Resolution

A formal technical resolution process was designed to direct the deliberative process between RES and EPRI. The process ensures that divergent technical views are fully considered, yet encourages consensus at many points during the deliberation. If, in the end, a consensus could not be reached, each entity could maintain their positions. In practice, no such cases were encountered and consensus positions between the EPRI and RES Technical Development Teams were reached for all tasks.

The technical resolution process worked as follows. Initially, the EPRI and RES counterpart Technical Area Experts would work together to develop a general task analysis process, including identification of the critical issues and how they will be addressed. These process descriptions were then circulated within the two Technical Development Teams for review. This step ensured that all issues of concern, including task interactions, were addressed. Then the EPRI and RES Technical Area Experts drafted an analysis task procedure to document the approach and technical bases needed to support the analysis task. The EPRI and RES Technical

Development Teams then reviewed these procedures. The process was designed in particular to ensure that task and discipline interfaces were identified and treated in a consistent manner.

If opposing views were expressed during this process within the EPRI and/or RES Technical Development Teams, the opposing views were discussed and resolved within the Technical Development Teams. If the two counterpart Technical Area Experts could not agree, the EPRI and RES Technical Program Managers would moderate further debate seeking a team consensus. If consensus was still not reached the EPRI and RES Project Managers would moderate further debate. Differing positions would be documented if consensus was not reached at the Project Manager level.

1.3.2 Peer Review

An extensive peer review process was implemented in parallel with the methods development efforts of the EPRI and RES Technical Development Teams. Participants in the peer review team were drawn from the utilities participating in the collaborative project including both the pilot plants and the non-pilot participants. The scope of the peer review included the recommended analysis methods themselves, the use and interpretation of supporting data, the appropriateness of underlying assumptions, and the adequacy of the procedural documentation.

The peer review team was involved at three separate stages of the development process as follows.

- The methods development process began when the Technical Area Experts issued a statement of intent to begin development of an analysis task procedure (step by step instructions covering a particular aspect of the overall analysis method). The peer review team was asked to provide recommendations relating to the scope and content of the proposed analysis task procedure.
- Draft analysis task procedures were initially developed by the responsible Technical Area Experts and reviewed by other members of the EPRI and RES Technical Development Teams. Once completed, an initial draft was circulated to the peer review team for comment. For some tasks, two or more iterations of this part of the peer review process were undertaken. These efforts typically included discussion of the comments and proposed alternatives or resolutions with the commenter(s).
- The responsible Technical Area Experts addressed peer review comments and generated a final draft of each analysis task procedure. Insights and lessons learned from the demonstration studies were also incorporated in the analysis task procedures. A final draft of the full set of analysis task procedures was circulated to the peer review team for further comment.

All comments and recommendations from the peer review team were documented on an electronic form. Technical Development Team actions relevant to comment resolution were also recorded on these electronic forms. The Technical Development Team implemented all recommendations judged to be technically defensible. The majority of peer review recommendations were implemented. If the initial exchange between the peer reviewers and the Technical Area Experts did not resolve comments to the satisfaction of the commenter(s), the EPRI and RES Technical Program Managers moderated further debate. In the end, the EPRI and NRC Technical Development Teams would take their final positions, generally a consensus position within the two Technical Development Teams. If this final team position did not satisfy the commenter, the Technical Development Teams would maintain their recommended position and acknowledge the unresolved comment.

1.3.3 Role of the Demonstration Studies

Development of the methods included conduct of demonstration studies at two pilot plants. The demonstration studies were used to test the viability of the proposed methods, provide feedback, and gain risk insights. At the outset, it was intended that the demonstration studies would be complimented by full-scope Fire PRAs to be completed by each pilot plant.

The demonstration studies were intended to collectively represent a complete demonstration of all of the analysis task procedures. The intent was to follow a select set of plant fire scenarios through the entire analysis process, i.e., a "top-to-bottom slice" of the complete Fire PRA. In practice, neither of the two pilot plants has followed through with completion of their Fire PRA. There is a great deal of inter-dependency between various analysis task procedures. Given that some of the key tasks were not carried to completion by the pilot plants, some of the demonstration studies were conducted based on incomplete (and potentially inaccurate) information. While the proposed methods were each tested in full or in part, this was done in a somewhat piecemeal, rather than integrated, fashion. Given that a complete top-to-bottom slice of the Fire PRA was not achieved, the ability to gain specific and quantitative risk insights was correspondingly limited. Many risk insights were gained (see Chapter 3), although these insights relate to specific pieces of the analysis process rather than the implications of the overall process. However, insights related to the impact of the proposed procedures on overall plant fire risk estimates were not acquired.

1.4 Intended Audience and Needed Expertise

This document is aimed primarily at Fire PRA practitioners involved in the analysis of NPP fire risk. Conduct of a Fire PRA needs a team effort. No single individual can bring the full range of expertise and knowledge needed to complete the Fire PRA. Hence, this report is intended to serve the needs of a Fire PRA team by providing a structured framework for conduct and documentation of the analysis. The document includes specific recommended practices reflecting the current state-of-the-art that address each key aspect of the analysis. This document pays particular attention to task interfaces and interactions between the various disciplines that should be addressed. Such attention is somewhat lacking in prior methodology documents. Successful integration of the team activities is critical to overall success of the Fire PRA.

The fire risk analysis team should include individuals with expertise in four key areas. While one individual may be capable of covering all aspects of a given discipline, it is also likely that more than one individual will be needed to fill the cited role. The needed areas of expertise are as follows.

- *Fire analysis* involves a number of subsidiary areas of expertise. Fire protection engineering expertise is needed, including specific knowledge of the NPP fire protection strategies, systems, and features, as well as the plant's fire protection regulatory compliance practices and documentation. The fire analysis discipline also should encompass an understanding of basic fire behavior and fire modeling. In general, the proposed methods are dependent on the application of fire modeling tools ranging from closed-form engineering correlations to integrated compartment fire models (e.g., zone models or fire field models). Expertise in the fire modeling tools chosen to support a particular analysis is necessary.
- *General PRA and plant systems analysis* expertise and knowledge of plant design and operation is necessary. This discipline also includes system interactions and dependency analysis, system reliability analysis, system success criteria definition, and plant accident sequence analysis. Like internal events PRA, Fire PRA is typically dependent on the application of event tree/fault tree analysis, and the PRA discipline includes this area of expertise. A specific knowledge of the plant's internal events PRA and the plant's normal and abnormal operating strategies including post-fire safe shutdown (SSD) will also be necessary.
- *Human reliability analysis (HRA)* involves the general assessment and quantitative analysis of plant-specific, post-fire SSD operator actions. Hence, the needs in this discipline area include knowledge of plant practices relating to operations, staffing, training, emergency preparedness, general emergency operating procedures, and fire-specific operating procedures. The HRA expert should assist the PRA analyst to incorporate human actions in the plant post-fire SSD response model, including the identification of key operator inputs (e.g., key instrumentation, indications, and controls). The likelihood that credited manual actions might fail should then be quantified at both a screening and detailed level.
- *Electrical analysis* involves circuit failure modes and effects analysis conducted for specific plant circuits. This discipline supports several aspects of the analysis, including the selection of circuits and systems, cable and component routing, development of the Fire PRA database, development of the plant post-fire SSD response model, and quantification of failure mode likelihood values. Individual(s) performing these activities should have a sound working knowledge of electrical engineering principles and knowledge of the plant's post-fire SSD strategies and supporting analyses. Knowledge of cable failure modes and effects is also critical.

1.5 Estimate of Resources to Conduct a Fire PRA Using this Methodology

This report is a documentation of the state-of-the-art for conduct of a Fire PRA. A user may chose to pursue varying levels of depth while implementing the recommended methods, depending on the intended application of the Fire PRA. This section is intended to provide decision-makers with an estimate of the nominal range of resources they should expect to spend in the conduct of a Fire PRA project using this document, as well as the key factors that introduce the uncertainty into these estimates.

Based on experience with the demonstration studies and the collective experience of the authors of this methodology, at least 4000 engineering hours would be needed to perform a complete plant-wide Fire PRA using the methods recommended in this report. This estimate is predicated on a large number of positive factors in terms of the quality of the plant analyses and the level of sophistication desired in the Fire PRA. The upper bound, on the other hand, is significantly harder to pin down. An industry average case could have an upper bound estimate of approximately 7000 engineering hours.

The largest sources of uncertainty in estimating needed resources derives from efforts associated with selection, tracing, and, to a lesser extent, the failure modes analysis of the circuits and cables included in the Fire PRA SSD plant response model. Of these three tasks (selection, tracing, and analysis of circuits and cables), the most significant single source of uncertainty derives from the scope of the cable tracing effort needed to support the analysis. Pre-existence of readily accessible cable and component routing information can substantially lower the level of effort necessary to complete the Fire PRA. The level of effort expended on these three tasks can easily vary by one order of magnitude - from 600-6000 hours. For the remaining tasks, the level of effort estimates would vary by no more than a factor of two.

The low-end manpower estimate for the circuit and cable selection, tracing, and analysis efforts (600 hours) represents a case where the following three factors apply:

- The plant has a pre-existing state-of-the-art deterministic post-fire SSD analysis;
- There is a pre-existing and well-documented electronic system for tracing the 10 CFR 50 Appendix R cables and components; and
- There is a pre-existing and well-documented Fire PRA SSD plant response model that includes primarily those components credited in the 10 CFR 50 Appendix R SSD analysis supplemented only by those components whose failure (e.g., including multiple spurious operations) might compromise the credited functions.

The upper end of the manpower estimates for the circuit and cable selection, tracing, and analysis efforts (6000 hours) represents a case where the following three conditions apply:

- The plant has a pre-existing deterministic post-fire SSD analysis that has not undergone significant review and/or revision since it's original development;
- The plant has a paper (non-electronic) cable and raceway system (CRS) and/or 10 CFR 50 Appendix R database; and
- The Fire PRA SSD plant response model is intended to include at least all components that are credited in the internal events PRA.

Note that the upper-end manpower estimate does not explicitly account for revising existing 10 CFR 50 Appendix R analyses and databases. Although the conduct of Fire PRA related circuit and cable selection, tracing, and analysis activities would certainly provide a substantial "head start" on any intended 10 CFR 50 Appendix R re-baselining effort.

1.6 Report Structure

This report is presented in two volumes. Volume 1 provides general background and overview information, including both programmatic and technical overviews. Chapter 1 of Volume 1 has provided the programmatic overview and other general background information. Chapter 2 provides an overview of the analysis process, including general descriptions of each technical task. Chapter 3 discusses technical insights gained to date, including a comparison of previous methods to the current recommended practice, an overview of general technical insights, and recommendations related to remaining technical challenges and areas of analysis where additional work might be appropriate.

Volume 2 provides the detailed discussion of recommended methods, data, and tools. Each chapter in Volume 2 focuses on one analysis task. Each task is described in detail. Input and output relationships between tasks are also identified. Volume 2 also includes numerous appendices detailing various aspects of the analysis, defining recommended input values, and documenting the technical bases.

1.7 References for Chapter 1

1.1 Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plant, National Fire Protection Association, Brainerd, MA, Standard 805, 2001 Edition.

1.2 Voluntary Fire Protection Requirements for Light Water Reactors, USNRC, 10 CFR Part 50, RIN 3150-AG48, Federal Register, June 16, 2004 (Volume 69, Number 115).

1.3 Title 10 of the Code of Federal Regulations (10 CFR) part 50.48, "Fire protection", Appendix R, "Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979."

1.4 *Fire-Induced Vulnerability Evaluation (FIVE),* EPRI, April 1992. EPRI TR-100370.

1.5 *Fire PRA Implementation Guide*, EPRI, December 1995. EPRI TR-105928 (Including Supplement: EPRI SU-105928).

1.6 Perspective Gained From the Individual Plant Examination of External Events (IPEEE) Program, U.S. NRC, Washington, DC, NUREG-1742, April 2002.

1.7 Memorandum Of Understanding (MOU) on Cooperative Nuclear Safety Research Between ERPI and NRC, Amendment on Fire Risk, Revision 1, 2001.

2
OVERVIEW OF THE FIRE PRA METHODOLOGY

2.1 General Scope

The methodology in this document describes the process and the technical bases for the performance of a Fire PRA that focuses on a Level 1 PRA (core damage frequency - CDF) with consideration of large early release frequency (LERF). The scope of this methodology does not include:

- Fire risk during shutdown and low power modes of operation,
- Accidents not related to the reactor core, such as spent fuel pool accidents,
- Sabotage, and
- Level 3 PRA (including offsite release and consequences).

2.2 Overview of the Fire PRA

The methodology described in this document follows a process that, in principle, is similar to the methods used in the past, for example, as documented in the EPRI Fire PRA Implementation Guide [2.1], NUREG-1150 [2.2], and NUREG/CR-4840 [2.3].

Figure 2-1 shows the overview of the Fire PRA process described in this report. The color-coding in this figure is intended to visually indicate improvements over previous methods, such as EPRI FIVE and Fire PRA Implementation Guide. The following considerations are important in the use of this figure.

- A Fire PRA is iterative, i.e., certain tasks may need refinement after conduct of one or more of the subsequent tasks. It may also be appropriate to incorporate only limited detail in the first pass through an analysis task, deferring the pursuit of additional detail pending the results of a later task. For example, the number of components and circuits credited in Tasks 2 and 3 is likely to be revised after attempts at screening in Tasks 4 and 7. The flow chart in Figure 2-1 does not attempt to incorporate potential feedback loops. There is a potential for feedback loops at virtually every stage of analysis, each potentially returning to almost any earlier stage of analysis. To illustrate all of the potential feedback paths would render the figure unreadable. Analyst judgment is needed to ensure that an appropriate overall analysis process is followed consistent with study objectives.

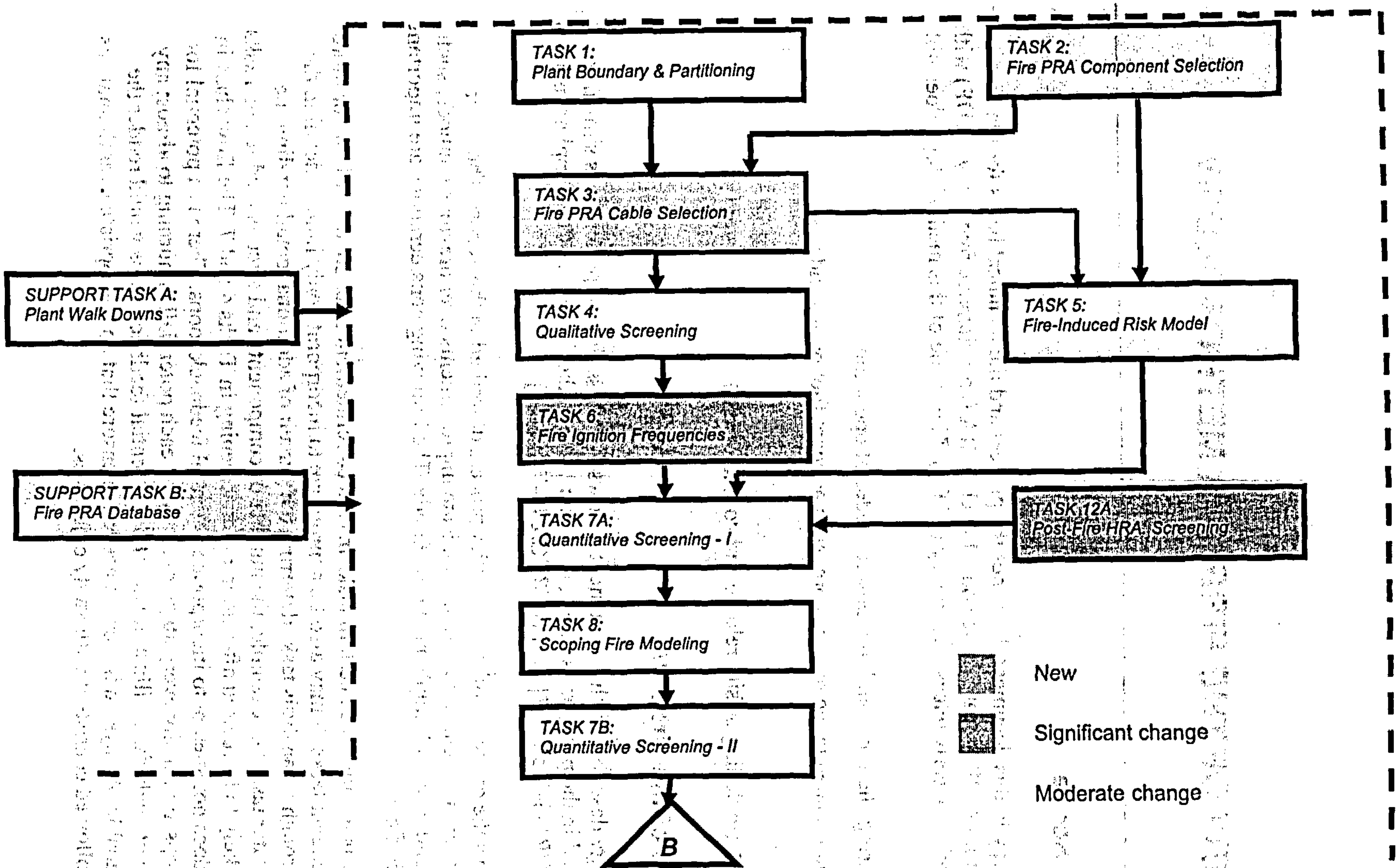

Figure 2-1
Overview of the Fire PRA Process

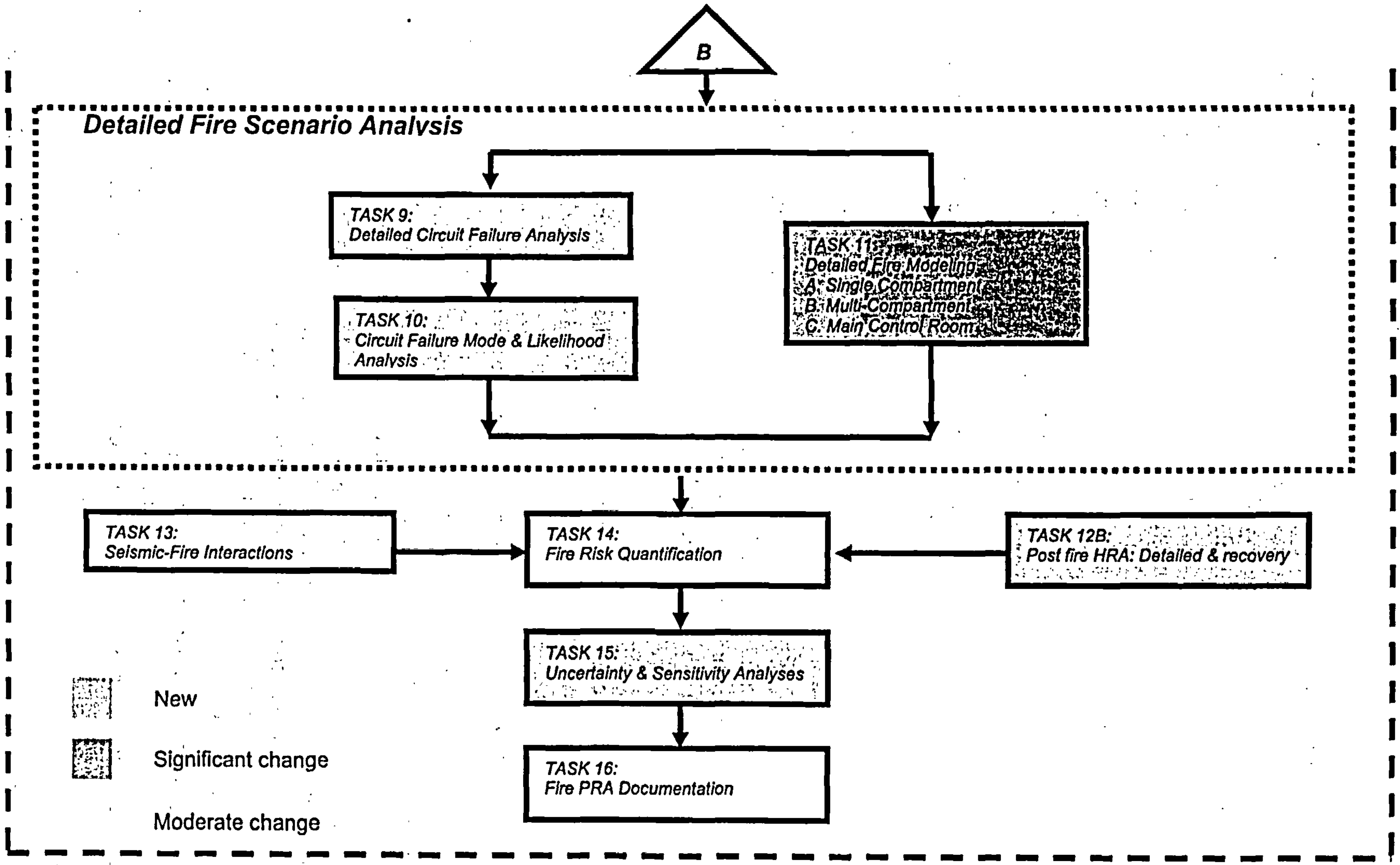

Figure 2-1
Overview of the Fire PRA Process (Continued)

- Even though the process flow illustrated in Figure 2-1 should work for predominant cases, users may find other analysis task sequences to be more appropriate for their objectives. Task sequence choices may, for example, be influenced by plant-specific fire protection features as well as the availability and depth of plant information supporting the Fire PRA. Each analysis task incorporates added detail into a given aspect of the Fire PRA. Task ordering is subject to practitioner judgment. The analyst may implement alternative task ordering when such alterations provide a more efficient or more effective process. Indeed, the task ordering applied to one set of fire scenarios may differ from that used in another set of scenarios within the same overall analysis. Such alterations are acceptable, as long as the principal task interactions described in each analysis task procedure are satisfied and overall consistency is maintained.

The following is a short description of each technical task for the overall Fire PRA methodology. For further details, refer to the individual task descriptions in Volume 2.

- *Plant Boundary Definition and Partitioning (Task 1).* The first step in a Fire PRA is to define the physical boundary of the analysis, and to divide the area within that boundary into analysis compartments.
- *Fire PRA Component Selection (Task 2).* The selection of components that are to be credited for plant shutdown following a fire is a critical step in any Fire PRA. Components selected would generally include any and all components credited in the 10 CFR 50 Appendix R post-fire SSD analysis. Additional components will likely be selected, potentially including any and all components credited in the plant's internal events PRA. Also, the proposed methodology would likely introduce components beyond either the 10 CFR 50 Appendix R list or the internal events PRA model. Such components are often of interest due to considerations of combined spurious actuations that may threaten the credited functions and components.
- *Fire PRA Cable Selection (Task 3).* This task provides instructions and technical considerations associated with identifying cables supporting those components selected in Task 2. In previous Fire PRA methods (such as EPRI FIVE and Fire PRA Implementation Guide) this task was relegated to the SSD analysis and its associated databases. This document offers a more structured set of rules for selection of cables.
- *Qualitative Screening (Task 4).* This task identifies fire analysis compartments that can be shown to have little or no risk significance without quantitative analysis. Fire compartments may be screened out if they contain no components or cables identified in Tasks 2 and 3, and if they cannot lead to a plant trip due to either plant procedures, an automatic trip signal, or technical specification requirements.
- *Plant Fire-Induced Risk Model (Task 5).* This task discusses steps for the development of a logic model that reflects plant response following a fire. Specific instructions have been provided for treatment of fire-specific procedures or preplans. These procedures may impact availability of functions and components, or include fire-specific operator actions (e.g., self-induced-station-blackout).
- *Fire Ignition Frequency (Task 6).* This task describes the approach to develop frequency estimates for fire compartments and scenarios. Significant changes from the EPRI FIVE

method have been made in this task. The changes generally relate to use of challenging events, considerations associated with data quality, and increased use of a fully component-based ignition frequency model (as opposed to the location/component-based model used, for example, in FIVE).

- *Quantitative Screening (Task 7).* A Fire PRA allows the screening of fire compartments and scenarios based on their contribution to fire risk. This approach considers the cumulative risk associated with the screened compartments (i.e., the ones not retained for detailed analysis) to ensure that a true estimate of fire risk profile (as opposed to vulnerability) is obtained.
- *Scoping Fire Modeling (Task 8).* This step provides simple rules to define and screen fire ignition sources (and therefore fire scenarios) in an unscreened fire compartment.
- *Detailed Circuit Failure Analysis (Task 9).* This task provides an approach and technical considerations for identifying how the failure of specific cables will impact the components included in the Fire PRA SSD plant response model.
- *Circuit Failure Mode Likelihood Analysis (Task 10).* This task considers the relative likelihood of various circuit failure modes. This added level of resolution may be a desired option for those fire scenarios that are significant contributors to the risk. The methodology provided in this document benefits from the knowledge gained from the tests performed in response to the circuit failure issue.
- *Detailed Fire Modeling (Task 11).* This task describes the method to examine the consequences of a fire. This includes consideration of scenarios involving single compartments, multiple fire compartments, and the main control room. Factors considered include initial fire characteristics, fire growth in a fire compartment or across fire compartments, detection and suppression, electrical raceway fire barrier systems, and damage from heat and smoke. Special consideration is given to turbine generator (T/G) fires, hydrogen fires, high-energy arcing faults, cable fires, and main control board (MCB) fires. There are considerable improvements in the method for this task over the EPRI FIVE and Fire PRA Implementation Guide in nearly all technical areas.
- *Post-Fire Human Reliability Analysis (Task 12).* This task considers operator actions for manipulation of plant components. The analysis task procedure provides structured instructions for identification and inclusion of these actions in the Fire PRA. The procedure also provides instructions for estimating screening human error probabilities (HEPs) before detailed fire modeling results (e.g., fire growth and damage behaviors) have been developed. Estimating HEP values with high confidence is critical to the effectiveness of screening in a Fire PRA. This report does not develop a detailed fire HRA methodology. There are a number of HRA methods that can be adopted for fire with appropriate additional instructions that superimpose fire effects on any of the existing HRA methods, such as SHARP, ATHEANA, etc. This would improve consistency across analyses i.e., fire and internal events PRA.
- *Seismic Fire Interactions (Task 13).* This task is a qualitative approach to help identify the risk from any potential interactions between an earthquake and fire.
- *Fire Risk Quantification (Task 14).* The task description provides recommendations for quantification and presentation of fire risk results.

- ***Uncertainty and Sensitivity Analyses (Task 15).*** This task describes the approach to follow for identifying and treating uncertainties throughout the Fire PRA process. The treatment may vary from quantitative estimation and propagation of uncertainties where possible (e.g., in fire frequency and non-suppression probability) to identification of sources without quantitative estimation, where knowledge of a quantitative treatment of uncertainties is beyond the state-of-the-art. The treatment may also include one-at-a-time variation of individual parameter values to determine the effect on the overall fire risk (sensitivity analysis).
- ***Fire PRA Documentation (Task 16).*** This provides suggestions for documenting a Fire PRA.

The set of analysis procedures provided in Volume 2, to a large extent, represent a single integrated analysis procedure. Many of the analysis tasks have been built around the foundations and assumptions of other inter-related tasks. The maintenance of task-to-task consistency is a requirement of any quality Fire PRA. Hence, the user should be very cautious whenever an alternative approach is undertaken. In particular, piece-meal modifications to task approaches, assumptions, recommended numerical values, or procedures may introduce inconsistencies or untreated dependencies. The authors acknowledge that alternative analysis methods do exist, and that their incorporation into the overall analysis framework presented here may be appropriate. However, implementation of an alternative approach to any given aspect of the analysis should include explicit consideration of the implications for other tasks. It is the analyst's responsibility to ensure that analysis consistency and task independence is maintained, or that any dependencies introduced are appropriately treated.

2.3 General Assumptions and Technical Positions

There are a number of general assumptions that govern this methodology and positions relevant to the application of these methods. These assumptions and positions are summarized in this section. Note that this section is not intended to provide an exhaustive listing of analysis assumptions. Each task procedure (see Volume 2) discusses relevant assumptions. The discussion here is intended only to highlight certain key aspects of the method that reflect a substantive change in analysis approach and/or high-level methodological limitations.

2.3.1 Component Selection and Fire-Induced Risk Model

2.3.1.1 General Component Selection Process

The methodology related to component selection and development of the Fire PRA model for post-fire SSD response is substantially more explicit than has been typical of past Fire PRA methodology documents. Past practice has typically given analysts wide latitude to choose which systems and functions, and which specific components, to include in the SSD response model. Component selection still involves analyst judgment, but the new approach provides a structured approach to this task that is specific to the risk analysis context. The approach is designed to ensure that those components whose failure or mal-operation may compromise a credited system or function are also included in the model. Reliance on less complete or less structured methods (e.g., past practice) could lead to the development of an optimistic SSD response model.

2.3.1.2 Post-Fire SSD Procedures

Past practice has been inconsistent in the treatment of fire-specific SSD operating procedures. For many plants, the fire-specific procedures are substantially different from the general emergency operating procedures. Use of the internal events plant response model, which considers only the general emergency operating procedures, is likely to lead to inaccurate fire risk predictions particularly for those plants with fire-specific procedures and pre-plans. In this document, the analyst is directed to incorporate any fire-specific operating procedures into the fire-induced risk model. In some cases, it may be necessary to consider both the general and fire-specific SSD procedures, and to assess operator transition from one set of procedures to the other.

2.3.1.3 Inclusion of Instrument Circuits

The impact of fire-induced spurious indications on operator performance (not just on system response) may be significant; hence there is a need to list and model key diagnostic equipment failures (especially where little to no redundancy exists) in the Fire PRA. This unique Fire PRA step is necessary and goes beyond the systems response modeling done for the Internal Events PRA where the diagnostic instrumentation is largely assumed to be available. Special treatment in Fire PRA is necessary because the fire-induced failure probability may be orders of magnitude greater than the random failure probability (which is generally very low).

2.3.2 Circuit Selection and Analysis

The selection, routing, and failure analysis of cables and circuits have not generally been covered by past Fire PRA methodology documents such as Reference 2.1. These aspects of previous Fire PRAs have typically relied on other existing plant documentation, databases, and analyses, and in particular, have relied on the 10CFR Appendix R related databases and analyses. This document provides an approach for cable and circuit selection and analysis for two specific reasons:

- There was a need to re-examine some of the scope and approach issues applied to circuit selection and analysis within the context of risk. The approach recommended in this document is, for the most part, consistent with current industry best practice with the added benefit that risk perspectives are used to streamline the process.
- One specific objective of this project was to develop a single comprehensive document that brings together the best current practices and state-of-the-art relevant to conduct of a Fire PRA.

2.3.2.1 Proper Polarity Three-Phase Hot Shorts on AC Power Conductors

In developing analysis rules for three-phase proper polarity hot shorts, three cases were considered and an approach for each case developed. The three cases are summarized below. Detailed discussions are provided in the associated analysis task procedures.

Case 1: Grounded AC System with Thermoset-Insulated Cable: Three-phase proper polarity hot shorts are evaluated as extremely low probability events for grounded three-phase AC power systems. It is the opinion of the Technical Development Teams that this failure mode is not risk significant. It is recommended that this failure mode not be included in the Fire PRA cable selection process for grounded three-phase AC circuits involving thermoset-insulated cable.

Case 2: Ungrounded AC System or Thermoplastic-Insulated Cable: For ungrounded systems and thermoplastic-insulated cable, it can be reasoned that three-phase proper polarity hot shorts are of low probability, but not as low as that for grounded systems with thermoset cable (Case 1). It cannot be conservatively argued that the failure mode likelihood is low enough to screen out for all cases. It is recommended that for these configurations, three-phase proper polarity hot shorts should be considered only for high consequence equipment. See volume 2, section 2.5.6 for the definition of high consequence equipment.

Case 3: Armored Cable or Cable in Dedicated Conduit: Three-phase proper polarity faults are not considered credible for armored power cables or for a single triplex cable in a dedicated conduit.

2.3.2.2 Circuit Selection and Analysis – System-Wide Safety Signals.

The systematic treatment of system-wide safety signals (e.g., safety injection, containment isolation, feedwater actuation, etc.) is difficult. These signals are manifested as auxiliary contacts within the control circuits of important plant equipment. Integrating logic combinations of instrument circuit failures that might trigger a safety signal in the context of scenario specific failure modes exceeds the capability of analytical tools generally available to a plant (for example, rolling up the combined instrument circuit failures of a two-out-of-three logic network for a containment isolation signal). Consequently, this aspect of circuit analysis is treated qualitatively, rather than quantitatively, in this report.

2.3.2.3 Multiple High-Impedance Faults

The recommended method does not include quantitative assessment of multiple high-impedance faults that may cause circuit protection features to activate (e.g., breaker opens or fuse blows) above the first level of electrical protection for the cables assumed to be threatened by the fire. The multiple high impedance fault mode for electrical power circuits is considered to be of a very low likelihood based on:

- The narrow range of fault quality (i.e., insulation resistance of the fault) needed to create a sustained fault current below the first level of circuit protection, and

- The need to have multiple sustained faults of the necessary fault quality.

2.3.3 Fire Frequency and Fire Modeling Assumptions

The fire frequency estimates, fire severity estimates, and fire severity approach are considered an integral set. That is, the fire frequencies have been estimated using an analysis and event screening approach that is explicitly tied to the subsequent assumptions relating to fire severity characteristics. The fire frequency estimates cited in this report are based on the assumption that only a subset of the reported fire events is risk-relevant. In particular, the screening of fire events as non-challenging or potentially challenging (i.e., for exclusion from or inclusion in the fire frequency estimates) includes some implicit credit for factors that have in some past studies been credited through a fire severity factor. Thus, the assumed fire severity characteristics reflect the fire event set retained in the fire frequency calculations. Any alterations to either the fire frequency value or the fire severity characteristics approach should be considered in this joint context. The authors recommend that practitioners exercise extreme caution in this regard.

2.3.4 Low Likelihood Fires

A state-of-the-art Fire PRA should explicitly include the risk contribution from low likelihood–high intensity (and hence potentially high consequence) fires. Past practices where fire modeling considered only a point estimate of the most likely fire will not capture this contribution. The recommended fire severity approach provides an appropriate treatment of these low likelihood fires.

2.3.5 Long Duration Fires

A state-of-the-art Fire PRA should explicitly include the risk contribution from low likelihood–long duration fires. Past practices related to fire suppression analysis, such as in the IPEEE analyses, have often dismissed the potential for fires lasting longer than 15-20 minutes for most plant areas. In contrast, the event experience clearly shows that fire durations in excess of 30 minutes are not uncommon. The recommended fire suppression analysis approach provides an appropriate treatment of low likelihood, long duration fires.

2.3.6 General Application of these Methods

The methods documented in this report are considered to represent the current state-of-the-art. In many ways, the methods should be viewed as a self-consistent set. Modifications made to any one task can impact the validity of other tasks. However, that does not necessarily imply that all tasks should be executed in the full level of detail and complexity implied by the cited state-of-the-art. Rather, in many cases, analysts may exercise discretion in determining the scope and depth of their analysis given the intended application. The authors of this document urge practitioners to exercise caution, carefully document their decisions, and provide associated bases.

2.4 References for Chapter 2

2.1 *Fire PRA Implementation Guide*, EPRI, December 1995. TR-105928 (including Supplement: EPRI SU-105928).

2.2 *Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants*, NUREG-1150, U.S. NRC, Washington, DC, 1990.

2.3 *Procedures for the External Event Core Damage Frequency Analyses for NUREG-1150*, NUREG/CR-4840, U.S. NRC, Washington, DC, 1990.

3 CONCLUSIONS AND CLOSING REMARKS

3.1 Status of Program Objectives

The principal objective of this project was to document the methodology and the technical bases for conducting a Fire PRA that would clarify issues affecting application of fire risk methods. Specific objectives of this effort, and the current status of work efforts relative to each objective, are summarized as follows.

- "Develop methodology for conducting a Fire PRA at nuclear plants. This methodology will provide insights regarding the applicability of results generated using earlier Fire PRA methods, tools, and data; the Fire PRA technical issues identified in past NPP Fire PRAs; and practical limitations and constraints in the application of the NRC and EPRI research results."

The methods documented here make significant improvements over the most recent EPRI and NRC methods published over a decade ago. This method represents the current state-of-the-art for conduct of a Fire PRA. The primary focus of the methods development efforts was consolidation of existing methods, tools, and data. In some areas, the new methods include improvements that went well beyond simple consolidation, but rather needed collection and analysis of new or expanded data and/or development of new models, approaches, and techniques. In other areas, e.g., development of a detailed post-fire HRA methodology, the level of effort necessary to establish substantial advancements in the state-of-the-art was beyond the scope and time limitations of this project.

- "Develop state-of-the-art fire risk estimates that reflect the use of the improved Fire PRA methods, tools, and data developed since publication of the EPRI FIVE and Fire PRA methods", and
- "Determine the qualitative and quantitative impact on predicted fire risk associated with the use of these improved Fire PRA methods, tools, and data."

Critical technical tasks documented in this report were tested individually during pilot demonstration studies. These demonstration studies were intended to ensure the viability and reasonableness of the recommended methods, assess their ease of application, and assess the adequacy of the documentation. It had been intended that the pilot plants would follow through with the balance of their plant analyses and provide feedback and risk insights to the Technical Development Teams. Neither of the two pilot plants completed their full analyses. Based on the demonstration studies performed, quantitative risk insights are limited to specific analysis tasks. No global insights related to plant-wide fire risk estimates or the relative ranking of risk contributors have yet been gained. In the absence of a full application of the recommended procedures, the authors are unable to predict their impact on overall fire risk estimates with high confidence. It is expected that the pilot application at a BWR (2004-2006), and insights provided by an independent pilot plant study, will provide those insights.

- "Provide specific insights on the elements of a Fire PRA expected to form the basis for RI/PB applications in fire protection"

The methodology documented in this report is intended as a reference to develop estimates of risk to support RI/PB fire protection. However, this report does not provide any guidance on the acceptability of the recommended practice in the context of any specific application. Those issues are left to other activities, including the American Nuclear Society (ANS) Fire PRA Standard, Fire Protection Rulemaking and related documentation, Nuclear Energy Institute (NEI) Guidance documents, and others.

- "Develop insights on strengths and weaknesses of the Fire PRA models and results"

Section 3.3 discusses risk insights gained to date under this study. The documented risk insights include several elements relevant to this objective. However, pending a complete application of the proposed methods, this objective has not been fully achieved.

- "Transfer the technology through workshops and training course."

As a part of project efforts, a number of conference papers describing various aspects of the Fire Risk Requantification Study have been published. Forums where technical publications have appeared include the American Nuclear Society (ANS) International Topical Meeting on Probabilitistic Safety Assessment (October, 2002), the Structural Mechanics in Reactor Technology Post Conference Seminar on Fire Protection in Nuclear Installations (August 2003), the 14th Pacific Basin Nuclear Conference (March, 2004), and the Probabilistic Safety Assessment and Management Conference (June, 2004).

EPRI and RES also conducted a joint workshop on this methodology in Charlotte, NC, June 14-16, 2005.

3.2 Improvement in the State-of-the-Art in Fire PRA

This section summarizes the Technical Development Team's collective opinions on the extent and significance of advances in the state-of-the-art that have been incorporated in the recommended Fire PRA practices. Advances in the state-of-the-art have been made in several areas. These advances range from incremental improvements in preexisting approaches, to the development of entirely new approaches. In certain key areas, such as circuit analysis, the methods documented represent substantial and fundamental advances over previous methods.

The methods documented in this report represent the current state of the art in Fire PRA. Fire PRA is an evolving discipline. The most effective way to allow these methods to further evolve is through their use in practical applications.

3.2.1 Post-fire Plant Safe Shutdown Response Model

Typical practice in past Fire PRAs has been to utilize a simplified version of the internal events plant accident SSD response model in the analysis of fire risk. The recommended methods continue to endorse adaptation of the internal events model for fire analyses. However, the recommended approach provides a structured framework for dealing with technical challenges that have not always been recognized or addressed in past Fire PRAs.

One specific challenge involves the selection of systems and functions that will be credited in the post-fire SSD response model, and identification of the corresponding components and cables that should therefore be modeled. The procedure identifies a systematic process for accomplishing the following tasks:

- Choosing which plant components, systems, and functions to include in the post-fire SSD response model,
- Identification of components and cables whose fire-induced failure could adversely impact the operability of the credited systems,
- Identification of instrument circuits providing critical support to the operator's post-fire shutdown response,
- Incorporation of operator actions uniquely associated with post-fire SSD, and
- Accommodating unique fire-induced failure modes, such as spurious operation (SO), that are not considered in the internal event analysis.

Choices made during the development of the post-fire SSD model can strongly influence the overall analysis scope. All items on the Fire PRA Component and Cable list should be mapped to specific fire analysis compartments. The tracing of cables not considered in the deterministic post-fire SSD analysis may need significant resources. To manage the level of effort devoted to these activities, an iterative process is outlined whereby the analysis can proceed based on a relatively minimal set of components, systems, and functions. As the analysis proceeds, decisions can be made as to where the crediting of additional systems, and functions might provide the most risk analysis benefit.

A second challenge often overlooked in past Fire PRAs is reconciling differences between the internal events plant response model and the post-fire SSD procedures. The methodology recommends that the analyst review the post-fire SSD procedures in comparison to the assumptions made in the internal events plant response model. Any differences should be reconciled.

3.2.2 Fire Compartment and Scenario Screening

One common aspect of most Fire PRAs is use of a graduated analysis process, including one or more screening steps followed by detailed quantification of unscreened scenarios. The recommended practice follows a similar graduated approach, although in some regards, the screening process has been formalized.

Future Fire PRA applications may introduce unique needs that would not be met given the screening approaches applied in most past analyses. Future applications will involve more complex objectives, and will likely seek to retain potential risk contributors at a much more detailed level. For example, NFPA 805 [3.1] uses Fire PRA in the evaluation of plant changes. Plant changes may impact previously screened fire scenarios or fire analysis compartments. Hence, the new method recommends that information on screened fire scenarios and compartments be retained in the PRA process documentation. Retaining such information will allow a user to revisit the original screening basis, and to assess the impact of a plant change on the screening decision.

3.2.3 General Treatment of Fire Event Data and Fire Frequency Analysis

Consistent with common practice, fire event frequencies are estimated based on the analysis of past fire experience [3.2]. The analysis documented here follows common and accepted practice with regard to issues such as fire ignition source binning, fire location binning, and treatment of fire events reported during non-power operational modes. One area of advance in fire frequency estimation is an increased use of the plant-wide fire ignition source approach and an expanded list of plant-wide fire ignition sources (more ignition source bins).

Under the recommended approach, the fire frequency estimates are tied to component level fire ignition frequencies. For example, the plant-wide fire frequency for electrical control panels is specified, and this fire frequency is partitioned to individual electrical control panels based on the total count of such panels in the plant. For example, to estimate panel fire frequency for a fire analysis compartment, the total plant wide frequency is multiplied by the number of panels in the compartment and divided by the total number of panels in the plant.

3.2.4 Fire Severity Treatment

The issue of fire severity has been an important area of ongoing technical debate. Past practice has often utilized severity factors to characterize the fraction of all fires that were actually risk-important. The recommended practice documented in this report represents a largely new approach that specifically minimizes the potential for double-counting errors.

Fire severity is accounted for through a two-step process. The first step involves analyzing fire event data and the generation of fire event frequencies. The second step involves the input assumptions used in fire modeling.

In the first step, reported fire events are screened for inclusion in, or exclusion from, the fire event frequency using a specific set of objective and subjective criteria. Fire events are included only if they actually did, or under other circumstances may have, represent(ed) a potential threat to plant safety (e.g., fire spread to secondary combustibles and/or damage to one or more targets other than the fire ignition source itself). Given this approach, the fire event frequency estimates already include some aspects of the overall concept of fire severity that, in past practice, would have been captured under the general fire severity factor.

The second step in the fire severity assessment deals more directly with fire severity as a physical property of a fire. Fire intensity (e.g., fire heat release rate (HRR)) is a critical factor in the fire modeling input assumptions. Under the recommended approach, a fire intensity distribution is assigned to each fire ignition source. The assigned intensity profile directly incorporates the severity/likelihood concept.

These two steps are integral and highly dependent on each other. That is, given the initial screening conducted in the analysis of fire event data, the retained fire events represent a range of fire intensities. Many fires will ultimately reach only a modest intensity even if left unchecked by fire suppression efforts. Other fires involving the same fire ignition source might grow to high intensity. This reflects the random behavior of fires.

The fire intensity profile is intended to represent the potential fire behavior of a given fire ignition source should the fire be allowed to grow unchecked. Under this approach, a net fire severity factor can be estimated on a scenario-specific basis. The severity factor represents the fraction of the fire intensity distribution that lies above the minimum fire intensity leading to fire spread and damage. The severity factor is calculated for each unique fire scenario based on the specific conditions relevant to that scenario (e.g., proximity of secondary combustibles, proximity of damage targets, damage target failure criteria, compartment conditions, etc.).

3.2.5 Detection and Suppression Analysis

The analysis of detection and suppression in past Fire PRAs has typically involved one of two approaches; namely, use of historical evidence regarding fire duration gleaned from the fire events, or use of fire brigade response times as demonstrated by unannounced fire drills. The analysis method documented here combines aspects of both approaches.

The overall fire detection/suppression process is captured in an event tree. Quantification involves two factors; namely, the split fractions associated with each event in the event tree, and the event transition times.

One specific aspect of the fire suppression analysis is the manual fire brigade. In the recommended approach, the fire brigade response is assessed based on the scenario-specific brigade response time and historical evidence regarding fire suppression times for similar fires. Fire suppression time curves are derived for various groupings of specific fire ignition sources, fire locations, and fire types based on analysis of the fire event database (FEDB).

3.2.6 Circuit Analysis

The issue of circuit analysis, including the spurious operation of components and systems, continues to be an area of significant technical challenge. The approaches recommended here provide a structured framework for the incorporation of fire-unique cable failure modes and effects in the Fire PRA. The circuit analysis issue impacts Fire PRA methods and practice broadly. Circuit analysis impacts the following steps:

- Identification of Fire PRA components and cables,
- Mapping of Fire PRA components and cables to fire analysis compartments,

- Development of the plant post-fire SSD response model,
- Incorporation of circuit failure modes in the quantitative screening analysis,
- Detailed analysis of cable failure modes and effects,
- Detailed analysis of circuit fault modes and effects, and
- Quantification of human actions in response to a fire.

This project has taken advantage of other ongoing activities in the circuit analysis area. As a result, methods are now available to estimate the likelihood that any specific circuit fault mode will be observed given cable failure. However, detailed analysis of such faults is a tedious process. The recommended practice includes both screening approaches and methods for detailed quantification. These methods represent a substantive improvement in the overall Fire PRA process.

3.2.7 Human Reliability Analysis

HRA for Fire PRA is an area of significant technical challenge. While HRA methods in general have experienced substantial advancement, they have not yet fully matured, and relatively little HRA research specific to an NPP Fire PRA has been conducted. Three general areas of HRA have been addressed in the recommended methodology: namely, the initial quantitative screening analysis, detailed quantification of general fire scenarios, and analysis of scenarios leading to Control Room abandonment.

It is often desirable to credit certain human actions in assessing the potential for achieving SSD during the initial quantitative screening tasks. However, it is important that the quantitative screening analysis credit only those actions that are both reasonable and feasible, and that they are assigned appropriate reliability values. The recommended approach identifies those factors to consider in the assignment of screening human error probability (HEP) values, and provides explicit quantification methodology. Essentially, three levels of fire-induced degradation are defined depending on the level of impact the fire might have on the action being credited; namely, virtually unaffected, moderately affected, and highly affected.

Many aspects of a HRA are driven by the method chosen. This study has not endorsed any given HRA method. Hence, it does not give step-by-step instructions on how to conduct a post-fire HRA. Rather, this document consolidates current HRA insights and provides more general instructions as to what factors should be considered in the HRA. How to specifically treat any given factor (e.g., the impact of smoke on human performance) is not specified, in part because no clear consensus has yet developed among HRA experts, and in part because the exact analysis procedure will be heavily dependent on the selected analysis method.

MCR abandonment and/or the reliance on alternate shutdown actions (i.e., control actions taken outside the MCR) introduce unique factors into the HRA. At least 14 important considerations related to such actions have tentatively been identified. The approach related to remote shutdown analysis is similarly limited.

3.3 Limitations to the State-of-the-Art and their Importance

The Technical Development Teams reached a few technical areas where advancing the state-of-the-art is either unattainable within current knowledge, and/or where the cost associated with obtaining the necessary knowledge is prohibitive. Note that the discussion here is not intended to exhaustively explore analysis limitations, but rather, to highlight specific limitations relevant to current topics of potential interest to users.

3.3.1 Number of Combined Fire-Induced Spurious Actuations

It is impractical to exhaustively explore all potential electrical cable failure modes in a fully dynamic context except for the most simplistic of component damage state scenarios. Hence, it is widely recognized that some optimization of the circuit analysis process is both necessary and desirable. The recommended circuit analysis approach attempts to focus attention on those electrical cables, cable failure modes, and circuit fault modes that may be risk-significant.

The approach for the selection of components and cables recommends that analysts limit consideration to combinations of two or three concurrent spurious operations in any one system. The analyst may, of course, consider more concurrent spurious operations, but as the number increases, the level of effort increases geometrically. The analyst will likely find that a point of diminishing returns is quickly reached (substantial effort necessary to add low likelihood failure combinations). Once incorporated into the Fire PRA plant SSD response model, combinations involving any number of spurious operations impacting multiple systems concurrently can be quantified. The proposed approach does not provide a systematic method to identify the potential functional dependencies between the failed components of different systems. The NEI/EPRI/NRC [3.3, 3.4, 3.5] testing showed that the likelihood of occurrence of the combinations decreases exponentially with the number of the postulated spurious actuations. It is the authors' judgment that the recommended approach would capture dominant risk contributors and offers substantial improvement over other alternative approaches available to date for dealing with this issue.

3.3.2 Estimating Spurious Actuation Probabilities

Task 10, Circuit Failure Mode Likelihood Analysis, provides methods for estimating the spurious operation probability for one or more components. These methods rely largely on previously available estimates of the conditional probability of spurious actuation given cable failure. This project has not attempted to tabulate alternate spurious operation likelihood values[2]; however, the consensus of the EPRI and RES Technical Development Teams is that additional consideration of the circuit failure mode likelihood values is warranted.

[2] An analytical equation has been suggested for "fine tuning" spurious actuation likelihood estimates to a specific case, but this approach fundamentally relies on the same underlying data. It should also be noted that the equation based method has received only limited peer review and application experience.

The predominant root source for current estimates of spurious actuation likelihood is testing performed by NEI and EPRI in cooperation with NRC [3.3, 3.4, 3.5]. In particular, the values cited in Task 10 are those recommended by an EPRI-convened expert panel [3.4], with limited supplemental insights derived from the subsequent EPRI full data analysis report [3.3].

Insights gained through the demonstration studies, the peer review process, and the public comment process have highlighted mismatches between the needs of a Fire PRA and the current estimates of spurious actuation probability. In general, the consensus of the EPRI and RES Technical Development Teams is that when all relevant factors associated with the Fire PRA application are taken into consideration, the cited spurious actuation probability values are generally conservative. The degree of conservatism will clearly vary depending on the specific case circumstances and in all cases remains unproven. Our judgment in this regard includes consideration of several interacting factors associated with the cable physical behaviors, fire exposure, circuit configuration, and failure modes considered in the Fire PRA.

For the purposes of illustration, the following discussion focuses on internal or intra-cable shorting behavior in multi-conductor cables to the exclusion of external or inter-cable shorting behaviors. Inter-cable shorting behaviors would face similar considerations.

The input data provided to the EPRI expert panel focused on the likelihood that either of two specific target conductors experienced a hot short from either of two energized source conductors for the surrogate motor operated valve (MOV) control circuit tested. A Fire PRA is typically interested in a somewhat different question. For example, given a MOV where the desired position is "open", the risk-relevant question would be "what is the likelihood that the valve spuriously closes?" In the context of the experiments, this would correspond to a hot short energizing the one target conductor representing the "close" side of the surrogate MOV control circuit. While the probability of a valve going closed is likely lower than the spurious actuation probability promulgated by the expert panel, one cannot simply divide the expert panel value by two. That is, one cannot assume that a hot short impacting the "close" target conductor is half the likelihood of impacting either the "open" or "close" target conductors. In many of the tests, if one target conductor experienced a hot short then both target conductors experienced hot shorts. This implies a dependency that would not be properly quantified by a simple "divide by two" solution.

Now consider a case cited during the peer review process. The cited case involved a specific circuit configuration on a normally open MOV. Circuit analysis found that if the "open" conductor experienced a hot short first, then permanent valve damage could occur because the fault would bypass the valve limit switches, over-driving the valve into its "open" seats. In this case, the valve would remain open until repaired. However, if the valve experienced a hot short on the "close" conductor first, the valve would close with no valve damage because the limit switches remain effective for this fault configuration. For this example, the questions of hot short timing, and potentially duration, come into play. These subtleties are not currently captured by the methods recommended in Tasks 9 and 10.

As a final illustrative example, consider a case involving a normally closed high/low-pressure interface MOV. Depending on the overall piping configuration and likely given other concurrent failures, a hot short that even partially opened the MOV might lead to permanent damage and rupture of the low pressure piping. In such a case any prior <u>or</u> subsequent shorting behavior and considerations of hot short duration would be essentially irrelevant to the risk calculation. For such a case, the expert panel results might well be the most appropriate interpretation of the available data.

The above examples illustrate the complexity of the problem. Refinement of any given spurious actuation likelihood value requires a clear understanding of the available data, consideration of the specific circuit configuration, and a clear understanding of the Fire PRA application and scenario implications. The team has identified, but not resolved, some mismatches between the expert panel values and Fire PRA applications. Cases such as this suggest, for example, that event tree type methods might provide added insights regarding the relative likelihood of various circuit/component end states tailored to a specific circuit.

Based on our insights to date, additional efforts to refine the quantitative methods associated with Task 10 are recommended. In particular, as additional data on cable failure modes and likelihood becomes available, estimates for the spurious actuation likelihood should be updated. Even supplemental analysis of the existing data could provide new insights not incorporated in the current estimates. It is also suggested that supplemental methods of circuit likelihood analysis for Fire PRA could be developed. For example, the application of event tree approaches to a given circuit might yield more realistic results.

3.3.3 Dynamic Versus Static Modeling of Fire Damage and Operator Response

Both failure sets and operator response are modeled in the context of static interface conditions. That is, fire leads to loss of a full target set, then operators respond. Fire damage time is assessed, but only in the context of a full target set. Operator response considers the available time, but does not consider operator actions in the context of an ongoing fire with progressive fire damage. This approach does not, for example, take credit for the anticipatory diagnostic process that takes place among the operators concurrent with the fire event. Even though the impact of this approach on the results and conclusions is unknown, it is expected that selecting fire effects that represent the largest damage set taken at one point in time should be conservative for most fire scenarios.

3.3.4 Multiple Fires

The issue here is not one fire that spreads to secondary combustibles, nor is it a fire initiated in one compartment that spreads to a second compartment; rather, it relates to the occurrence of two or more fires concurrently and in different locations due to the same root cause. Such cases are generally tied to electrical equipment failures. While the proposed methods can handle some aspects of problem (e.g., one can model the impact of two fires in two areas), an integrated approach to the analysis of such events is lacking (e.g., frequency, where to put multiple fires, establishing common cause/root cause ties, etc.). The risk importance of multiple fire scenarios remains uncertain. Events of this type have occurred both in the U.S. and abroad [3.6], but are rare.

3.3.5 Multiple Initiating Events from the Same Root Cause

This document offers an approach to qualitatively address those interactions resulting between fire and a seismic event; however, it does not discuss other combinations, for example, fires in conjunction with flooding. There is no evidence of such events occurring in the U.S. nuclear power industry.

3.3.6 Limitations in Internal Events Analysis that Carry Over to Fire

Limitations in current internal events analyses include full quantification of uncertainties, uncertainty in completeness of plant response model, errors of commission, and success criteria. These limitations are common to a Fire PRA as well. In addition, fire will introduce new challenges in the area of uncertainty. For example, limitations to an analyst's ability to predict the physical behavior of a fire introduce uncertainties that go beyond those of internal events analysis.

3.3.7 Smoke Damage

The approach provided here is based on qualitative rather than quantitative estimates of smoke impact. Fire test evidence exists to support the qualitative judgment for damage to electrical equipment excluding high-voltage equipment such as switchgear.

3.3.8 Seismic/Fire Interactions

The recommended approach includes a qualitative assessment of seismic/fire interactions in lieu of quantification. Seismic/fire interactions are expected to generally be of low risk importance given the seismic ruggedness requirements imposed on U.S. nuclear power facilities. The authors also note a lack of historical evidence of such problems in the nuclear industry.

3.3.9 Administrative Aspects of the Fire Protection Program

Aspects of a plant's administrative programs (e.g., training of operations staff, fire brigade practices such as reliance on a brigade vs. a dedicated fire department, combustible controls programs, etc.) are issues that hold the potential to impact fire risk, but cannot be quantified given the current knowledge base. These issues will likely have some impact on plant-to-plant fire risk variability.

3.3.10 Effectiveness of Fire Protection Systems

The methodology described in this document relies on analyst judgment to assess the effectiveness of fire detection and suppression systems in the context of a particular fire scenario. This approach weighs code compliance heavily in the effectiveness assessment. Nominally, a code compliant system is considered effective unless the analyst observes specific features that would compromise effectiveness (e.g., blockage of sprinkler heads, an especially challenging fire source, fire suppression agent not effective for postulated fire source, etc.).

3.3.11 Effectiveness of Passive Fire Barriers

No specific method for modeling barrier response to actual fire scenarios has been developed that is suitable for incorporation into a Fire PRA. Pre-existing estimates of fire barrier failure probabilities have not been updated. This report accounts for availability of these systems derived from historical data (which includes impairments). The unavailability, rather than failure probability and effectiveness, should be the dominant factor for the active fire barriers such as fire doors and damper. In the case of passive fire barriers such as electrical raceway fire barrier systems the current methods rely on "qualification," a process that prescribes design, installation and maintenance of the fire barrier in accordance with an approved fire protection program.

3.3.12 Pre-Initiator Human Events for Fire Protection Systems, Features and Program Elements

Pre-initiator human errors may impact fire risk through errors that; 1) may affect operability of systems and components used for plant safe shutdown or 2) may affect the operability of fire protection systems (active or passive) or the effectiveness of other fire protection program elements (e.g., transient combustible control or the plant fire brigade).

The human reliability analysis (HRA) procedure (Task 12) addresses pre-initiator human errors dealing with operability of plant safe shutdown system components (item 1 above) only to the extent that such errors have been embedded in the internal events PRA model. Such features of the plant safe shutdown response model are to be retained in the fire-specific plant model. Task 12 emphasizes the post-initiator manual actions dealing with the operability of the plant safe shutdown systems and components and does not explicitly treat pre-initiator human errors that might be fire-specific.

The methodology described in this document deals with fire-specific pre-initiators human errors (as well as post-initiator human errors) affecting the operability of fire protection systems, features, and program elements (item 2 above) using a generic approach which relies on a combination of historical and experimental data where possible. This treatment is embedded in other aspects of fire scenario analysis such as fire frequency estimates, generic fire suppression system reliability/availability estimates, fire brigade response times, and fire brigade suppression success times. For example, the procedures associated with Tasks 6 and 11 use reliability/availability data for fire protection systems (active and passive) that include system failures caused by pre-initiator human errors. However, fire-specific pre-initiator human errors are not treated in the context of the HRA (Task 12). The net result is a generic rather than plant- or scenario-specific treatment.

3.4 Insights and Observations

In the course of this project, a number of issues and insights became evident.

- The addition of spurious operation faults to the post-fire SSD response model holds the potential to substantially alter the existing perspectives on fire risk. The limited depth and completeness of the demonstration studies completed to date means that quantitative insights into the general magnitude of fire risk, and the impact of such fault modes on fire risk, have not yet been developed. However, the demonstration studies did involve fire risk scenarios where the dominant cutsets involved two or more spurious operations. These scenarios would likely not have been captured in risk studies conducted using earlier analysis procedures. The ultimate risk significance of these effects remains to be seen.
- The incorporation of high-energy arcing faults as a failure mode for high-energy electrical switching equipment (e.g., switchgears) could lead to some shifts in the perception of the relative risk importance of these fire ignition sources. Based on the best evidence to date, arcing faults in such equipment, while relatively rare occurrences, hold the potential for significant fire-induced damage in very little time. Hence, fire suppression features (either fixed or involving the fire brigade) may not be effective at preventing the initial damage. Depending on the plant-specific configuration and proximity of the critical damage targets to the faulting component, this could imply the existence of risk-important fire scenarios that would not have been identified in fire risk analyses based on earlier analysis methods and assumptions.
- The Fire PRA method documented here includes substantial changes compared to previous Fire PRA methods (e.g., NUREG-1150, FIVE, and the EPRI Fire PRA Implementation Guide). Fire risk analyses based on a direct application of these earlier methods may be of limited usefulness, even as a starting point for an updated analysis. Fire vulnerability assessments conducted under the Individual Plant Examination of External Events (IPEEE) program have not adequately addressed many of the factors now considered important (e.g., spurious actuations and proper treatment of fire severity). Note that plant-specific data collected under the earlier methods should be applicable to this methodology.
- It has generally been presumed that use of a post-fire SSD response model that credits (and therefore includes) only those components, systems, and functions credited in the deterministic 10 CFR 50 Appendix R safe shutdown analysis will lead to conservative risk estimates. The experience gained in this study shows that this presumption may not necessarily be true. Consideration of multiple concurrent spurious actuations is beyond the current design basis for most plants. The 10 CFR 50 Appendix R post-fire SSD component list was developed accordingly. Multiple spurious actuations involving non-Appendix R components may hold the potential to compromise 10 CFR 50 Appendix R SSD functions. The failure to include these functional dependencies could result in optimism in the Fire PRA SSD model. Crediting systems and components beyond the plant's existing safe shutdown strategy could offset the impact of these failure modes.

- Selection and tracing of the components and cables, and to a lesser extent the analysis of their fire-induced failure modes, continues to present the biggest challenge in terms of estimating the resources needed to conduct the Fire PRA. In some cases, more than half of the resources needed for implementing the methodology documented in this report will be directed to cable and component selection, analysis of the credited systems and function, and routing of the credited cables and components. Note that introducing spurious operation fault modes into the post-fire plant SSD response model involves substantial use of resources, but is not the driving factor. Rather, increasing the depth and rigor pursued in the component and cable selection task leads to additional burden in component and cable tracing, and supporting circuit analyses. The 10 CFR 50 Appendix R SSD components carry some level of analysis pedigree that carries over to the Fire PRA. However, consideration of multiple concurrent spurious actuations may need additional analysis of even the Appendix R components. When crediting components beyond the Appendix R SSD list, the supporting cable failure mode and effects analyses should be performed at the same order of rigor and depth as those performed for the 10 CFR 50 Appendix R systems and components.
- A Fire PRA is a multidisciplinary project that needs expertise and knowledge that rarely reside in one person. A team of people who collectively provide all of the necessary expertise is needed to ensure quality and control cost.

A number of conclusions have been drawn that help to put the above insights in perspective. These conclusions are based on the knowledge and judgment of the authors who, collectively, have been deeply involved in the development, application, and review of the methods used by the industry and the NRC for the past two decades. These conclusions are considered tentative because they have not yet been verified by full application of this methodology (as stated in other parts of this report).

- Under the IPEEE program, use of the EPRI FIVE and EPRI Fire PRA Implementation Guide methods by the U.S. nuclear power plants resulted in fire-induced core damage frequencies ranging from 4E-8 to 2E-4/reactor-year with vast majority between IE-6 to IE-4/reactor-year [3.7, 3.8]. The results reported that fire contribution to the combined fire and internal events risk range from 1% to 90% [3.7].

  The authors do not expect either of these industry-wide fire risk perspectives to change substantially as the result of the use of this methodology. However, the plant-specific estimates of fire risk may change. While the improvements in these methods can drive risk estimates upward in some areas, such as consideration of spurious operations, they may have a downward impact in others, such as control room fire scenarios. The net effect however, for a specific plant is unknown. While the fire risk may increase for a plant more vulnerable to spurious operations, the fire risk may decrease for plants with better separation of critical circuits and/or robust deterministic post-fire safe shutdown analyses. Those plants whose IPEEE fire risk estimates fall at the lower end of the IPEEE spectrum (4E-8 to 2E-4/RxYr) would be more likely than those that fall at the upper end to see some increase using the new methods.

- Another perspective gained during the IPEEE program was the relative importance of fire scenarios or plant locations with respect to fire risk. For example, 35 studies, or nearly 1 of every 3 studies, reported the risk associated with control room fires as the highest contributor to the fire risk. Switchgear rooms came in a close second (21 studies), and turbine building third (12 studies) [3.7, 3.8]. A range of other fire areas were reported as important risk contributors on a plant-specific basis.

  It is likely that the relative importance rankings of plant locations will be impacted by the use of this method. When considering any given fire area, risk estimate changes will be driven more by plant-specific factors than by generic industry-wide practices. Relatively few industry-wide trends are anticipated with respect to changes in the relative risk importance rankings. In some specific cases, such as the main control room, the IPEEE risk estimates are generally based on conservative screening analyses rather than detailed analysis. For these cases, the new methods will likely result in risk estimate reductions. The new methods also give rigorous treatment to issues not systematically considered in most IPEEEs (e.g., circuit analysis issues and post-fire manual actions). As a result, areas with concentrations of electrical control cables in particular could see increases in fire risk estimates. The new methods also give more systematic treatment to fire protection attributes than that applied in most IPEEE analyses. These attributes include fire protection systems and features, administrative controls of fire hazards, circuit design and separation, post-fire safe shutdown strategies, and other design and operation related elements influencing fire risk. The addition or enhancement of specific areas of analysis will undoubtedly lead to substantive insights that were not available from the previous method. The current method offers more pedigree and balanced realism (as opposed to unbalanced conservatism) in modeling these attributes. Overlap between these factors leading to changes (e.g., increasing the general level of analysis detail *and* adding consideration of spurious operations) will also lead to offsetting effects on risk estimates (as noted above).

3.5 Recommendations

The EPRI and RES Technical Development Teams identified a number of areas where further improvements to the state-of-the-art may be beneficial. However, the effort needed to implement the identified improvements proved beyond the time and resources available to this project. Some of the identified areas of need may present considerable challenges both in technical know-how and needed resources.

3.5.1 Low Power and Shutdown Operating Modes

The scope of this methodology is limited to fire risk during at-power mode of operation. NFPA 805, in particular, requires consideration of non-power modes of operation. A methodology to study the risk associated with these other modes would be beneficial to the implementation of a risk-informed fire protection program.

3.5.2 Detailed Fire HRA

The recommended practice documented here represents a significant improvement in the conduct of HRA at the screening level. However, this project did not develop a stand-alone methodology for conduct of detailed post-fire HRA. The development of detailed quantification methodology is heavily dependent on the method of analysis selected, and hence, such methodology was deemed to lie beyond the scope of this document. The recommended procedures have neither endorsed nor precluded any specific HRA method(s). In many regards, HRA in general remains a substantial technical challenge, and no clear consensus relating to quantification methods has emerged. Fire HRA adds additional challenges that have not yet been addressed by the broader HRA community.

3.5.3 Automated Fire PRA Information Tracking Tools

A comprehensive Fire PRA of the type described in this report is a significant undertaking that needs compilation, storage, manipulation, and maintenance of a substantial amount of data, as well as the capability to maintain and exercise many supporting models. Automation tools for recording, integrating, and tracking the PRA information would likely enhance the viability of Fire PRA as a practical tool for plant operators.

3.5.4 Plant-Specific Assessment of Manual Firefighting

The recommended model for the analysis of manual firefighting does not consider plant-to-plant variability in the fire brigade training and capability. The current method is based on generic, industry-wide average performance statistics. As such, it is not currently designed to assess the risk benefits of, for example, a dedicated site fire department versus a fire brigade, or enhanced hands-on training of fire brigade personnel. As a part of Technical Development Teams' discussions, a framework for enhancing the method to allow for such considerations was outlined, but the available resources and time were not sufficient to implement the proposed strategy. Implementation would need further definition of the proposed approach, convening of an expert panel to provide key inputs, peer review, and baselining of the approach against a sample of actual plant applications.

3.5.5 Estimating Component Failure Mode Likelihoods

The recommended approach to quantitative circuit analysis includes a methodology for generating case-specific component fault mode likelihood estimates (e.g., the probability of spurious operation given failure of a specific cable in a specific circuit). The method extends beyond the specific circuit and cable configuration tested by EPRI/NEI circuit test configuration. The methodology was developed by "reverse engineering" the EPRI/NEI circuit failure mode test data [3.3]. Hence, the approach is nominally consistent with the available test data. However, the methodology has not been extensively peer reviewed, and additional validation would be appropriate.

3.6 References for Chapter 3

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11. ABSTRACT (200 words or less)

This report documents state-of-art methods, tools, and data for the conduct of a fire Probabilistic Risk Assessment (PRA) for a commercial nuclear power (NPP) application. This report is intended to serve the needs of a fire risk analysis team by providing a structured framework for conduct of the overall analysis, as well as specific practices to address each key aspect of the analysis. The methods have been developed under the Fire Risk Requantification Study. This study was conducted as a joint activity between the Electric Power Research Institute (EPRI) and the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) under the terms of an NRC/EPRI Memorandum of Understanding on Cooperative Nuclear Safety Research and an accompanying Fire Risk Addendum. Participants from the U.S. nuclear power industry supported demonstration analyses and provided peer review of this methodology. Methodological issues raised in past fire risk analyses, including the Individual Plant Examination of External Events (IPEEE) fire analyses, have been addressed to the extent allowed by the current state-of-art and the overall project scope. While the primary objective of the project was to consolidate existing state-of-art methods, the newly documented methods represent a significant advancement over previously documented methods in many areas.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Fire, Fire Risk, Risk Analysis, Probabilistic Risk Assessment, PRA, Probabilistic Safety Assessment, PSA, Risk-Informed Regulation, Performance-Based, Fire Protection, Fire Safety

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