NUREG/CR-6738
SAND2001-1676P

Risk Methods Insights Gained From Fire Incidents

Sandia National Laboratories

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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Manuscript Completed: August 2001
Date Published: September 2001

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Washington, DC 20555-0001
NRC Job Code Y6037

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ABSTRACT

This report presents the findings of an effort to gain new fire probabilistic risk assessment (PRA) methodology insights from fire incidents in nuclear power plants. The study is based on the review of a specific set of 25 fire incidents including fires at both U.S. and foreign reactors. The sequence of actions and events observed in each fire incident is reconstructed based on the available information. This chain of events is then examined and compared to typical assumptions and practices of fire PRA. The review focuses on two types of actions and events. First are events that illustrate interesting insights regarding factors that fall within the scope of current fire PRA methods. Second are events observed in actual fire incidents that fall outside the scope of current fire PRA methods. Fire PRA insights are then drawn based on these observations. The review concludes that the overall structure of a typical fire PRA can appropriately capture the dominant factors involved in a fire incident. However, several areas of potential methodological improvement are identified. A few factors are also identified that fall outside the scope of current fire PRAs including the occurrence of multiple initial fires or secondary fires, multiple simultaneous initiating events, and some aspects of the smoke control and human response assessment.

CONTENTS

FOREWORD

The design and operation of commercial nuclear power plants (NPPs) include multiple defenses to reduce the likelihood and consequences of potential fire-initiated accidents. These defenses include:

- administrative programs (to reduce the likelihood and potential severity of fires)
- detection and suppression systems and programs (to rapidly extinguish any fires that might occur)
- separation of safe shutdown equipment trains (to reduce the potential effects of a fire on key plant systems) and
- operating procedures and training (to deal with potential fire-induced losses)

Because of these defenses, the frequency of fire-initiated accidents is not expected to be large. Indeed, to date, there have been no fire-induced core damage accidents in the history of commercial nuclear power.

However, neither the existence of defenses nor the lack of fire-induced core damage accidents imply that such accidents cannot occur, nor do they demonstrate that fire is necessarily an unimportant contributor to a given plant's risk profile. To develop fire risk estimates that can be used in plant-specific decision making, models reflecting the design and performance of the plant's defenses against fire must be used.

The models used by current fire probabilistic risk assessments (PRAs) incorporate plant- and area-specific considerations of the defense elements mentioned above. To address key areas of uncertainty identified by reviews of fire PRAs, including those performed as part of the Individual Plant Examination of External Events (IPEEE) program, the Office of Nuclear Regulatory Research (RES) initiated a fire risk research program in 1998. One of the tasks in that program involves the review of actual nuclear power plant fire events to determine if these events indicate any areas of weakness in the current overall fire PRA approach or in any elements of that approach.

This report reviews selected nuclear power plant fire events to gain insights on current fire PRA models and methods. The events were selected to address fires that posed significant challenges to nuclear safety, significant challenges to fire protection, or significant challenges to key elements in fire PRA. Because the events were been selected to identify potential issues rather than to make quantitative statements concerning the likelihood of various phenomena or events, the event selection process did not employ any formal sampling scheme. Furthermore, because of the rarity of serious nuclear power plant fire events and the associated scarcity of detailed information on such events, the selection process included events which occurred several years ago and events which occurred outside of the United States.

Despite the uncertainties introduced by these features of the study, this report provides a useful perspective on the individual elements of a current fire PRA. It indicates which elements of fire PRA appear to appropriately address observed phenomena and identifies a limited number of areas where fire PRAs may need to be expanded. In addition, the report provides a useful perspective on the overall structure of current fire PRAs, by indicating that this structure appears to adequately address all issues identified. In other words, the lessons learned from the event review can be incorporated through improvements in specific fire PRA elements, and do not imply any significant revisions to the general fire PRA approach currently being used.

The staff believes that the information contained in this report will be useful to a broad variety of readers. The staff will use the report's insights when performing any future fire risk assessments, and will consider the report's recommendations when updating the current NRC fire PRA research plan. Furthermore, the staff will broadly disseminate the report, recognizing that the report's detailed discussions of individual events may be useful in applications outside of the report's scope (e.g., in the identification of fire safety lessons, in the identification of key factors in the general treatment of plant operator responses to challenging events).

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ACKNOWLEDGMENTS

This study was performed as Task 5 of the USNRC Office of Research (RES) sponsored Fire Risk Methods Program. The USNRC program technical lead is provided by H. W. 'Roy' Woods. The contributions of Dr. Nathan Siu, also of USNRC/RES, to the development of the study approach and objectives are also gratefully acknowledged.

Many colleagues and friends assisted us in gathering information about various incidents. Special thanks are due to Mr. Enric Pla, and Ms. Marika Sarkisova who spent many hours researching and compiling valuable information that were otherwise not available in the open literature. Thanks are also due to Ms. Ana Gomez-Cobo, Ms. Hiroko Tezuka, Mr. Stefan Brosi, Mr. Jouko Martilla, Mr. Dennis Bley, Ms. Marina Rowekamp and Mr. Mika Yli-Kauhaluoma who assisted us in obtaining information about various incidents. We also thank Andrew Minister of Pacific Northwest National Laboratory (PNL) for his assistance in the review and revision of this report, particularly as related to certain of the fire incidents documented for plants in the former Soviet Union. Also assisting the review process were Robert Kalantari of Engineering Planning and Management Inc. (EPM), Susan Cooper of Science Applications International Corp. (SAIC), Mohamad 'Ali' Azarm of Brookhaven National Laboratory (BNL).

1.0 INTRODUCTION

1.1 Problem Statement and Objectives

Methods of probabilistic risk assessment (PRA) for the analysis of fire incidents (fire PRA)[1] have been developed primarily during the last two decades.[1-6] These methods have seen extensive application in both individual plant risk assessment efforts and in the Individual Plant Examination for External Events (IPEEE) initiative. One source of information that has influenced methods development and the quantification of certain input values for fire risk analysis is actual fire experience in nuclear power plants, especially that of U.S. plants. Fire experience has been widely used to identify anticipated fire sources and for statistical evaluation of such analysis parameters fire initiation frequency and fire duration.[3,4,7-10] In the regulatory arena, nuclear industry fire incidents have been reviewed to establish root causes and to assess the potential need for additional fire protection features or new fire protection approaches. However, none of the previous studies has used fire incidents to glean insights into the underlying assumptions, methodology and results of fire PRA. That is, none of the previous studies has examined the chain of events observed during actual fire incidents in an attempt to glean insights into the current fire PRA practice.

This report presents the analysis and results of a study of a select set of fire incidents from a fire PRA perspective. The study was done as part of a research project sponsored by the U.S. Nuclear Regulatory Commission (USNRC).[11] The study objectives are defined as follows:

- Identify key fire risk and fire PRA insights from serious U.S. and international nuclear power plant fires.

- Develop recommendations for fire PRA improvements and areas for further investigation.

In this study, 25 fire incidents were examined for insights regarding various aspects of the overall fire PRA process; that is, methodologies currently employed, underlying assumptions of those methodologies, and supporting data. In order to reach the first objective of the study, this review in effect is seeking the answer to the following three questions:

- How do fire incidents verify (or contradict) various elements of fire scenario models as developed in current fire PRAs?

- Does the actual fire experience lend any insight into the current areas of methodological debate?

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[1] The term “fire PRA” will be used in this report to represent the analysis of nuclear power plant fire risk using quantitative probabilistic methods.

– Do actual fire incidents indicate the existence of any new phenomena that have not been considered in past PRAs?

In selecting the events included in this review a large number of fire events were considered. However, no attempt was made to ensure an exhaustive search of all fire incidents in any specific context (see Section 2.2 for further discussion of the completeness of the selected incident set). Furthermore, no attempts have been made to perform statistical analyses of various fire PRA analysis parameters based on this review. While event reviews often take on these tasks, this was not the intent of this particular study. Rather, a select set of fire incidents was reviewed in order to glean insights into the completeness and validity of current PRA methods and assumptions. Each fire incident in the review set either involved a severe fire in the traditional context of fire protection, a fire that challenged nuclear safety, and/or a fire that provides some specific insight into current fire PRA methods and assumptions.

1.2 Organization of Report

Section 2 provides a description of the methodology used in reviewing each fire incident. Section 3 identifies the incidents that were reviewed in this study. The insights gained from various incidents are given in Section 4. Final conclusions, summary of insights, and recommendations are presented in Section 5. Section 6 cites the referenced documents. Individual incident reviews are provided in Appendices 1-25 (both the Table of Contents and Table 3.1 provide a cross reference of events to appendices).

2.0 METHODOLOGY

2.1 Overall Approach

The approach used in this study can be divided into the following steps: identification of fire incidents, collection of relevant information, chronological listing of the chain of events, analysis of the incident, and identification and consolidation of insights.[2] Based on observations made in the course of the reviews, a set of topical categories were identified and the final results were presented in terms of these categories. The topical categories are based on the different elements of fire PRA methodology. Note that in the development of insights only qualitative arguments are used. That is, because the incidents reviewed do not represent a complete set in any given context, no attempts are made to derive specific statistical insights. In a very few cases broad insights associated with the apparent relative frequency of certain types of events are drawn.

2.2 Identification of the Fire Incidents for Review

All of the fire incidents reviewed in this study occurred in the nuclear power industry. Three categories of incidents were considered. The first category is large or severe fires. These are fires that led to severe or widespread damage. This group reflects fires that were severe in the traditional context of fire protection, and in particular, in the context of property protection/loss.

The second category is fires that led to a significant challenge to nuclear safety. This includes fires that impacted more than one train of safety equipment. While there is some overlap between the first and second categories (i.e., large fires that also challenged nuclear safety) the two sets are not identical. In a small number of cases relatively modest fires, from a traditional fire protection standpoint, led to significant nuclear safety challenges. An example of this is the 1975 Browns Ferry fire. While that fire significantly challenged plant safety, it was not especially severe from a traditional fire protection standpoint. The fire was initiated in and affected a small area within the cable spreading room. Numerous cables within a relatively confined region of a second adjacent compartment were also burned. However, the fire did not lead to any substantial challenge to plant structures, nor were fire barriers seriously challenged.[3] Furthermore, a number of the identified large fires did not present serious challenges to nuclear safety.

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[2] A note on terminology: This report distinguishes between "incidents" and "events" in the following manner: "Incident" refers to the overall fire occurrence from beginning to end. "Event" refers to the individual actions and occurrences within the overall incident that make up the observed "chain of events."

[3] The only challenged fire barrier was the incomplete penetration seal that was the ignition point for the fire which quickly spread through a gap in the incomplete seal.

The final category of incidents is "interesting fires." These are generally small fires that had little or no safety impact but demonstrate some important insight into fire PRA methods and assumptions. That is, most of the fires in the final category did not cause major damage nor challenge nuclear safety. These incidents are included if they involved an interesting chain of events or unusual phenomena, particularly if the observed behaviors are relevant to current areas of methodological debate or if they involve events considered very unlikely given current methods and assumptions.

The incidents were selected for review using the information provided in a number of different sources. Sources of information included articles published in the open literature[12-16], USNRC documents[10,17,18], the Sandia National Laboratories (SNL) fire incident data base[19], and the Electric Power Research Institute (EPRI) fire incident data base[20]. A large number of incidents were reviewed during the selection process (for example, 492 in [10], 498 in [17], 354 in [19] and 753 in [20]). It must be noted that there is considerable overlap among these data bases. The incident descriptions provided in these sources were reviewed and a determination was made about the applicability of each incident to the current study based on the selection criteria described above.

A comment on the completeness of the incident set chosen for review is appropriate. An attempt was made to select as complete a set of fires leading to a significant challenge to nuclear safety as was practical. Ultimately, the authors are confident that all such incidents have been included. With regard to the severe fires, since the sources of information used in selecting fire incidents are focused primarily on U.S. plants, it is not clear whether all large fires were captured. Furthermore, for a small number of known fire incidents the authors were unable to obtain sufficient information to support the objectives of this review, and these incidents have not been included. An example is the 1984 turbine-generator fire at Maanshan in Taiwan. This fire is covered in the study, but only in very limited detail due to a lack of publicly available information (see Appendix 13). Based on discussions with fire experts and cross checks with sources other than the nuclear industry itself (e.g., the property insurance industry), it has been concluded that the majority of the large fires that have occurred in the nuclear industry are addressed in this study.

With regard to the "interesting" fires, it is not possible to claim completeness. The selection of interesting incidents was based primarily on the authors' judgement supplemented by input from colleagues and reviewers. Most certainly there are many other minor fire incidents that would illustrate particular points of interest. The scope of this effort was simply not sufficient to attempt to capture all such incidents.

2.3 The Review Process

The analysis of a given fire incident started with the collection of relevant information. In some cases, this involved direct interaction with knowledgeable individuals. The chain of events that had occurred was studied carefully to ensure that, to the extent possible, every detail of the specific occurrences (events or elements of the incident) observed, the principal root causes, any special conditions prevailing at the time of the incident, the physical characteristics of the plant and the nature and arrangement of the plant systems were understood. Each incident was then reviewed from two perspectives. First, looking at the chronological chain of events, we asked how fire PRA would model the specific occurrences observed. Second, looking at the different elements of a fire scenario as modeled in fire PRAs, we asked how each of those elements was realized during the incident.

It may be noted here that the approach used in this study to select the events for review is quite similar to the incident screening methodology proposed for the USNRC Accident Sequence Precursor (ASP) project.[21] Both ASP project and the current study attempt to gain PRA insights from an actual incident. In the ASP effort, an incident is considered as sufficiently interesting to warrant analysis based on a screening process that considers incident features such as the occurrence of an initiating event, loss of a safety system, degradation of multiple safety systems, an unusual level of severity, observance of unique behaviors, and/or an unusual or unexpected plant response. Similar criteria were applied to the selection of events in the current study. However, the approach used in the current study differs from ASP study in one important area. In the current study, no attempt is made to estimate the conditional core damage probability associated with a given event. That is, the ASP study included methods to quantify the conditional probability of core damage given the physical plant damage realized in the incident. The current study has made no attempts to perform an analysis of this type.

For the current study, the first step in the analysis of an incident was to document the observed chain of events. That is, each incident was broken down into a chronological sequence of elemental parts (the chain of events). The available documents were carefully reviewed to ensure that each specific occurrence observed in each incident was recorded and cataloged in the proper chronological order. When the exact timing of an occurrence could not be established, the order of occurrence in the overall chronology was surmised based on the information available.

Once the chain of events was established, the next step in the analysis was to examine each elemental occurrence, or event, to assess whether or not (and if so how) a typical fire PRA would have addressed the event. From this process many methodological elements of fire PRA were verified as being a reasonable reflection of actual experience. In a few cases, issues, conditions, or events that are not typically addressed in a fire PRA, or are assumed to be highly improbable, were identified. For example, in some of the incidents an electrical upset led to ignition of fires in more than one area of the plant. Fire PRA methods do not address multiple fires; hence, these incidents illustrate a fire related condition that currently lies outside the scope of a typical fire PRA (see further discussion of this topic in Sections 4.1.2 and 4.1.3).

A third step in the analysis reversed this view of the fire incidents. A fire PRA is based on a probabilistic analysis of fire scenarios. Each fire scenario typically starts with the ignition of a combustible material and ends with damage to some set of plant equipment. Included in the quantification of each scenario is the likelihood that core damage will result from the fire damage, including the impact of the fire and fire damage on operator effectiveness. Each fire scenario can be described in terms of a set of phenomena and specific events. To support the third step in the current analyses, a standardized list of phenomena and events that are considered in a typical fire PRA scenario analysis was developed (see Section 2.4 for this list). This listing was then used like a checklist against the chain of events for each incident reviewed. That is, for each item in the list, the chain of events for an incident was reviewed to see how the specific phenomena described in that item were manifested in the actual fire incident. Insights were gained by comparing what had actually happened to what is typically considered or assumed in a fire PRA. Thus, the current framework for developing fire scenarios in a fire PRA was reviewed to determine whether or not the overall framework itself, the associated analysis assumptions, and the assumed significance of each scenario element to the outcome of the overall scenario are consistent with the experience from the actual incidents.

For those incidents for which sufficiently detailed information was available, and where the incident was of sufficient complexity to warrant this treatment, the above two approaches were explicitly documented via two matrices (e.g., see Appendix 3). One matrix compares the elements of the incident's chain of events to typical PRA practice. The second matrix compares the elements of a typical fire PRA scenario to the events observed during the actual incident. Within each matrix, significant findings are identified as appropriate.

2.4 Elements of a Fire Scenario

The main objective of a PRA is to estimate the frequency of occurrence of such adverse plant conditions as core damage, radio-nuclide release, etc. This is done by identifying chains of events in terms of equipment failures and human errors that may lead to a demand for safe shutdown of the reactor, and/or compromise the ability of the plant to achieve safe shutdown. Systematic methods are used to identify the potentially risk significant chains of events. A fire PRA is conducted by identifying fire scenarios that may affect the safe operation of the plant (through impacts on equipment and human actions), and estimating the frequency of occurrence of those scenarios.[1-3]

The primary output of a fire PRA is typically the estimated frequency of a fire leading to core damage. This value, the fire-induced core damage frequency (CDF), can be expressed as the product of three terms. These three terms are (1) the frequency of the postulated fire or class of fires (f_i), (2) the conditional probability that the postulated fire will cause damage to some set of plant equipment ($P_{ed,j|i}$), and (3) the conditional probability that given the postulated equipment damage the plant operators will fail to recover the plant and core damage would result ($P_{CD:k|i,j}$). This is expressed mathematically as:

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

Each of these three terms is quantified based on the consideration of a number of specific underlying factors. For the purposes of this study, the fire PRA process has been considered in the context of these underlying factors. That is, this study has sought insights at a more detailed level of PRA analysis. The definition and quantification of the underlying factors is accomplished through the development of detailed fire scenarios as implied by the summation terms in the above expression.

Methodology

A fire scenario is a specific chain of events that starts with the ignition of a fire and ends either with successful plant shutdown or core damage. The fire is postulated to occur at a specific location in a specific fuel package and progresses through various stages of fire growth, detection and suppression. Along the way, the fire damages some set of plant equipment (most often electrical cables). For a given fire source, the analysis may postulate damage to different sets of equipment depending on how long the fire burns and how large the initial fire is presumed to be. The postulated or predicted fire damage either directly or indirectly causes an initiating event (such as a plant trip, loss of offsite power, or loss of coolant accident (LOCA)). The possible plant responses to each initiating event are characterized by a set of event trees (or fault trees). Each path through the tree represents one sequence of events that may be realized depending on whether or not other random equipment failures occur and on operator actions. Each event path ends either with recovery of the plant to a safe state (most commonly hot or cold shutdown) or with core damage.

More specifically, the fire scenario first establishes the potential for a fire to occur in a given location and involving a specific fire source. The scenario then follows two parallel and competing processes; namely, fire growth, detection, suppression and eventual extinguishment on one hand and equipment and cable exposure, component or system damage, and operator response on the other hand. The following is a list elements, i.e., the underlying factors, considered in the development of fire scenarios in a typical fire PRA analysis. Note that the list has been divided into three major elements consistent with the three term model presented in Equation (1).

Fire Initiation Frequency:

<u>Combustibles, ignition sources and ignition</u>

- Presence of combustible materials or flammable materials
- Presence of an ignition source
- Uniting of the fuel and ignition source and ignition of the fire

Conditional Probability of Fire Damage:

<u>Fire growth and propagation</u>

- Fire growth within the combustible material or component of original ignition
- Fire propagation to adjacent combustibles
- Development of room effects (plume, ceiling jet, and hot gas layer) within the compartment of origin
- Propagation of effects of the fire or fire effects (i.e., hot gas, flames, and/or smoke) to adjacent compartments

<u>Fire detection and suppression:</u>

- Automatic fire detection
    - Presence of a local automatic fire detection system
    - Operability of the detection system
    - Sounding of an alarm in the control room, locally and/or at other locations

- Manual fire detection
  - Detection by personnel in the area where fire occurs
  - Operators detect/suspect fire based on plant behaviors
  - Plant personnel alerted / fire notification (operators alerted, a fire incident is declared, alarms are sounded, etc.)
- Automatic/fixed fire suppression
  - Presence of a fixed fire suppression system
  - Operability of the suppression system
  - Automatic activation of fire suppression system
  - Dispersion of fire suppressant inside the fire area
- Manual fire suppression
  - Intervention by on-scene personnel
  - Activation of, and response by, the plant fire brigade
  - Manual activation/recovery of a fixed suppression system
  - Manual application of a fire suppressant

<u>Equipment and cable exposure and damage</u>

- Damage to equipment and cables by heat and smoke
- Additional damage as fire continues to burn and propagate
- Impact on plant safe shutdown equipment
- Impact of suppressant on the fire
  - Electrical equipment failure from exposure to water
  - Adverse impact on equipment from the cooling effect of CO_2
  - Flooding of compartments because of discharged fire water

Conditional Probability of Core Damage:

<u>Independent failures</u>

- Aggravation of safe reactor shutdown and core cooling after the occurrence of the fire because of special plant or equipment conditions (e.g., open penetration seals) present
- Degradation in plant response because of random equipment failures upon demand or equipment unavailable because of testing or maintenance activities

<u>Plant and operator recovery actions</u>

- Response of automatic systems to the effects of the fire
- Response of the operators in the control room based on indications and alarms on the control board
- Impact of smoke or other influences on the operators
- Proper plant control by operators and safe shutdown

In reviewing each of the identified fire incidents, the above listed specific fire scenario elements were considered. That is, insights were specifically sought in each of these identified areas. Ultimately, insights were developed in many of these areas, though not all. This is covered in detail in Section 4.

2.5 Quality and Completeness of Available Information

The information available for each of the incidents initially considered for inclusion in this study varied from a few lines in a sketchy summary of an incident report to a full discourse with the persons who were present at the time of the incident. It is interesting to note that even in the case of those incidents for which a large amount of information was available, many questions remained unanswered. Certainly, the availability of detailed information was instrumental to obtaining useful insights and contributed substantially to the authors' confidence in the associated findings and conclusions. However, a lack of complete information did not pose a serious obstacle in allowing us to glean useful insights. That is, even with relatively sketchy information on a given incident, some interesting insights could typically be obtained. In only a very few cases were known incidents excluded due to a lack of information. It is, however, likely that additional insights would have been obtained and that in some areas more definitive conclusions could have been reached if more complete information on some of the incidents had been available.

In a few minor cases conflicting information was discovered. In all such cases, mismatches did not undermine any of the insights and conclusions cited here. As the quantity of information increased for an incident, it became easier to understand the chain of events that took place and to discern the reasons underlying the observed chain of events. Overall, a higher quantity of information greatly facilitated the process of gleaning insights. Also, a higher quantity of information allowed for cross checking of facts and findings (for example between information sources), increasing the authors' confidence in the accuracy of the information and in the validity of our own findings and conclusions.

3.0 SELECTED FIRE INCIDENTS

Twenty-five fire incidents are included in the current review. These incidents include both U.S. and international incidents. Table 3-1 presents a list of the incidents included in this review. The list is presented in simple chronological order and presents the name of the plant, country, incident date and the basis for selecting the incident for review. Detailed descriptions of each incident and the references upon which these descriptions are based are provided in the appendices. The numbers provided in the first column of Table 3-1 refer to the specific appendix that provides the detailed description and analysis of each incident reviewed.

Table 3-1: List of incidents included in the review.

App. #	Plant	Country	Date of Incident	Reason for Inclusion
1.	San Onofre, Unit 1	U.S.	March 12, 1968	Self-ignited cable fire that led to changes in industry's approach to sizing of cables (a similar Feb. 1968 fire is also considered.)
2.	Muhleberg	Switzerland	July 21, 1971	First known large turbine building fire in a nuclear power plant
3.	Browns Ferry, Units 1 and 2	U.S.	March 22, 1975	Cable spreading room and reactor building fire that challenged nuclear safety and led to important changes in USNRC fire protection regulations
4.	Greifswald, Unit 1	GDR / Germany	December 7, 1975	Switchgear and cable fire leading to station blackout and stuck open PORV
5.	Beloyarsk, Unit 2	USSR / Russia	December 31, 1978	Large cable fire that started in the turbine building and spread to other areas of the plant - caused severe damage to the control building and main control room panels - damaged redundant trains
6.	North Anna, Unit 2	U.S.	July 3, 1981	A severe fire involving a large transformer that did not affect any safety related components or electrical circuits.
7.	Armenia Nuclear Power Plant, Units 1 and 2	USSR / Armenia	October 15, 1982	A large cable gallery fire that severely impacted core cooling capability, caused a station blackout and severed power sources to several parts of the plant.

Table 3-1: List of incidents included in the review.				
App. #	Plant	Country	Date of Incident	Reason for Inclusion
8.	Rancho Seco	U.S.	March 19, 1984	Hydrogen fire and explosion in the turbine building
9.	South Ukraine, Unit 2	USSR / Ukraine	December 14, 1984	Cable fire inside containment that propagated to a large area
10.	Zaporizhzhya, Unit 1	USSR / Ukraine	January 27, 1984	Large cable fire lasting nearly 18 hours that damaged several areas of the plant.
11.	Kalinin, Unit 1	USSR / Russia	December 18, 1984	Large fire in the turbine building involving multiple initial fires on a power cable.
12.	Maanshan, Unit 1	Taiwan	July 1, 1985	Large turbine building fire
13.	Waterford, Unit 3	U.S.	June 26, 1985	Main feedwater pump fire involving operator error leading to loss of redundant trains
14.	Fort St. Vrain	U.S.	August 16, 1987	Large turbine building fire involving hydraulic oil that affected control room habitability via smoke ingress
15.	Ignalina, Unit 2	USSR / Lithuania	September 5, 1988	Large, self-ignited cable fire confined to one room that damaged a number of cables - extinguished by the automatic fire suppression system of the room
16.	Oconee, Unit 1	U.S.	January 3, 1989	Fire in a non-safety related switchgear led to human error in proper control of the cooldown rate of the reactor.
17.	H. B. Robinson, Unit 2	U.S.	January 7, 1989	Hydrogen fire at multiple locations during an outage because of maintenance crew error
18.	Calvert Cliffs, Unit 2	U.S.	March 1, 1989	Incident with multiple initial fires including a small fire in the control room
19.	Shearon Harris	U.S.	October 9, 1989	Incident with multiple initial and secondary fires involving one of the main transformers and electrical equipment in the turbine building

Table 3-1: List of incidents included in the review.				
App. #	**Plant**	**Country**	**Date of Incident**	**Reason for Inclusion**
20.	Vandellos, Unit 1	Spain	October 19, 1989	Large turbine building fire that damaged a water pipe expansion joint which led to flooding of the turbine and auxiliary buildings
21.	Chernobyl, Unit 2	USSR / Ukraine	October 11, 1991	Large turbine building fire caused by back-feeding of a generator from the grid - the roof of the turbine building at the location of the fire collapsed from the heat
22.	Salem, Unit 2	U.S.	November 9, 1991	Turbine building fire caused by turbine blade failure and ejection
23.	Narora Atomic Power Station, Unit 1	India	March 31, 1993	Large turbine building fire caused by turbine blade failure - fire led to station blackout and control room abandonment for two units
24.	Waterford, Unit 3	U.S.	June 10, 1995	Switchgear fire that burned the vertical cable drop, jumped over a fire stop, and propagated in a horizontal tray overhead
25.	Palo Verde, Unit 2	U.S.	April 4, 1996	Incident involving multiple initial fires including a small fire in the main control room

4.0 INSIGHTS

The majority of the incidents analyzed in this study were included because they caused significant damage to some part of a nuclear power plant. However, only six of the reviewed fire incidents led to significant challenges to nuclear safety (see Section 4.5.2). One additional event would have led to such challenges had the plant been in operation. Other incidents were included in the study because they demonstrated phenomena that are rarely modeled in a fire PRA, are relevant to a current area of methodological debate, are considered unlikely or illustrate a complex chain of events. Analysis of these phenomena revealed insights that are potentially relevant to fire PRA methods, underlying assumptions and data. In this section, a consolidated listing of various insights and a discussion of the potential implications for fire PRA are provided.

The presentation of insights is organized into five sections (Section 4.1 through Section 4.5) based on the elements of a typical fire PRA analysis as discussed in Section 2.4 above. Recall that a typical fire PRA addresses three primary topics based on the three-term model (Equation (1)); namely, the fire initiation frequency, the conditional probability of equipment damage given the fire, and the conditional probability of core damage given the fire-induced equipment damage. Many of the insights gained are related to the second topical area, the conditional probability of fire damage. Hence, insights in this area have been further divided into three sub-topics; namely, fire propagation, fire detection and suppression, and equipment damage.

Fire initiation covers issues related to ignition of fire, fire occurrence frequency analysis, the possibility of multiple fires from a common cause and the possibility of a fire leading to secondary fires. Related insights are presented in Section 4.1. Fire propagation includes issues related to fire growth, propagation to adjacent combustibles and adjacent compartments, smoke propagation and barrier failure. Issues related to the occurrence of large fires are discussed as part of this category. Related insights are presented in Section 4.2. Fire detection and suppression addresses the availability and effectiveness of fire suppression systems, the possibility of fixed suppression systems being overwhelmed by a fire and, more generally, the duration of fires. Insights in this area are presented in Section 4.3. Insights relating to the possibility, timing and modes of fire-induced equipment damage are discussed in Section 4.4. Section 4.5 covers insights relating to the impact of fires on plant safety including issues related to plant response to equipment failure, fires that challenged nuclear safety and operator actions.

A summary of the incidents reviewed is presented in Table 4-1. This table identifies each incident, calls out some of the salient points for each, and identifies some of the specific areas of interest identified in the incident review. The bases of assignment of different sub-categories to each incident are provided in the Appendices and are summarized in the sections that follow.

Table 4-1 Summary of Incident Review Results (page 1 of 4)

Appendix #	Plant	Country	Date	Fire Initiation				
				Cause of Fire	Building or Room of Origin	Multiple Fire	Secondary Fire	Self Ignited Cable Fire
1	San Onofre, Unit 1	US	07-Feb-68	Cable overheated	Penetration area	No	No	Yes
			12-Mar-68		Switchgear room			
2	Muhleberg	Switzerland	21-Jun-71	Turbine oil system failure	Turbine building	No	No	No
3	Browns Ferry	US	22-Mar-75	Open flame	Reactor and control buildings	No	Yes*	No
4	Greifswald, Unit 1	GDR	05-Dec-75	Electrical short	Control building*	No*	No*	No
5	Beloyarsk, Unit 2	USSR	31-Dec-78	Turbine oil system failure	Turbine building	No	Yes (8)	No
6	Fort St. Vrain	US	16-Aug-80	Turbine oil system failure	Turbine building	No	No	No
7	North Anna, Unit 2	US	03-Jul-81	Transformer fault	Yard	No	No	No
8	Armenia NPP	USSR	15-Oct-82	Short in power circuit	Cable Tunnel (and Turbine Building)	Yes	Yes	Yes
9	Rancho Seco	US	19-Mar-84	Hydrogen release	Turbine building	No	No	No
10	South Ukraine, Unit 2	USSR	14-Dec-84	Shorts in cables	Containment	No	Yes	Yes
11	Zaporozhye, Unit 1	USSR	27-Jan-84	Electric Panel	Control building	No	No	Yes*
12	Kalinin, Unit 1	USSR	18-Dec-84	Breaker fails to open	Service water pump area	Yes	No	Yes
13	Maanshan, Unit 1	Taiwan	01-Jul-85	Turbine blade ejection	Turbine building	No	No	No*
14	Waterford, Unit 3	US	26-Jun-85	Manufacturer error	Turbine building	No	No	No
15	Ignalina, Unit 2	USSR	05-Sep-88	Cable failure	Control room	No	No	Yes
16	Oconee, Unit 1	US	03-Jan-89	Switchgear failure	Switchgear room	No	No	No
17	H. B. Robinson, Unit 2	US	07-Jan-89	Hydrogen release	Turbine building	Yes	No	No
18	Calvert Cliffs, Unit 2	US	01-Mar-89	Electrical panel and solenoid	Control building and turbine building	Yes	No	No
19	Shearon Harris	US	09-Oct-89	Bus duct ground fault	Turbine building and yard	Yes	Yes	No
20	Vandellos, Unit 1	Spain	19-Oct-89	Turbine blade ejection	Turbine building	No	No	No
21	Chernobyl, Unit 2	Ukraine	11-Oct-91	Grid back feed into generator	Turbine building	No	No	No
22	Salem, Unit 2	US	09-Oct-91	Turbine blade ejection	Turbine building	No	No	No
23	Narora Unit 1	India	31-Mar-93	Turbine blade ejection	Turbine building	No	No	No
24	Waterford, Unit 3	US	10-Jun-95	Breaker failure to open	Switchgear room	No	No	No
25	Palo Verde, Unit 2	US	04-Apr-96	Short to ground	Control room and auxiliary building	Yes	No	Yes

Table 4-1 Summary of Incident Review Results (page 2 of 4)

Appendix #	Plant	Fire Protection					Nuclear Safety			
		Severe Fire (1)	Fire Propagated to Other Compartments	Smoke Propagated to Other Compartments	Smoke in the Control Room	Control Room Evacuation	Challenging Fire (2)	Multiple Safety Systems Impacted	Loss of All Core Cooling for Some Period	Loss of All Instrumentation
1	San Onofre, Unit 1	No	No	No*	No	No	No	No	No	No
2	Muhleberg	Yes	Yes*	Yes*	No	No	No	No	No	No
3	Browns Ferry	No	Yes	Yes	Yes	No	Yes	Yes	No	No
4	Greifswald, Unit 1	Yes	No*	No*	No*	No*	Yes	Yes	Yes	No*
5	Beloyarsk, Unit 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Not Known	Yes*
6	Fort St. Vrain	Yes	No	Yes	Yes	No	No	No	No	No
7	North Anna, Unit 2	Yes	No	No*	No	No	No	No	No	No
8	Armenia NPP	Yes	Yes	Yes	Yes	No*	Yes	Yes	Yes	Yes*
9	Rancho Seco	Yes	No	No	No	No	No	No	No	No
10	South Ukraine, Unit 2	Yes	Yes	Yes	No	No	No (4)	Yes	No	Yes*
11	Zaporozhye, Unit 1	Yes	Yes	Yes	Yes	No*	No (4)	Yes	Yes(4)	Yes*
12	Kalinin, Unit 1	Yes	No*	No*	No	No	No	No	No	No
13	Maanshan, Unit 1	Yes	No*	No*	No*	No*	No	No	No	No
14	Waterford, Unit 3	No	No	No	No	No	No	No	No	No*
15	Ignalina, Unit 2	Yes	No	No	No	No	Yes	Yes	No	No*
16	Oconee, Unit 1	No	No	Yes	Yes	No	No (3)	No	No	No
17	H. B. Robinson, Unit 2	No	No	No	No	No	No	No	No	No
18	Calvert Cliffs, Unit 2	No	No	No	Yes*	No	No	No	No	No
19	Shearon Harris	No	No	No	No	No	No	No	No	No
20	Vandellos, Unit 1	Yes	No	Yes	Yes	No	Yes	Yes	No	No
21	Chernobyl, Unit 2	Yes	No	No	No	No	Yes	Yes	No	No
22	Salem, Unit 2	Yes*	No	No*	No	No	No	No	No	No
23	Narora Unit 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
24	Waterford, Unit 3	No	No	Yes	No	No	No	No	No	No
25	Palo Verde, Unit 2	No	No	No	Yes (7)	No	No	No	No	No

Table 4-1 Summary of Incident Review Results (page 3 of 4)

Appendix #	Plant	Indications of Spurious Equipment Actuation	Included Some Strucural Damage (5)	Fire Detection and Suppression: Time to . . . . [hr:min] (6): Last Damage	Fire Detection and Suppression: Time to . . . . [hr:min] (6): Fire Under Control	Fire Detection and Suppression: Time to . . . . [hr:min] (6): Fire Out	Fire Detection and Suppression: Manual Suppression Used	Fire Detection and Suppression: Automatic Suppression System	Fire Detection and Suppression: Suppression System Overwhelmed
1	San Onofre, Unit 1	No	No	--	--	<0:05	Yes	No	No
		No*		--	--	0:39			
2	Muhleberg	No	Yes	--	--	2:07	Yes	No	No
3	Browns Ferry	Yes	No*	5:10	6:55	7:25	Yes	Yes	No
4	Greifswald, Unit 1	No*	No*	--	--	1:32	Yes*	No*	No*
5	Beloyarsk, Unit 2	No*	Yes	--	17:05	21:40	Yes	No*	No
6	Fort St. Vrain	No	No	0:09	--	0:16	Yes	No	No
7	North Anna, Unit 2	Yes	Yes*	--	1:00	>1:00	Yes	Yes	Yes
8	Armenia NPP	Yes	No	2:50	6:05	7:03	Yes	No	No
9	Rancho Seco	No	No*	--	--	0:14	No	Yes	No
10	South Ukraine, Unit 2	Yes*	No	--	--	8:00	Yes	No	No
11	Zaporozhye, Unit 1	No*	No	--	--	17:50	Yes	Yes	No
12	Kalinin, Unit 1	No*	No	--	1:46	2:52	Yes	Yes	No
13	Maanshan, Unit 1	No*	Yes*	--	--	10:00	Yes	No	No*
14	Waterford, Unit 3	No	No	--	--	0:10	Yes	Yes	No
15	Ignalina, Unit 2	No*	No	0:18	--	0:38	No	Yes	No
16	Oconee, Unit 1	No	No	--	--	0:59	Yes	No	No
17	H. B. Robinson, Unit 2	No	No	--	--	very short	Yes*	No	No
18	Calvert Cliffs, Unit 2	No	No	--	--	very short	Yes	No	No
19	Shearon Harris	No	No	--	--	2:40	Yes	Yes	No
20	Vandellos, Unit 1	No	Yes	1:54	3:51	6:21	Yes	Yes	Yes
21	Chernobyl, Unit 2	Yes	Yes	--	3:31	6:10	Yes	No*	No
22	Salem, Unit 2	No	No*	--	--	0:15	Yes	Yes	No
23	Narora Unit 1	No	Yes	0:30	1:30	9:00	Yes	No*	No
24	Waterford, Unit 3	Yes	No	0:10	1:24	2:37	Yes	No*	No
25	Palo Verde, Unit 2	No	No	--	--	very short	Yes	No*	No

Table 4.1 Summary of Incident Review Results (page 4 of 4).

Notes for Table 4.1:

* - Entry is based on the judgement of the authors

(1) "Severe" is in the context of traditional fire protection; that is, a severe fire impacts a large area or caused extensive damage

(2) "Challenging" is in the context of nuclear safety; that is, a fire is challenging if it created a demand for safe shutdown systems and rendered such systems unavailable

(3) The Oconee fire is not classified as challenging because no safety systems were lost to the fire itself. However, an operator error did lead to an overcooling transient.

(4) At the time of the fire, the plant was not yet in operation. Had the plant been in operation, a severe nuclear challenge would have been experienced in the judgement of the authors.

(5) Structural damage is defined as deformation or collapse of a structural element.

(6) All time periods reported here are measured from the moment that some indication of an abnormal condition was received by plant personnel.

(7) In this case, the smoke observed in the control room was due to the small simultaneous fire that occurred there rather than due to movement of smoke about the plant.

(8) The secondary fire at Beloyarsk involved the explosion of an oil-filled transformer. The exact cause of this event is not known.

4.1 Fire Initiation

4.1.1 Self-ignited Cable Fires

Electrical cables are often considered as a source of fires in fire PRA because they carry electric power (a potential source of ignition) and are constructed of materials that can sustain combustion. A fire that initiates from a cable, either due to a fault in the cable or due to a current overload, is referred to as a self-ignited cable fire. Special precautionary measures are incorporated in the design, selection and installation of cables in nuclear power plants that will tend minimize the probability of such events (i.e., limits on ampacity (current carrying capacity) and requirements to use low-flame-spread cables in new installations). Self-ignited cable fires are commonly assumed to be very low probability events. Therefore, occurrence of such fires is of particular interest.

Self-ignited cable fires have occurred at San Onofre in the U.S., and at various Soviet[4]-designed plants (e.g., Armenia, Kalinin, South Ukraine and Zaporizhzhya). The Palo Verde fire reviewed in this study may also be considered a self-ignited cable fire. The Browns Ferry (1975) fire may also have included a secondary fire (in the main control room, see Section 4.1.3 for a description of this secondary fire) that can be categorized as a self-ignited cable fire. It appears that in all cases the ignition was the result of either a cable electrical design overload (i.e., inadequate cable design), mechanical damage to cables or excessive current due to other electrical faults. It is interesting to note that, as shown by the fire incident at Ignalina, a self-ignited cable fire may occur in circuits with a voltage level as low as 220VAC.

The incidents reviewed in this study involving self-ignited cable fires at Soviet-designed reactors caused substantial to very large fires (i.e., they were not minor fires). In some cases the fires ultimately impacted a large collection of cables and/or plant areas, and had a major impact on the core cooling capability. Of the U.S. incidents known to the authors, only the San Onofre (3/1968) fire has shown significant fire propagation beyond the initiating cable. In that case it was reported that three horizontal stacked cable trays were burning at the time that the fire brigade arrived on the scene (several minutes after the apparent time of ignition). The fires observed in the other U.S. incidents have all remained very small (i.e., the ensuing fires have not propagated beyond the initiating cable). None of the self-ignited cable fires in U.S. plants led to a substantial nuclear safety challenge.

This sharp difference between the U.S. and Soviet experience indicates that there are likely substantial differences between the U.S. and Soviet plants that are impacting this behavior. It can be argued that if significant differences did not exist, that is, if the frequency and behavior of self-ignited cable fires were similar, then based on the experience in Soviet designed plants there should have been several occurrences of substantial self-ignited cable fires at the U.S. plants by now. This is because U.S.

[4]Practically all fire events analyzed in this study involving a Soviet-designed plant occurred before the break-up of the Soviet Union. Therefore, these plants are referred to as Soviet-designed plants.

nuclear power plants have logged close to three times as many reactor-years as have plants in the former Soviet Union. Hence, one would nominally anticipate several significant self-ignited cable fires in U.S. plants if the factors leading to the initiation and growth of such fires were substantially similar. The available evidence contradicts this; hence, there is likely some substantial differences between the U.S. and Soviet-designed reactors that would account for this difference. The differences are likely rooted in cable manufacturing and materials selection, installation and maintenance practices, and electrical design characteristics. Based on this argument, one can conclude that the Soviet reactor experience relating to self-ignited cable fires may not be directly relevant to plants in the U.S. and should be extrapolated with caution.

Very few events involving self-ignited cable fires were identified in the initial screening of fire incidents for this study. This nominally confirms, at the least for U.S. plant applications, the basic understanding in fire PRA that such fires are low frequency events. It is also noteworthy that San Onofre, apparently the only plant in the U.S. that has experienced a propagating self-ignited cable fire, was a relatively old plant (commercial operation began in 1968 and the plant is now permanently shut down). San Onofre was constructed before the development of the cable flammability standards currently applied to U.S. reactor cables (the flammability test included in IEEE-383).[22] This nominally confirms typical fire PRA assumptions that a propagating self-ignited cable fire is more likely to occur in older style cables than in modern low-flame-spread cables. The San Onofre experience does illustrate that, at the least for the older style pre-IEEE-383 cables, the possibility of a self-ignited cable fire with the potential to propagate to nearby fuels (e.g., nearby cable trays) cannot be dismissed. The fact that several significant self-ignited cable fires involving Soviet-designed plants were identified is perhaps of greater interest to PRA analysts working with non-U.S. plants than it is to U.S. plants. Overall, current methods of analysis are capable of dealing with such fires, but the underlying assumptions and methods of analysis may warrant further review.[5]

4.1.2 Simultaneous Ignition of Multiple Fires

All current fire PRAs are conducted based on the assumption that, at any given time, only one fire ignition will occur. This has been recognized in past reviews as a potential weakness of existing methods.[23] Although, some fire PRA methodology sources have addressed multiple fires (e.g., Reference [24] uses the methodology presented in Reference [25] for this purpose), it has commonly been assumed that the occurrence of multiple fires, while possible, is a very low probability event. Several of the incidents reviewed here involved simultaneous ignition of multiple fires. That is, fire appeared at two or more distinct plant locations, within a very short time period, due to a single root cause. Most of the current methodologies do not address the occurrence possibility of multiple simultaneous fire incidents because there is no basis established for predicting under what conditions such fires might occur.

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[5]Note that Task 3 of the USNRC/RES Fire Risk Methods research program, JCN Y6037, is specifically addressing the question how self-ignited cable fires are treated in fire PRA.[11]

Several incidents (Armenia, Kalinin, South Ukraine, H. B. Robinson, Palo Verde, Shearon Harris and Calvert Cliffs) demonstrate that multiple fires can occur. The common element in most of these incidents is a common electrical connection. Since an electrical circuit may be connected via cables to several items in different and potentially remote compartments, a circuit fault that impacts the cables may impact several locations. Case examples identified in this review are as follows:

– In the cases of Palo Verde and Calvert Cliffs, a short in a circuit led to sparks, smoke and signs of ensuing fire ignition at two separate locations that were considerably far apart but were linked by the same faulty electrical circuit. In both incidents, the fires remained very small and did not propagate substantially. Also in both incidents, one of the areas effected was the main control room.

– During an outage at H. B. Robinson, because of a maintenance crew error, a high pressure hydrogen gas source (the generator hydrogen) was connected to the plant air system. The air system was being used at various points to power air tools and other applications. As a result, several minor fires were ignited in the turbine building. This is the only identified multiple fire incident that did not, at some level, involve a common electrical circuit.

– The fire at the Armenia plant was caused by a faulty breaker in a power circuit. This fault caused a power cable to overheat and catch fire at several places in more than one room. This led to rapid propagation of the fire into two adjacent rooms and the loss of many of the plant power, instrumentation and control cables.

– At Kalinin, there were three ignitions on three different items at three different locations. When control circuits and breakers failed, a service water pump motor started rotating in the wrong direction and started sparking. This led to a cable fire nearby. Also, a switchgear cubicle associated with the pump caught fire. Finally a 6 kV power cable inside the turbine building feeding the switchgear caught fire at several locations along its length. In this case, all ignitions took place inside the turbine building, and the common link was association with the same electrical system.

– At Shearon Harris, ground faults near the “B” main transformer eventually led to three different fires at two general locations. Two of these fires are regarded as simultaneous fires (the third is considered a secondary fire, see Section 4.1.3). The ground fault caused low voltage bushings in the transformer to crack spilling transformer oil which ignited. The electrical disturbance cascaded to the transformers neutral conductor which was not designed to withstand the imposed voltage. Electrical current arced through an insulating tape opening holes in the generator hydrogen piping. This led to a hydrogen leak and fire.

The identification of several incidents in which there were multiple initial fires suggests that the statistical frequency of these incidents may not be as low as previously assumed. Hence, it may be appropriate to further investigate incidents of multiple fire initiations to better understand the circumstance that lead to such fires, and to more clearly define the potential risk implications. If the risk implications are potentially significant, then some development of appropriate analysis methods would also be needed.

4.1.3 Secondary Fires

Secondary fires are considered as distinct from multiple initial fires (see Section 4.1.2 above). Note that the simple or direct spread of fire from one fuel package to another (for example, from one cable tray to another adjacent tray) is not classified as a secondary fire ignition. Rather, a secondary fire as defined here is a fire ignited as the result of some mechanical or electrical failure caused by the initial fire. Case examples identified in this review are as follows:

– In the Armenia fire, a generator and start-up transformer caught fire due to shorts caused by the initial fires in the cable galleries. The generator breaker closed due to cable faults and allowed the generator to rotate in the motor mode. The start-up transformer exploded and the generator failure led to a turbine oil fire that damaged a significant area of the turbine building. In this incident the secondary fires were very severe.

– At South Ukraine a cable fire started inside the containment due to mechanical damage to power cables (the initial fire). In addition, relay coils were found burning in panels outside of the containment (a set of secondary fires). The fires involving the relays were attributed to fire-induced shorts in the associated control cables within containment. In this case, the secondary fires did not propagate and had little impact.

– Also at South Ukraine, secondary fires were ignited in rooms adjacent to the initial fire room within the containment. In some of these cases, there was apparently no direct flame spread path and the secondary ignitions are attributed to the spread of hot gasses alone. It is postulated here that the hot gasses caused failure of energized cables in the adjacent space, and the resultant arcing was sufficient to ignite the cables. This would be consistent with test data from Sandia National Laboratories (SNL).[26] In the SNL tests it was observed that cable electrical shorting led to ignition of the cables during air-oven tests. The SNL report concluded that the failure of an energized electrical cable might lead to fire propagation. This incident appears to confirm this observation.

– In the Browns Ferry (1975) fire a large number of cables associated with penetrations between the cable spreading room and the reactor building burned. There are indications in the congressional record that a small secondary fire was ignited in the main control room.[27] The fire was apparently quite minor, and was quickly suppressed by an operator, who reported seeing smoke coming from the panel, using a hand-held extinguisher. This secondary fire had no apparent impact on the chain of events observed. Cables shorting in the larger fire may have led to current overloads on a cable leading into the main control room panels and in turn to a secondary fire.

- At Shearon Harris, in addition to multiple simultaneous fires (see Section 4.1.2), the hydrogen fire (caused by the initial electrical disturbances) impinged on the generator housing leading to a secondary oil leak and fire.

- At Beloyarsk, while the primary fire was associated with burning turbine lube oil that spread into a cable shaft and the control building, at one point an oil-filled transformer also ruptured and the oil caught fire igniting additional cables in the area. The cause of this secondary transformer fire is not known (possibilities would include direct fire exposure or electrical faulting).

Secondary fires, similar to multiple fires (see Section 4.1.2), are not modeled in a fire PRA. Most current methodologies do not address this issue. There is currently no basis for estimating when, how often, and where secondary fires might occur. Without such a basis, PRAs will be unable to quantitatively assess the risk implications of secondary fires. It may be noted that if a methodology existed for identifying secondary (or multiple initial) fire scenarios, current fire PRA methods could be used to establish their plant impact and risk significance. Given that a number of such cases were identified, a study to assess the potential risk implications, similar to that recommended for multiple initial fires in Section 4.1.2 above, may be appropriate.

4.1.4 Fire During an Outage

During a major outage, when the reactor is in cold shutdown, a plant's configuration is commonly altered to accommodate repair and maintenance activities. Under such conditions, the fire risk profile is quite different from the conditions of normal plant power operation. For example, the H.B. Robinson, January 7, 1989 incident demonstrates that new hazards may be introduced into the plant. In this incident, a hydrogen source was erroneously connected in such a way that hydrogen back-fed into the plant compressed air system. This error created a potential for hydrogen explosion and fire at several locations of the plant that would otherwise be considered free of major combustibles. Several small fires were observed, though none was ultimately significant. This scenario could only happen during an outage when the turbine is shutdown. Relatively few shutdown fire PRAs have been performed to date. In a shutdown fire PRA it may be appropriate to consider the possibility of such special conditions and the potential for introduction of fire sources and fuels not present during power operations.

4.2 Fire Propagation

4.2.1 Barrier Failure and Room-to-Room Fire Spread

The incidents reviewed illustrate that fire can spread past fire barriers, including room-to-room fire spread, even when the initial fire is not overly severe. Case examples identified in this review are as follows:

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- At Waterford 3, a non-safety related switchgear fire propagated up along a vertical cable riser and then horizontally along an intersecting cable tray. The fire stopped its progress on the horizontal trays at a fire stop constructed within the cable tray. However, a similar fire stop existed in the vertical section of the cable trays that proved to be ineffective. The fire propagated past this barrier. (This case did not involve any room-to-room spread of the fire.)

- From the information available on the cable fire at Zaporizhzhya, it can be inferred that at one point the fire overwhelmed existing and intact fire barriers and propagated to adjacent areas.

- During the fire at South Ukraine hot gases and flames damaged the seals in the ceiling of the initial fire compartment, opened a path for fire spread and caused the cables in the upper compartment to start burning. Also at South Ukraine fire spread to an adjacent compartment apparently due to the spread of hot gasses alone rather than via a direct path of flame propagation (see Section 4.1.3 for further discussion of this behavior).

- At Armenia, open hatchways, open doors and unsealed cable penetrations allowed the fire to propagate from the cable gallery into a cable shaft.

- At Browns Ferry, the fire initiated in the cable spreading room and initially involved the readily combustible and exposed polyurethane foam of an incomplete cable penetration seal. The fire propagated immediately through a gap in the penetration seal into the adjacent reactor building. This spread was enhanced by air flow through the penetration seal gap caused by the negative pressure in the reactor building. In this case the penetration seal was not complete (i.e., the seal was still under construction and lacked non-combustible cover panels). Hence, the implications for a completed seal system cannot be directly inferred.

- At Beloyarsk, the fire began in the turbine building and propagated into the adjacent control building via open cable penetrations and other openings. In the control building, the fire propagated upwards inside cable shafts and spread through open cable penetrations and leaking or open doors and hatches into various adjacent areas. The fire also propagated into the control panels of the Main Control Room (MCR) and caused damage there.

In fire PRAs it is assumed that all barriers are designed and constructed properly and that they can confine the effects of a fire such that the likelihood of propagation beyond the barrier is very small. This assumption is typically verified by a walkdown of the plant conducted in the early stages of a fire PRA. In fire PRAs barrier failures are modeled probabilistically. That is, a typical fire PRA will assume a nominal random failure probability for a fire barrier element given a substantial fire exposure (typically a value of on the order of 0.01 is cited as a conservative estimate of the probability of failure per demand). The incidents reviewed in this study point out that some attention to the specific condition of the barriers (e.g., incomplete or degraded barrier seals and left open doors) is warranted. Plant walkdowns should be able to identify these special conditions.

Several of the fires reviewed involving Soviet-designed plants experienced significant room-to-room fire spread. It is concluded, however, that these incidents are not proper examples of the anticipated behavior in U.S. plants. In these specific incidents unsealed or poor quality cable penetrations were cited as a significant factor in the observed fire spread. In one case (Armenia) open doorways and hatchways were also cited as contributing to fire spread. The only case of room-to-room fire propagation experienced to date in a commercial U.S. reactor is the 1975 Browns Ferry fire. In this case, the spread of fire from the cable spreading room into the reactor building is directly attributable to the incomplete nature of the cable penetration seals at the time of the fire and the air pressure difference between the two sides of the wall. The experience of the authors would support a conclusion that there is much more attention to detail paid to fire barrier penetration seals in the U.S. While there is a statistical likelihood that a fire barrier penetration might be found degraded or missing, the experience in the Soviet-designed plants illustrates far more significant problems in this regard than that experienced in the U.S. It should also be noted that the current operators of the Soviet-designed plants now recognize the importance of intact and quality fire barriers to plant safety. Considerable effort has been, and is being, expended to ensure that fire barrier penetrations are appropriately sealed at reactor sites in the former Soviet Union.[28]

Fire PRA methods are capable of identifying potentially risk significant room-to-room fire propagation or fire damage scenarios. Most fire PRAs will include a specific analysis of room-to-room fire scenarios. In most cases in the U.S., these scenarios are ultimately found to be of little risk significance. In part, this can be attributed to typical practice with regard to defining fire zones and fire areas. The defined fire zones or fire areas often encompass several inter-connected compartments. As a result, a fire analysis involving such fire zones or areas may inherently include the possibility of fire propagation to several compartments. It would appear that the adverse experience in the Soviet designed reactors can be attributed to a lack of attention to sealing penetrations and maintaining fire barriers intact (e.g., open doors and open hatchways). Considerable attention is given to the topic of fire barriers and penetration seals in U.S. reactors.[29] Also, an integral part of fire PRA methodology is a detailed walkdown of the plant. Communication paths among compartments and often the as-built condition of the fire barriers are specifically addressed in those walkdowns. Also, the possibility of hot gas layer propagating from one compartment to another is included in fire PRA methodology (e.g., Reference [3] addresses this issue). Hence, it appears reasonable to conclude that current methodology for the analysis of room-to-room fire spread in U.S. reactors is adequate.

4.2.2 Propagation of Fire Effects to Adjacent Compartments

Several fire incidents addressed in this study included propagation of fire effects (e.g., hot gases and/or smoke) to areas of the plant other than the compartment where the fire originated. (This section will address the spread of smoke and heat between general plant areas. See Section 4.2.1 for a discussion of the spread of actual fire past fire barriers and Section 4.2.3 for a specific discussion of smoke movement impacting the main control room). Indeed, in many of the major incidents reviewed there was some substantial propagation of smoke to adjacent areas. In the cases involving Soviet-designed reactors, the lack of, or deficiencies in, fire barriers and barrier penetration seals was a significant contributing factor to fire, heat, and smoke spread from compartment to compartment. Case examples identified in this review are as follows:

– At Muhleburg, dense smoke spread throughout the turbine building. Ultimately, the long-term indirect impact of the fire was considerably more extensive than direct heat damage. The hydrochloric acid vapors generated in the process of burning PVC cable insulation and interaction with moisture impacted a large set of equipment. Ultimately some of the electronic equipment, pump motors, 380VAC motor control centers, switchgear and some of the mechanical equipment had to be replaced because of chloride deposits and corrosion.

– During the Browns Ferry fire, parts of the reactor building remote from the fire were filled with dense smoke such that several attempts to manually adjust valves failed.

– At Beloyarsk, the fire started in the turbine building and rapidly propagated into several areas in the control building (as noted in Section 4.2.1 above). Smoke spread through the various rooms hampered fire fighting efforts.

– At Armenia, the fire initiated simultaneously in two compartments. However, open hatchways, open doors and unsealed cable penetrations allowed the fire to propagate to a cable shaft and ultimately allowed smoke to enter the control room.

– At South Ukraine during the containment fire, two propagation scenarios are of particular interest. First, hot gases propagated from one compartment, via openings, into an adjacent compartment and caused the cables in the second compartment to catch fire. No direct path for flame spread apparently existed. In this study, it has been surmised that the secondary ignition may have been the result of arcing in thermally failed energized cables. Second, hot gases and flames damaged seals in the ceiling of the source compartment, opened a propagation path, and caused the cables in the upper compartment to start burning.

– At Zaporizhzhya, the fire started at or near an electrical cabinet. It propagated, via burning cables, into cable shafts. The cable penetration seals were not complete or were intentionally opened for maintenance at the time of this incident (the plant was still under construction). Also, from the information provided, it appears that at one point the fire overwhelmed existing intact fire barriers and propagated to adjacent areas. The fire propagated to a large number of areas and affected almost all elevations of the control building.

– At Vandellos, where ejected turbine blades caused a rupture in several oil lines and a large oil and hydrogen fire, smoke from the turbine building fire entered the control room and several other parts of the plant. Automatic fire suppression systems were activated in areas remote from the actual fire due to smoke. Furthermore, plant personnel had to wear self-contained breathing apparatus (SCBA) to enter certain areas of the reactor building to manually adjust flow control valves (note that these manual actions were successful as discussed further in Section 4.5.4).

– At Narora, where similar to Vandellos, ejected turbine blades caused an oil spill and fire, the fire propagated along a set of cable trays towards a wall separating the turbine-generator area from a control equipment room. Because of ineffective fire barriers, the fire entered the control equipment room.

– At Waterford (1995) a dense plume of smoke reportedly billowed out of the switchgear room where the fire was burning when the door to that room was opened.

For the Soviet-designed reactors smoke spread was a significant factor in each of the fire incidents reviewed in this study. It was also a significant factor in the Vandellos and Narora fires as well. The primary impact of smoke spread was the hampering of operator recovery actions and fire fighting activities. In one case, the spread of heat and smoke alone is attributed with causing fire spread to an adjacent compartment. The U.S. experience also includes incidents where smoke has propagated from the room of fire origin to other plant areas. However, none of the cases in U.S. reactors led to significant damage or other adverse effects, although some hampering of operator actions is evident (e.g., Browns Ferry and Section 4.2.3 below).

The incidents, both in the U.S. and abroad, demonstrate that the propagation of smoke from one area to another can have a significant impact on the progression of the events. Several incidents led to the ingress of smoke into the main control room, although only one case (Narora) actually led to control room abandonment (see Section 4.2.3).

Smoke movement is not explicitly modeled in current fire risk assessments. While there are models available that can predict smoke movement, these models are not typically applied to nuclear plant risk assessments. As mentioned above, smoke prevented mitigative actions in the Browns Ferry fire and complicated recovery actions during the Narora and Vandellos fires. Current PRA methodologies, through human error analysis, have provisions to address this issue.

In the specific case of smoke movement and fire suppression actuation, as a result of the USNRC attention to the issue of adverse environmental effects on fire suppression systems[30], few fire suppression systems in the U.S. are currently designed to actuate on a smoke detector signal alone. Hence, actuation would typically require that a substantial quantity of heat find its way from room-to-room (to activate a fusible link or other heat detector). This review is inconclusive on this particular problem. As noted above, in the case of Vandellos fire suppression systems in areas not directly involved in the fire were activated. It would appear that smoke movement and smoke detectors were the cause of these actuations.

4.2.3 Smoke in the Control Room

In several incidents, both in U.S. and non-U.S. plants, smoke has entered the control room as a result of fires elsewhere in the plant. In some cases the smoke does appear to have affected the operators' effectiveness. Case examples identified in this review are as follows:

Insights

– At Browns Ferry, some smoke from the cable spreading room did enter the control room. Short term air packs were available for the operators. An air hose was brought in to pump fresh air into the control room. Operator actions were not seriously impacted.

– At Beloyarsk, where the fire started in the turbine building and propagated into the control building, the smoke in the control room was so heavy that it adversely affected the operators. There were also reports that the fire actually propagated to the control room and caused some damage there. However, the operators were ultimately successful in preventing any core damage. The actions that the operators took and the locations of those actions are not provided in the available information. It does appear that at least some operators did man the control room throughout the event.

– At Fort St. Vrain smoke from the turbine building fire found its way into the main control room. The smoke was initially drawn in through ventilation system intakes located in the turbine building. The ventilation system was switched to smoke purge mode which isolated this source, but smoke continued to enter the control room. The smoke did not lead to control room evacuation and apparently did not cause any significant adverse effects on the operators. Breathing apparatus was available for the operators, although some reports state that not enough masks were available so they had to be shared between operators.

– During the Armenia fire, smoke entered the control room via a cable shaft. Although the operators remained in the control room at all times and continued to monitor and control the plant, the smoke apparently was relatively dense and made habitability difficult.

– At Zaporizhzhya, smoke apparently spread to most areas of the control building including the main control room. The plant was not in operation at the time of the fire so there was no impact on plant operations.

– At Oconee 1, a non-safety related switchgear caught fire and caused damage to the integrated control system (ICS) and tripped several important, but non-safety related, pieces of equipment. One report states that smoke found its way into the control room and affected the control room operators.[31] This reference states that the burden on the operators was not inconsequential because of integrated control system failures, presence of the fire in the plant, smoke in the control room and other problems.

– Reports of the fire at Calvert Cliffs do cite smoke in the main control room as one factor that contributed to the operator error that led to the overcooling transient. No information is provided as to how, nor how much, smoke made its way into the control room.

– During the Vandellos fire, the control room ventilation system drew in smoke-laden air from the turbine building. Smoke entered the control room in the first few minutes of the fire. SCBAs were made available to the operators, but no one felt the need to wear them indicating that the quantity of smoke must have been relatively low. In a short time, plant personnel provided portable fans for the control room, pumped fresh air into that room and cleared the room of smoke.

– At Narora, smoke entered the main control room through a ventilation system connection with the turbine building and from a fire inside the control equipment room that was adjacent to the control room. Smoke ingress took place rather rapidly. The operators had to leave the main control room about 10 minutes into the accident and were not able to re-enter for about 13 hours.

In the incidents reviewed, with the exception of Narora, the operators managed to take the proper actions from the control room despite adverse environmental conditions. In a typical fire PRA it is assumed that if smoke enters a compartment, no credit can be given to operator actions within that compartment. In the case of the control room, few fire PRAs have explicitly considered smoke ingress into the main control room from fires outside the control room, although the impact of smoke arising from fires initiated in the main control room is explicitly considered.

It appears that the typical PRA treatment of operator actions in general plant areas impacted by smoke (i.e., not crediting such actions) would be conservative when applied to actions that take place in the control room. The experience demonstrates that even given significant smoke ingress into the control room, operators can continue to operate the plant from the control room. However, it would also appear that smoke ingress into the control room from general plant fires is more likely than is inherently assumed in current fire PRAs. Several incidents involved substantial smoke ingress, and some the use of self-contained breathing apparatus (SCBA) by operators. In a number of these cases some operational difficulties are reported as a result of smoke in the control room. However, only under very severe conditions did smoke alone lead to main control room abandonment (i.e., Narora).

Fundamentally, existing human reliability methods are capable of dealing with smoke and donning of SCBA as performance shaping factors (this is discussed further in Section 4.5). What is lacking is a basis for predicting when and how much smoke might find its way into the main control room in any given fire incident and specific guidance regarding modification of human error probabilities to reflect smoke effects or use of SCBA. Typical PRA practice assumes that fires outside the control room will have no impact on operator reliability for actions that take place in the main control room. The experience appears to contradict this assumption. That is, the experience shows that smoke from ex-control room fires may well reach the control room and may lead to some increase in the probability of human error.

No fire PRA known to the authors has postulated that smoke ingress into the main control room from an ex-control room fire could lead to abandonment and use of alternative shutdown. Rather, main control room abandonment scenarios typically arise from a fire-induced loss of control functions (due for example to a fire in a cable spreading room) and/or due to smoke from fires within the main control room itself. The Narora incident in particular illustrates that a large plant fire may cause control room habitability problems even if the fire is outside the main control room. Clearly, plant specific configuration features (such as ventilation intake locations, ventilation strategy, and proximity of the control room to the fire) would impact this potential.

4.2.4 Large Turbine Building Fires

All of the more severe fires reviewed in this study, with the exception of Browns Ferry fire and certain cable fires at nuclear power plants in the former Soviet Union (see Section 4.2.5), occurred on the power production side of the plant, and most of these occurred inside the turbine building. Turbine blade failure leading to lube oil line rupture is the root cause of the most significantly damaging turbine building fires (e.g., Salem, Vandellos, Maanshan, and Narora). In some cases the release of hydrogen also played a role (e.g., Vandellos and Maanshan). Fort St. Vrain and Muhleberg involved a leaking oil system that eventually led to a large fire. In two cases (Armenia and Chernobyl 2) the off-site power grid back-fed into a turbine generator causing bearing failure, lubricating oil spills and fire in the turbine building. In the case of Armenia, the turbine hall fire was actually a secondary fire caused by short circuits induced by the initial cable fire.

The presence of large quantities of oil and hydrogen are important contributors to the severity of the reviewed turbine building fires. Very large quantities of hot oil may be released into the turbine building in a very short time period. In several cases, the installed fire suppression systems were unable to control the fires. Spillage of the oil also plays an important role in the progression of the fire in that oil cascading from the point of the spill to other areas was a factor in some of the incidents (e.g., Vandellos).

The majority of large turbine building fires identified in this review have occurred outside the U.S. Fundamentally, the main features of turbine buildings are similar between U.S. and foreign plants. Therefore, non-U.S. incidents should be considered as applicable to U.S. plants. These incidents illustrate that the consequences of fire in the turbine building can be substantial in terms of the amount of equipment damaged, smoke generation, smoke propagation to other areas, and threats to the structural integrity of the building itself. However, they also illustrate that not all such fires will present a significant challenge to nuclear safety. For example, while the Vandellos fire caused extensive damage and ultimately led to permanent closure of the plant, the fire presented few nuclear safety challenges. In contrast, the Narora fire illustrates that turbine building fires can, under different circumstances, present a severe challenge to nuclear safety. (See Section 4.5 for a further discussion of fires leading to nuclear safety challenges.)

In fire PRAs, the risk significance of turbine building fires has been found to be highly plant-specific. In many plants, there is little or no safety related equipment and no important cables inside the turbine building. In these cases, the turbine building is generally screened out as being risk insignificant. However, other analyses have identified turbine hall fires as risk significant (e.g., the Millstone and Quad Cities IPEEE fire analyses).[6] In general, the perception among fire risk analysts has been that turbine building fires, while potentially severe from a traditional fire protection perspective, are unlikely to be risk significant. This perception is clearly undergoing some appropriate change.

The incidents reviewed in this study indicate that it may be prudent to pay more attention to the turbine building than is typical of current practice. One may need to examine the potential that a very severe fire, potentially impacting adjacent compartments, may cause structural damage to the turbine building itself. This may impact on other adjacent structures. The incidents also demonstrate a potential for failure of large components nominally considered invulnerable to fire damage leading to other hazardous conditions (e.g., failure of a large water pipe joint and subsequent flooding of the turbine building and reactor basement as occurred at Vandellos). Finally, the incidents illustrate that, depending on the plant configuration, a turbine building fire may lead to a station blackout. Therefore, it appears appropriate for a fire PRA to pay special attention to the possibility of severe turbine building fire incidents, and to the potential chain of events that may ensue.

4.2.5 Significant Cable Fires

Several fires have occurred involving a large quantity of cables. The fires of this type reviewed in this study did cause the unavailability of a large number of safety related systems and equipment. The only such incident in the U.S. is the fire at Browns Ferry (1975). As noted above, in classical fire protection terms, the Browns Ferry fire was not especially severe; that is, the fire remained confined to a relatively small area and did not threaten either the plant structure nor the intact fire barriers. The Browns Ferry fire is considered significant because it led to a significant challenge to nuclear safety. Outside the U.S. however, several severe cable fires have occurred. Prominent among these fires are incidents at plants in the former Soviet Union (Armenia, Beloyarsk, South Ukraine, Zaporizhzhya, and Ignalina).

The fire at Browns Ferry demonstrates that given a sufficient initial source of readily combustible fuel (the polyurethane foam in this case) in close proximity to a large concentration of cables in open cable trays, a self-sustaining and propagating cable fire may result. In this case the fire did propagate both horizontally and vertically igniting and damaging numerous cables. Furthermore, cables inside conduits running near the burning cable trays were also damaged.

It would appear that the fire at Greifswald bears some substantial similarity to the Browns Ferry fire. In this case the fire again appears to have been of moderate severity in the context of classical fire protection and yet there was apparently a significant challenge to nuclear safety as a result of the fire-induced cable damage. The fire was extinguished within a relatively short time (92 minutes) in comparison to other cable fire events that have persisted for several hours. There is relatively little information available on this incident so the actual physical extent of the fire damage is unknown.

An important insight to be taken from these two incidents is that even a relatively modest fire occurring at a critical location can lead to substantial challenges to nuclear safety. This is often a central finding of fire PRAs; that is, fires that occur near a location where critical cables for redundant trains of safety equipment converge (a cable "pinch point") are commonly identified as dominant fire risk contributors. In these cases while the likelihood of a fire of sufficient magnitude occurring in just the right location may be small, the consequences of such a fire may be severe and the overall risk contribution may be significant. These two events confirm this aspect of fire PRAs, and also confirm the value of ensuring adequate physical separation of redundant safety trains (such as is specified in the 10CFR50 Appendix R requirements).[32]

The switchgear fire at Waterford, although small in terms of area of damage, may also be considered as a cable fire of special interest, although there was no direct challenge to nuclear safety as a result of the fire-induced cable damage. In that incident, a non-safety related switchgear failed catastrophically and ignited the cables above the cubicle where the fire started. The fire propagated upwards and then horizontally damaging a number of cables in the cable riser and in the impacted horizontal cable tray. The fire did "jump" past a fire stop in the vertical riser tray but was halted by an in-tray fire stop in the horizontal tray. The Waterford incident demonstrates that under special circumstances (i.e., given a sufficiently energetic exposure source), it is possible for IEEE-383 low-flame-spread cables (it is assumed by the authors that the cables at Waterford were IEEE-383 qualified based on the plant's construction dates) to sustain a fire and propagate it along a vertical riser, and into a horizontal cable tray.

None of the cable fires observed to date in the U.S., including the 1975 Browns Ferry fire, have led to physical damage as extensive as that seen in large cable fire incidents in the Soviet-designed plants. This study has surmised that differences in the materials used in the construction of the cables, penetration seal characteristics, construction and maintenance practices, openings among compartments and electrical circuit design characteristics were important factors contributing to the severity of the cable fires in the Soviet-designed plants as compared to those observed in U.S. plants under nominally similar conditions (e.g., San Onofre, Waterford (1995), and Browns Ferry).

In the case of Armenia, the fire was initiated by a short in the power circuits. The fire started inside cable galleries, propagated rapidly and became a large fire (including a secondary turbine building oil fire, see Section 4.2.2). In the case of Beloyarsk, the fire started in the turbine building due to a break in the oil system, but propagated to cables and from there into the control building. In that fire many cables were damaged at several locations of the control building. Perhaps the only comparable case in U.S. industry experience is the Browns Ferry fire, and even in that case the extent of the fire propagation and damage was not nearly as severe.

While this study has not attempted to develop specific fire event frequencies, it would nominally appear that the statistical frequency of large cable fires is about an order of magnitude lower[6] in U.S. plants than it is in Soviet-designed plants. The difference in the frequencies of severe cable fire occurrences between the U.S. and Soviet-designed plants may likely be attributable to two factors in particular. First is the use in the U.S. of low-flame-spread cables. In the Soviet-designed plants cables apparently are able to support and propagate fire more readily than will the cables currently

[6] There has been only one fire in a U.S. plant that could be considered a large cable fire (Browns Ferry 1975), and in that case damage was comparatively limited. U.S. plants have a total experience base of over 2000 years. The experience for Soviet-designed plants includes at least five large cable fires in less than 1000 years of experience.

used in U.S. plants. Second is the close attention paid in the U.S. to the sealing of all fire barrier penetrations and openings. For several of the Soviet incidents, the presence of unsealed barrier openings (in one case the plant was still under construction) allowed fire (and smoke) to spread virtually unchecked from room to room (see Section 4.2). Other potential factors include electrical maintenance and design practices and compartmentalization practices. It must be noted that no significant cable fires for Soviet-designed plants were identified in this review since the mid 1980s. This coincides with efforts in these plants to apply fire retardant coatings on their cables and to upgrade the status and quality of their fire barriers.[28]

4.3 Fire Detection and Suppression

4.3.1 Availability of Suppression System

In some of the incidents reviewed here, the automatic fixed suppression system failed to function. In these cases the suppression system failures occurred because the system was switched to the manual mode and/or because the systems control or power cables were damaged by the fire itself before the system could actuate. For example:

– There was a fixed foam system in the cable galleries at the plant in Armenia. The system's control switch was turned to the manual position at the time of the fire. The control cables for the system were damaged in the first few minutes of the fire and this rendered the system inoperable for the entire length of the incident despite attempts to manually actuate the system.

– At South Ukraine, the fixed suppression system for the containment was switched to manual mode at the time of the fire. The operators apparently failed to switch it back to automatic or to manually actuate the system after the existence of the fire was verified. The reasons for this failure could not be determined.

In fire PRAs, fixed fire protection systems are modeled using a reliability value obtained from generic industry sources. Plant specific analysis of the design condition, specific failure modes, and control switches of the system is often not conducted, although some exceptions can be cited (e.g., [9]). It is also inherently assumed that the fire protection systems are independent of the impacted fire area; i.e., fire protection system failures are random rather than fire-induced. It would appear that U.S. fire detection and suppression system standards may not require that independence from the protected space be assured in all applications (the fire pump standards are the one apparent exception). Further, in the U.S. nuclear industry full compliance with general industry fire protection system design standards cannot be assumed without verification. Hence, fire protection systems should be examined carefully as a part of the fire PRA to ensure that a fire in any given area does not hold the potential to render the system inoperable.

This would be of particular concern if manual recovery of a fixed suppression system is being credited. Indeed, this observation is also indirectly relevant to one area of current methodological debate arising from the EPRI Fire PRA Implementation Guide (the PRA Guide).[3] One of 16 generic Requests for Additional Information (RAIs) raised with regard to application of the PRA Guide to IPEEE analyses cited potential concerns for the dependency between manual fire fighting and manual recovery of a fixed suppression system.[33] This insight raises an additional potential concern regarding manual recovery of a fixed system. That is, a fire may burn for some time before manual recovery is attempted. Fire damage during that time may render the system inoperable and unrecoverable.

Overall, this experience illustrates a behavior that is not considered in current fire PRAs; namely, fixed fire suppression systems may be damaged and/or rendered inoperable by a fire. Some additional consideration of how fixed fire suppression systems are credited in fire PRAs appears warranted.[7] In particular, it would be prudent for fire PRAs to assess the potential for loss of a fixed fire suppression capability due to fire damage. Due to timing considerations, the potential for loss of system function before actuation would be of particular interest in the analysis of manually actuated fixed fire suppression systems and where recovery of an automatic fire suppression system is considered.

4.3.2 Fixed Suppression System Overwhelmed by the Fire

Relatively few of the fire incidents reviewed in this study involved the actuation of fixed fire suppression systems. However, in the majority of cases, when activated fixed fire suppression systems did control the fire as designed. However, in a few cases the suppression system was overwhelmed by the fire. That is, although the fixed suppression system functioned as designed, the fire was so severe that the system was unable to control the fire. Case examples identified in this review are as follows:

– At Vandellos, the lubricating oil and hydraulic oil storage tanks caught fire. Both tanks were protected by a deluge system. The lubricating oil storage tank fire was brought under control with the assistance of hose streams from the fire brigades. However, the hydraulic oil storage tank, despite the activation of the deluge system, burned completely because the fire was too severe.

– At Beloyarsk, although this is not explicitly stated, from incident descriptions provided in available sources it may be inferred that in several places the fixed fire suppression systems activated, but were not adequate to control or suppress the fire.

– The available information about the Chernobyl fire indicates that the suppression systems did actuate as designed. Reports also state that due to excessive usage, the fire water pressure was not sufficient to allow the fire fighters to reach the ceiling with their hose streams. Since

[7]Note that Task 2 of the USNRC/RES Fire Risk Methods research program, JCN Y6037, is specifically addressing fire detection and suppression modeling practices for fire PRA.[11]

a large team (63 persons) was required for close to six hours to extinguish the fire, it can be inferred that the fixed suppression systems were not effective and perhaps were overwhelmed by the fire.

– At North Anna, a fault in a main transformer caused severe transformer damage and an oil spill and fire. The oil fire was too severe for the deluge system although the system did activate as designed. Plant and outside fire brigades had to intervene to control the fire.

In fire PRAs it is commonly assumed that fixed fire protection systems are properly designed and installed. In some cases specific assessments may be undertaken to identify design features that might delay actuation (such as beam pockets or detectors and sprinkler heads located on pendants below the ceiling). However, it is widely assumed that if a fixed suppression system actuates, the fire will be brought under control and/or extinguished very quickly. In particular, it is commonly assumed that no further fire damage will be realized given actuation of a fixed fire suppression system (see further discussion in Section 4.3.3).

The incidents reviewed here demonstrate that there could be situations where the system operates as designed, but is rendered ineffective by the sheer magnitude of the fire. Certainly this requires a very severe fire that can only be caused by the presence of a large quantity of highly combustible fuels. This would typically apply to the turbine building, near large oil-filled transformers, or other areas where large quantities of flammable liquids are stored. Fire analyses for such areas should carefully consider the potential for a prolonged fire even if the fire suppression systems actuate as designed.

4.3.3 Fire Duration

In a fire PRA, a parameter of critical interest is the likelihood of controlling the fire before a critical set of equipment and cables are damaged (i.e., the time that fire stops propagating and will cause no further damage). For the larger fires addressed in this study, this time period (time to fire control) has ranged from one to 17 hours. The total duration (time to fire extinguishment) for several of the reviewed fires was rather long, including fires that lasted from six to over 24 hours. This is generally well beyond the maximum probable fire duration typically assumed in a fire PRA.

There were several incidents, in particular, where manual fire extinguishment was delayed for a long time. Case examples identified in this review are as follows:

– In the case of the Browns Ferry fire, effectively the fire was burning in two compartments: the cable spreading room and a reactor building compartment adjacent to the cable spreading room. The fire in the cable spreading room was immediately recognized and was brought under control by the fixed CO_2 system and manual efforts. On the reactor building side, the fire was in an inaccessible location well above the floor, and only hand held extinguishers were initially applied which failed to suppress the fire. Application of water on the electrical cable fire was, however, delayed close to seven hours. There were apparently concerns for both fire fighter safety and the potential systems impact that might result from water-induced shorts involving the damaged electrical cables. The reactor building side fire was extinguished quickly once water was applied.

- At South Ukraine, fire fighting efforts were delayed in large part because of the need to first reduce containment pressure. It took more than four hours after plant personnel realized that a fire was burning inside the containment before the fire brigade gained access to the fire area. Furthermore, this case involved a fire in an inaccessible group of cable trays and a cable shaft. It took the fire fighters more than three hours after entering the containment to extinguish the fires completely.

- At Waterford 3 (1995), the suppression activities were delayed for two non-related reasons. First, the shift supervisor insisted on personnel observing flames before declaring the existence of a fire and calling out the fire brigade. This took more than a half hour for operators to don self contained breathing apparatus, to enter the smoke filled room, confirm the existence of the fire, and report back to the main control room. Second, the fire brigade resisted the use of water and attempted to use non-water agents (hand-held extinguishers) repeatedly for more than one hour which failed to put out the fire. The fire was extinguished rather rapidly when water was finally applied.

- In the case of Oconee, effective fire suppression was also delayed by more than 40 minutes by repeated attempts to suppress the fire using hand-held fire extinguishers. Once water was applied, the fire was quickly suppressed.

- The fire at Beloyarsk lasted for over 17 hours. The main reason for the long duration was apparently the presence of heavy smoke blocking access to and visibility of the fire locations. This implies that the fire had grown to a substantial size before fire fighters arrived on the scene. The response was also hampered by the extensive and rapid propagation of the fire into adjacent areas so that a large fire fighting force had to be deployed. Electrically active cables and extremely cold weather were also cited as having hampered fire fighting efforts.

- The fire at Zaporizhzhya lasted for over 17 hours. The main reason for the long duration was apparently the presence of heavy smoke. In this case lack of knowledge about the plant layout by members of the off-site fire brigade also contributed to fire duration.

- It took more than three hours to bring the turbine oil fire at Chernobyl under control and close to six hours to completely extinguish the fire. Factors in this case were the severe initial intensity of the fire coupled with the early structural collapse of the turbine building roof.

- Several other turbine building fires were reviewed. In those fire incidents, fire fighting activities started a short time after ignition but because of the severity of the fire several hours were needed to bring the fire under control.

There are four specific factors that can be cited from these incidents as having led to an extended fire duration:

– In several fire incidents, the initial severity of the fire hampered fire fighting efforts (for example, the large turbine building oil fires and some of the rapidly growing cable fires).

– In other cases difficulty in clearly identifying fire locations due to heavy smoke, unfamiliarity with the plant, or difficulties in approaching an identified fire location interfered with fire brigade effectiveness.

– In some incidents (i.e., Browns Ferry, Waterford 1995 and Oconee), initial unsuccessful attempts to extinguish the fire using hand-held extinguishers delayed effective fire fighting.

– In some incidents (i.e., Browns Ferry, Waterford 1995, and Oconee) there were decisions made by management (in at least one case apparently based on written procedures, Waterford (1995)) that contributed to an extension of the fire duration. These included reluctance to declare the existence of a fire and reluctance to apply an effective suppressant (water) in a timely manner. It may be argued that the latter is dependent on the failure to control the fire by other means (e.g., use of hand-held extinguishers). In these cases it would appear that a fire that might have been suppressed quite quickly (within minutes) was instead allowed to burn for a prolonged period (from well over an hour to several hours). Delays in initiating effective fire fighting activities because of procedural requirements or management decisions are not generally considered in PRA models.

These incidents illustrate that various factors may delay the activation of the fire brigade, even for severe fires, and compromise their effectiveness once called out. There are currently two approaches commonly applied to assess manual fire brigade response in fire PRAs. The implications of these insights depend on which approach is being applied as follows:

– Under the first approach, a curve characterizing the probability of suppression versus time based on historical fire incident data is used to model the possibility of failure to suppress within a given time period.[3,5] The fire suppression time distribution is statistically compared to the critical damage time (either a point estimate or a distribution) to estimate the likelihood of critical damage occurring. This approach has one clear advantage in that it inherently includes the observed delays in decision making, failure of initial attempts, etc., because these are factors in the underlying incident data. However, the approach also has distinct disadvantages because fire duration data is actually rather sparse. This limits the analyst's ability to parse the data to reflect different fire sources or to address specific plant features. Hence, adaptation of the generic suppression probability curves to a specific fire scenario may not reflect the impact of location specific conditions.

– Under the second approach, the duration of a manually-suppressed fire is based on the time it takes for the fire brigade to reach the scene ready with equipment. This is, in turn, typically based on fire brigade practice drill response times. Under this approach it is common to assume that the fire brigade will be called out immediately upon initial indications of, or detection of, a fire. It is further assumed that fire fighting efforts will be immediately effective once initiated and that the fire will be brought under control within, at most, minutes. This approach has the advantage of being both plant-specific and case-specific. However, these methods as currently applied do not explicitly consider the types of decision making delays or effectiveness issues highlighted by the incident review preformed here.

Given this perspective, some additional refinement of manual fire fighting assessment methods appears appropriate. For example, the observations noted here might be addressed for the methods based on drill times through inclusion of an additional manual suppression failure probability or by assessing some probability of substantial delays in response times. However, the basis for such a refinement is currently lacking. A refined method might also be developed using a hybrid of the two currently applied methods, that is, use of historical probability curves adjusted to reflect case-specific assessments of brigade practices and fire scenario factors.[8]

Overall, typical PRA estimates of fire duration would not bound most of the fire incidents reviewed in this study. This is mitigated to some extent by the observation that for most fire scenarios considered in fire PRAs the critical damage occurs in a relatively short time frame, and subsequent fire damage is not risk significant. (Damage timing is discussed further in Section 4.4.3.) However, in many cases noted in particular in the IPEEE process fire scenarios were screened as risk insignificant based on relatively short fire duration estimates (e.g., assumptions that any fire anywhere in the plant would be suppressed within 10-15 minutes) despite the observation that a longer duration fire might cause more risk-significant fire damage.[6]

Based on this incident review, it can be concluded that long duration fires do occur, although the probability of occurrence is not known. For various reasons, fire suppression activities may be substantially delayed or ineffective. Fire PRA methodologies presented in References [3] and [5] include time to suppress probability curves that give very small probabilities to fire durations greater than one hour base on U.S. experience. Since fire durations of up to 24 hours have been recorded in the nuclear power industry, and several of the fires reviewed in this study lasted for several hours, those curves may need to be revisited or a methodology developed to account for plant- or scenario-specific conditions that may lead to long duration fires. The failure to account for long duration fires may well miss risk significant fire scenarios. While a significant unsuppressed fire may occur with a lower frequency, the consequences of such fires may sufficiently severe that the overall risk contribution is still significant. Fire risk methods are clearly capable of dealing with long-duration fires. However, it must be noted that scenario specific analysis of the suppression activities is seldom done in a fire PRA.

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[8] These issues are being addressed as part of Task 2 of the USNRC Fire Risk Methods research program, JCN Y6037.[11]

4.4 Equipment Damage

4.4.1 Spurious Actuation of Equipment

One area of current debate centers on the potential that fire-induced damage to cables might lead to spurious equipment operations rather than simply a loss of function, and the relative likelihood that one or more such events might be observed during a fire. Spurious actuations were observed in a number of the fire incidents reviewed here. Case examples identified in this review are as follows:

- In the Armenia fire there were three reported spurious actuations and other control and indication problems, all apparently caused by fire-induced cable failures:
    - The main generator breakers were closed inadvertently due to fire damage to the associated control cables. This led to the non-operating generators being connected to the grid and in turn to secondary fires in one of the turbine-generators and in the start-up transformer.
    - One of the diesel generators spuriously disconnected from its emergency loads apparently due to control cable damage. Attempts to correct the failure during the fire were not successful.
    - One feedwater pump spuriously started following damage to a cable, apparently, in the control circuits. In this last case, the fault that actuated the pump by-passed the normal start logic allowing the pump to start without first starting the lube-oil pumps. Hence, the pump ran for some period without proper lubrication. The fault also by-passed or defeated the normal control room start/stop functions and operator attempts to shut down the pump from the main control room failed. The pump was ultimately secured by electrical technicians who isolated the pump from the power bus manually.
    - Neutron flux and other reactor related instrumentation indicated conditions that may not have been the actual conditions of the reactor. This was likely because many of the instrument cables were degraded and/or failed by the fire. These indications led to the actuation of various emergency signals.

  This incident is one of the few incidents where there is specific information indicating that multiple spurious actuations actually occurred during a fire.

- In the Ignalina fire there were a number of cases where equipment was lost due to spurious trip signals caused by the failure of instrument and control cables. These included the following events:
    - The Control Room received oil level alarms for one of the main coolant pumps and the pump tripped automatically. Cable faults in the oil level indicator and alarm circuits are suspected to be the cause of the trip (rather than an actual drop in oil inventory).
    - Instrumentation and control cable faults led to the opening of supply breakers for two normal 6kV buses and two essential (non-safety) buses.
    - Control cable damage tripped Transformer 5 and prevented it from taking up the loads for these buses.

Insights

- At Chernobyl, a conductor-to-conductor short in a multi-conductor cable attributed to cable damage from poor cable pulling practices during construction led to spurious closure of a generator breaker, grid back-feed into the generator, generator rotor failure, turbine oil and generator hydrogen release and a large fire. In this case, a cable failure caused spurious component operations that in turn caused the fire.

- At the Waterford (1995) fire, the event sequence log and the control room operator observations indicate erratic behavior in the position indication of a breaker or a pump. There is no verification in the incident report regarding the behavior of these items in the field. Hence it is not clear if these are spurious indications only or are, in fact, spurious operations.

- During the Browns Ferry fire incident several spurious component and system operations were reported. For example, the control room received indications that the Residual Heat Removal, Core Spray and High Pressure Core Injection systems had started. A recent review revealed that conductor-to-conductor short circuits within the associated system control cables damaged by the fire were the most plausible explanation for the cited behavior in at least two of the reported spurious system actuation events.[34]

In summary, it can be concluded that spurious actuation of equipment or electrical control circuits may have taken place during at least four of the reviewed incidents. The Armenia fire appears to provide the most conclusive evidence, and in particular, evidence that multiple spurious actuations are possible to occur. A recent study of circuit failure modes appears to lend credibility to these findings.[34] These events can either result from, or lead to, a fire. With the exception of Chernobyl, for which the investigators could identify the specific wires that caused the spurious actuation of the breakers, the precise electrical failures that led to spurious actuations have not been discussed in the available incident reports. Hence, it is not possible to conclusively pinpoint the specific circuit failures that led to these conditions. It is also not possible on the basis of this study to estimate the likelihood of such effects being observed in any given fire. It may be added that several other fire incidents reviewed in this study involved control and instrumentation cables. However, from the information provided for the incidents, it is practically impossible to infer whether or not spurious actuations took place.

Fire PRA methods are capable of dealing with spurious component actuations, and efforts are currently underway to improve the available methods of analysis.[34] Perhaps the most challenging aspect of this problem for the PRA analyst is the need to include potential cable failures and the resulting systems effects into the internal events PRA models. Internal events models do not typically consider cables and their potential failure because the random failure probability of cables is considered very small. Nonetheless, the fundamental framework of a current fire PRA is capable of capturing and quantifying such spurious operation events as a result of fires.[34]

4.4.2 Cabinet Fires

Electrical cabinets, especially high voltage switchgear, are commonly identified in fire PRAs as one of the important sources of fire ignition in nuclear power plants. One current area of debate that arose from an USNRC sponsored review[33] of the EPRI Fire PRA Implementation Guide[3] (hereafter referred to simply as "the Guide") was related to the potential that a fire initiated inside of an electrical panel might propagate outside the panel. The Guide had recommended that closed electrical panels (panels with no openings or vents) could be screened as ignition sources; i.e., that the potential for propagation of fires outside the panel was sufficiently small that screening was appropriate. In the IPEEE reviews, this was commonly cited as an area of potential weakness in licensee submittals.[6] Reviewers expressed concern that some electrical panel fires might propagate outside the panel; hence, screening of such sources might eliminate a potential fire vulnerability from the assessment.

There was only one fire incident in the reviewed incidents that clearly involved a substantial cabinet fire; namely, Waterford (1995). The Waterford incident demonstrates that a fire initiated within a switchgear panel can propagate to the outside of the switchgear boundary and ignite cables above the panel. In this case, the top of the panel was damaged by the fire. The fire propagated up into the cable risers above the panel (cable drops into the panel), and ultimately to an overhead horizontal cable tray. It is not clear whether the damage to the panel top was the result of heat or direct effects of the apparently energetic switchgear fault (e.g., damage may have resulted from pressure or shrapnel from the switchgear failure). In this incident the fire also caused damage to a horizontally adjacent switchgear cubicle.

It must be noted that at Waterford the fire burned for over an hour and only two adjacent cubicles were severely affected. Other nearby cubicles suffered damage only to their external surfaces from reflected radiative heat. However, the fire also damaged the vertical riser cables for a distance of about 10 feet above the panel, and the intersecting horizontal tray for a distance of about eight feet. The incident demonstrates that panel fires can lead to external fire propagation. In this particular case the consequences of the fire were modest because the panels were not safety-related. However, as noted above, fires impacting safety-related switchgear are commonly found to be important risk contributors. Therefore, careful attention to the potential for fire spread outside of a switchgear panel (or other electrical panel), which may impact additional trains of equipment, is confirmed to be an important aspect of a fire PRA.

A second potential case is the fire at Greifswald. The available information appears to imply that the fire started in a 6kV switchgear panel and propagated outside the panel to overhead cables. This cannot, however, be confirmed given the available information. For example, it is also possible that the fire started in the cables due to a cable overload.

4.4.3 Damage vs. Suppression Timing

As discussed in the previous sections, in fire PRA, a parameter of critical interest is the likelihood of controlling the fire before critical damage occurs. In the events reviewed in this study the time to the last observed risk-significant equipment damage (i.e., beyond this time no additional cables or equipment of importance to risk were damaged) varied widely. Indeed, this time can be significantly shorter than the time that the fire was declared as under control. For the fires reviewed here the critical damage time period ranged from ten minutes to five hours (see Table 4-1). For example, in Waterford (1995) all damage apparently took place in the first ten minutes of the fire, but the fire was not brought under control until over an hour later. During the Browns Ferry 1975 fire, most fire-induced failures occurred during the first hour of the fire. However, it is interesting to note that more than five hours after fire initiation, one additional failure that impacted the core cooling process took place (a solenoid valve serving the four active relief valves failed).

Table 4-1 includes estimates of the time to last damage, fire control and fire extinguishment. All of the reported times are estimates based on the information provided for each incident. Blank spaces represent cases for which sufficient information was not available. From a comparison of the time to last damage and the time to fire control, it can be concluded that long damage times may occur in a fire incident. Conversely, time to the last risk significant cable/equipment damage may be significantly shorter than the time to complete extinguishment, and in many cases it is also shorter than the time to fire control as well. Two of the events were extinguished by an automatic suppression system with no manual fire fighting intervention. The remainder (i.e., 23 events) included manual actions. In eight of the 23 events, fixed automatic suppression systems activated but manual actions were needed to control and extinguish the fire.

In the screening phase of a fire PRA it is commonly assumed that all cables and equipment within a compartment are damaged. This is a conservative approach (appropriate to screening analyses) under which fire durations are not factored into the screening analysis. The observations outlined above would have no impact on this type of screening analysis. However, these observations will have a bearing on the detailed analysis of the un-screened fire scenarios. In some past fire risk studies, scenarios have been quantified assuming that if a fixed fire suppression system actuates, any fire damage will not be risk significant. From the information provided in Table 4-1, it can be concluded that damage may occur well before the suppression system can effectively suppress the fire and that consideration should be given to the cables and equipment within the damage zone of the fire.

4.4.4 Structural Failure from a Fire

There have been a few fire incidents where structural elements were severely affected by the fire. In all cases, the incidents occurred on the secondary (power generation) side of the plant. Case examples reviewed in this study are as follows:

- At Muhleberg, where a turbine oil connector failed and caused an oil spill and a large fire, some of the structural elements of the turbine building roof deformed and other structural damage was inflicted.

- At Beloyarsk, the turbine building roof collapsed within a few minutes of fire ignition.

- At North Anna, the transformer fire affected the turbine building. The outside wall of the turbine building was sprayed with burning transformer oil apparently leading to some damage to the building exterior cladding.

- At Chernobyl, similar to Beloyarsk, the turbine building was destroyed because of a turbine oil fire.

- Parts of the turbine building at Narora also experienced structural damage. Turbine-generator support structures and a portion of the slab around the turbine-generator set suffered damage from the intense heat.

- At Vandellos a deflagration of hydrogen caused damage to the movable ceiling above the point where fire had occurred.

Structural damage due to fires is not generally considered in a fire PRA. The risk significance of turbine building structural damage beyond the loss of the equipment in that building is certainly very plant specific. In many cases, structural damage may have no direct risk importance. However, for areas where that potential exists (e.g., the turbine building) it may be appropriate to consider the potential impact of a structural failure on subsequent plant recovery actions. Fundamentally, it would appear that the consideration of structural failure is possible within the framework of an existing fire PRA (i.e., consideration of additional damage or the potential for fire spread to adjacent areas due to barrier failures). However, no guidance for this type of assessment currently exists.

4.5 Impact on Plant Safety Functions

4.5.1 Impact on Multiple Safety Trains

The reviewed events did include a number of incidents where multiple safety trains were impacted by a fire. As noted by Houghten[10] and others, fires impacting multiple safety trains are rare occurrences. In the U.S. only the fire at Browns Ferry on March 22, 1975 affected multiple safety trains.[10] However, in non-U.S. plants there have been several incidents where multiple safety trains have been affected. In particular, in the Soviet-designed plants there have been several large cable fires where a large number of safety systems have been affected. Case examples involving damage to redundant safety trains reviewed in this study are as follows:

- In the case of the Armenia fire, a station blackout resulted from the fire and it lasted several hours.

Insights

- During the fire at Greifswald, the fire also caused a station blackout and led to loss of all active means of cooling the reactor core. These conditions persisted for at least five hours.

- For the South Ukraine fire, it is stated in available reports, that if the reactor had been activated prior to the incident (the plant was at the last stages of construction), the safety of the reactor would have been impacted severely.

- In the case of Zaporizhzhya, several electrical trains were affected.

- In Beloyarsk, one reference has stated that it was only fortuitous that core damage did not occur.[12]

- At Narora, a station blackout resulted from a turbine building fire because there was little separation between cables for both trains of the power distribution system. The blackout also rendered the alternate shutdown capability inoperable for one of the two units.

- At Chernobyl, the fire affected all high pressure feedwater pumps, some due to direct fire damage and the rest because they were taken off-line (de-energized) to allow fire-fighters to attack the fire. In this case, fire damage, other independent failures, and the strategy selected by plant management for reactor cooling worked together to cause difficulties in the operators' attempts to ensure adequate core cooling (no core damage was experienced in this incident).

In all of these cases, the operators played an important role in ensuring that at least one core cooling path remained functional or was recovered. This is discussed further below in the more general context of operator recovery actions. Fire PRA methodologies are specifically designed to explicitly model multiple train failures. The incidents given above would be properly addressed in a typical fire PRA.

These cases all involved fires that directly affected redundant safety trains. However, indirect effects of a fire may lead to an impact on redundant trains as well. This has been observed in two cases:

- At Oconee, one train of non-safety switchgear was involved in the fire, and the second train was de-energized to allow the use of water for fighting the fire in the first switchgear. Thus, effectively two opposite, albeit non-safety, trains of a system were taken out of service due to the fire.

- A similar incident took place at Chernobyl, when all electrical panels related to main and emergency feedwater were de-energized to allow the fire fighting activities in the area.

Current fire PRA methodologies include provisions for analyzing the actions that should be taken by the fire brigade. As a part of this analysis, special conditions such as de-energizing an undamaged component could be addressed. However, in the experience of the authors, no analysis to date has explicitly considered the potential that operating equipment would be purposely taken off-line in order to allow for fire fighting activities. Rather, a typical fire PRA will credit the operation of any and all systems not actually damaged by the fire. The incidents reviewed here indicate that it may be appropriate to review fire fighting procedures specifically to ensure that the possibility of indirect equipment loss (purposeful shutdown) is captured.

4.5.2 Severe Degradation of Core Cooling Capability

In six of the fire incidents reviewed here, not only were redundant trains were affected (see Section 4.5.1), but the core cooling function was severely degraded by a fire. This observation is directly linked with the loss of redundant trains that occurred at Browns Ferry 1975 fire, at Narora and during several of the cable fires at Soviet-designed plants. Case examples reviewed in this study are as follows:

- In the case of the Browns Ferry fire, all of the normal core cooling functions were lost. The operators boosted the flow rate on a CRD pump with a flow capacity of 130 gpm to provide core cooling. This approach was not, at the time, included in the plant procedures. Use of the CRD pump provided time for the plant personnel to restore normal core cooling functions (initially a condensate booster pump).

- The fire at Greifswald burned for about 92 minutes causing a station blackout and the loss of all active means of cooling the core. As a result, a pressurizer relief valve opened and failed to close (stuck open PORV). This situation persisted for at least five hours and led to depletion of the secondary and primary side coolant inventories. The plant was ultimately recovered through initiation of low pressure pumps (upon loss of pressure trough the stuck open PORV) and installation of a power cross-tie to the sister unit (Unit 2) and recovery of one auxiliary feedwater pump.

- Armenia experienced a station blackout during a fire that lasted for several hours. The large heat capacity of the steam generators provided time for the plant personnel to lay down a temporary cable from a diesel generator to the motor windings of a high pressure injection pump.

- At Narora, a station blackout resulting from a fire of several hours duration was also experienced. Again, steam generator capacity had an important role in allowing the operators ample time to take proper recovery actions. In this case, they opened the fire water system connections into the steam generators and started the diesel engine driven fire water pumps. Even this capability was temporarily lost when both fire pumps failed simultaneously. The capability was restored when one fire pump was recovered.

- For Beloyarsk, little information is provided as to how the reactor was controlled and core cooling was maintained. However, the conditions were certainly very severe. As mentioned earlier, one reference stated that it was "only fortuitous" that core damage did not take place.[12]

– During the Chernobyl turbine building fire, core cooling functions were never completely lost. However, all high pressure feedwater pumps became unavailable. The operators chose to follow a rapid cool-down strategy. This, augmented with failure of the Steam Dump Valve to close completely (a failure independent of the fire), caused the water pressure, and therefore the temperature, to drop rapidly. The water contracted and the level in the Steam Drum (the source of water for the circulating pumps of the core) dropped below the measurable level. For about 15 minutes, until makeup water was restored, it was not clear if core cooling remained adequate.

In addition, there were two fire incidents that, while the fires occurred just prior to plant start-up, should also be included as having had the potential to severely degrade core cooling functions.

– The fire at South Ukraine began inside containment during a pressure test of the containment structure and ultimately damaged numerous cables. While the reactor was not activated at the time of the fire incident, the damage caused by the fire would have severely challenged the safety systems.

– The fire at Zaparozh occurred during the final stages of plant construction. The fire destroyed many of the plant control, instrumentation and power cables damaging all three safety divisions of core cooling equipment. Hence, had the plant been in operation at the time of the fire, nuclear safety would have been challenged.

In fire PRAs, explicit consideration is given to the potential that multiple or redundant safety functions might be lost due to fire. Indeed, this is the central premise upon which fire PRA is based. Hence, in a fundamental sense, these events should be captured by existing PRA methodologies. In particular, the majority of the nuclear safety challenging fires reviewed here involved fires that damaged numerous safety-related cables. Fire PRAs often identify such fires as dominant contributors to fire risk. A typical fire PRA would likely have identified the impacted cable areas and the lack of train separation in these cases as significant potential contributors to fire risk.

One common element in each of these incidents that ultimately prevented core damage was the action of operators. This is discussed further below. Given that in a typical fire PRA no credit is generally given to actions taken outside the established procedures, if the above mentioned incidents were to be modeled in a PRA, in almost all cases, a very high conditional core damage probability (CCDP) would be assigned given the observed fire damage. The fact that none of these incidents actually led to core damage demonstrates that fire PRAs use conservative assumptions, in particular with regard to operator recovery actions and strategies.

4.5.3 Human Error Events

The possibility of human error events is commonly recognized as an important aspect of PRA in general. The incidents reviewed in this study confirm the importance of this perception in the context of fire PRA. Case examples reviewed in this study are as follows:

- In the Waterford (1985) incident, a main feedwater pump caught fire. The plant operator at the scene called the control room with the wrong pump tag number. This error resulted in the un-damaged pump being shutdown from the control room.

- In the H B. Robinson incident, during an outage a maintenance crew connected a hydrogen source to the plant compressed air system in error. The compressed air system was operating at a lower pressure than the hydrogen source. Hydrogen entered the compressed air system, was distributed to pipes throughout the plant, and exited the system at several locations (wherever the compressed air system was being used within the plant). The escaping hydrogen caught fire at various points where ignition sources were present.

- At Chernobyl, a fire involving one turbine generator led to a reactor trip. Operators failed to isolate the second turbine generator from the power grid. Hence, upon loss of the steam supply source, the generator acted as a motor drawing power from the grid for approximately 20 minutes. In this case, the error had no impact on the chain of events. However, it was similar behavior occurring in the first generator that led to the initial fire.

- During the Oconee fire, operators failed to close a main feedwater valve on reactor trip. Initiation of high pressure injection ultimately led to an overcooling transient.

- During the 1995 Waterford switchgear fire, operators failed to promptly declare a fire. The plant procedures apparently did call for operators to verify the presence of flames before declaring a fire emergency. However, the failure to declare a fire given the reports of “heavy smoke” issuing from the switchgear room is considered a human error event in the context of a fire PRA. This error led to a substantial delay in activating the fire brigade.

The operator errors in the above examples occurred after the fire had ignited. In three cases reviewed in this study errors by plant personnel preceding the fire have either led to fires or have compromised the effectiveness of the fire response as follows:

- At Browns Ferry (1975), the fire was ignited by a technician who allowed the lit candle that he was carrying near penetration seals to touch unprotected seal material. Several fires involving the same ignition scenario, albeit all of no significant consequence, had occurred prior to the incident on March 22, 1975. Plant management and operators failed to take note of the earlier events and to disallow further usage.

Insights

– At South Ukraine, the fixed fire suppression system for the containment had been switched to the manual actuation mode (disabling automatic initiation) sometime before the fire occurred. Plant personnel apparently also failed to switch the system back to its automatic mode or to manually actuate the system after the existence of the fire was verified.

– At Armenia, the fixed suppression system for the cable gallery where the fire started was switched to the manual actuation mode (disabling automatic initiation) prior to the event. Fire damage to associated system cables rendered the system inoperable relatively early in the incident. Repeated attempts to manually actuate the system failed.

These events demonstrate that errors by plant personnel, including both operators and maintenance technicians, may complicate the chain of events of an incident. Complications involved in the cited incidents include the loss of a redundant train not impacted by fire damage due to operator error, errors in the handling of post-fire safe shutdown activities, and fires involving unexpected ignition (i.e., a candle) or fuel (i.e., hydrogen) sources that would not be expected to exist in an area under normal circumstances. In the case of the inoperable fire suppression systems, the error-caused system failures (i.e., leaving the systems in manual mode) were likely a significant factor contributing to the ultimate severity of those incidents. That is, in each case early intervention by the fixed fire suppression system would likely have limited fire damage substantially. Similarly, delays in initiating effective fire response during the Waterford (1995) incident also likely allowed for more fire damage than might otherwise have been realized.

It is interesting to note that some of the human error scenarios described above (Robinson and Waterford (1985)) can be categorized as errors of commission. That is, the operators took an action that further complicated the situation or created a new undesired condition for the plant. The remaining case examples involved errors of omission. That is, operators failed to take an action that would have contributed to mitigation of the incident.

In general, current PRA methods are capable of identifying and quantifying risk significant human actions. In general, the same methods used in the analysis of internal events are applied to the fire analysis. The ability to identify and quantify errors of commission is a widely recognized weakness of the existing methods. The incidents reviewed confirm that both errors of omission and errors of commission are an important aspect of fire PRAs. Efforts are underway to improve PRA human factors analysis methods, and in particular, to address the process that leads to errors including errors of commission.[17] The methods under development shift the focus from human errors to "human failure events" based on a concept of an "error forcing context." That is, the approach presumes that people are led to take a particular action, or to not take an action, based on the context of information with which they are presented. This approach can address both errors of omission and errors of commission. Efforts to apply this approach to fire are ongoing.

4.5.4 Credited Human Recovery Actions

With regard to credited human recovery actions, insights were developed in two major areas. The first relates to crediting actions not cited in plant procedures. A typical fire PRA would not credit actions unless they are included in the plant emergency response procedures. In a number of the incidents reviewed here operators successfully implemented actions that were not a part of the plant procedures in order to recover the plant. Examples from the review are the following:

– In the incident at Armenia, operators routed a new power cable from a diesel generator directly to a pump in order to bypass fire-damaged cables and overcome, in effect, a station blackout condition.

– During the fire at Greifswald, operators routed a power feed from the sister unit to overcome the Unit 1 station blackout and recover one auxiliary feedwater pump.

– In the Browns Ferry fire, among other actions, operators tapped into containment electrical penetration feeds to obtain critical plant readings bypassing fire-damaged cables. They also relied on a CRD pump to provide core cooling make-up flow, an approach that was not, at the time, included in the plant procedures.

– In the incident at South Ukraine, the operators correctly diagnosed the presence of a fire inside the containment despite the failure of the fire detection system (based on increasing containment pressure).

– At Narora, the plant suffered a loss of all power, main control room abandonment and loss of the alternate control functions. Nonetheless, operators took appropriate actions to recover the plant. This included manually aligning borated water flow into the core and using a diesel engine driven fire pump to provide water flow into the steam generators. These actions ensured reactor shutdown and primary side cooling.

It would appear from the current review that operators can, and will, take actions that are not in their procedures if that is what is needed to prevent core damage. Hence, PRAs seem to be conservative in this regard.

The second area of insight is the impact of smoke and fire on operator recovery actions. This review identified both successes and failures in this regard; that is, some attempted actions could not be completed due to fire effects, but in a number of incidents operators have successfully completed actions despite adverse conditions. Case examples identified in this review are the following:

– During several of the incidents (Browns Ferry, Beloyarsk, Armenia NPP, Zaparozhye, Fort St. Vrain, Oconee, Calvert Cliffs, Vandellos and Narora) smoke from fires in other areas found its way into the main control room. The quantity of smoke varied substantially. With the exception of Narora, in each of these incidents the operators remained in the control room. In some of these cases it would appear that the smoke did have some adverse impact on operator performance (Oconee, Narora, Beloyarsk). Narora is the only known incident where a fire led to forced abandonment of the main control room.

– During the fire at Beloyarsk, operators performed successfully under very harsh conditions that included the spread of fire into the main control room.

– At Vandellos, operators wearing SCBA entered smoke filled compartments in order to manually manipulate critical valves. These actions were successful.

– During the Browns Ferry incident, parts of the reactor building filled with dense smoke. This smoke prevented operators from manually opening certain valves that were needed to establish torus cooling.

In this regard current PRA practices were shown to be somewhat dichotomous. On the one hand, fire PRAs commonly assume that no operator actions (other than fire fighting) can be taken in an area impacted either directly or indirectly by a fire. Nominally, this would include both areas where a fire is actually postulated and areas that become smoke-filled as a result of a fire elsewhere. On the other hand, fire PRAs rarely give explicit consideration to smoke movement. It is unlikely that the smoke movement observed during some of these fire incidents would have been predicted in a PRA analysis of corresponding scenarios. Hence the dichotomy - most PRAs would not credit actions in smoke-filled areas but would also fail to explicitly consider what plant areas might become smoke-filled during any given fire.

Given this perspective one can conclude that current PRA methods contain elements that may lead to conservative assumptions (assuming no credit for actions in smoke-filled rooms) while other omissions (the failure to explicitly consider smoke movement) may lead to some optimism. Achieving a proper balance between these two aspects of the analysis may require some added attention. It would appear clear that simply applying the human reliability values from the internal events PRA analysis, a practice applied in some of the IPEEE analyses in particular, is not appropriate for fires. In current practice, it is more common to apply performance shaping factors (PSFs) to reflect an increased probability of failure for manual recovery actions in the event of fire. These are often applied only to actions that take place outside the main control room. That is, actions that take place inside the main control room are commonly considered unaffected by fires that occur outside the control room. The PSF approach does have the potential to address probabilistically the potential that smoke spread might lead to operator errors or prevent some recovery actions. This could also include the potential for smoke ingress into the main control room as well. However, current guidance does not explicitly discuss potential smoke spread problems as an aspect of the PSF quantification. Some additional development of these methods, and in particular refinement explicitly for fire PRA, may be appropriate.

4.5.5 Multiple Events from the Same Root Cause

Several incidents have demonstrated that, under special conditions, it is possible to experience more than one major event at the same time. Examples identified in this study are as follows:

– The Vandellos incident was initiated by a turbine blade failure. Fragments of the ejected blades cut through turbine lube oil piping leading to a major turbine building fire. Fire-induced damage to a flexible joint in the main circulating water system piping allowed a very large quantity of seawater to enter the turbine building. This water flooded the lower levels of both the turbine and reactor buildings to a depth of about 32 inches.

– Both the Narora and Salem incidents were also initiated by a turbine blade failure. Again, in both cases this initial failure led to oil and hydrogen release, and a large fire.

In a typical PRA, only one initiating event is assumed to occur at any given time and it is assumed that all initiating event categories are independent. That is, a typical fire PRA would consider fires alone and would not, for example, consider fires coincident with internal flooding or a turbine blade ejection event. At most, a typical fire PRA might qualitatively assess the potential for flooding due to fire suppression water, but even in those analyses potential flooding concerns are not addressed quantitatively. The above mentioned incidents, and Vandellos in particular, point out the possibility that fires may occur concurrent with other initiating events. Some additional attention to such events in PRA may be warranted. It should be noted here that multiple events were only observed in turbine building related fire incidents.

4.5.6 Non-Safety Related Areas and the Use of Internal Events PRA Model

In a typical fire PRA, a fire scenario that can only affect non-safety related equipment and cables is considered risk insignificant. Such fires are widely screened out without a detailed analyses. Oconee, Waterford and North Anna were such fires; that is, if a fire PRA had considered these fires, they would have likely been screened in the initial stages of the analysis.

In the case of Oconee however, the chain of events that followed the switchgear fire led the reactor into an overcooling condition. The significance of this incident lies in the actions that the operators took from the control room. It is not clear how much the operators were influenced by the fire itself. The fire must have had some effect on the operators as it created a condition in the plant that was somewhat unpredictable (given failure of part of the integrated control system (ICS)). Also, one report states that some smoke got into the control room and cites this as a factor in the operator errors observed.

There are some similarities between the Oconee and the North Anna fire incidents. At North Anna a main transformer failed catastrophically and the ensuing fire damaged non-safety related cables. Although only non-safety related components and cables were involved, a spurious safety injection signal was received. In that incident, the operators carefully monitored and controlled the core temperature decrease.

In most fire PRAs, fire scenarios are retained during initial screening if they have the potential to either damage safe shutdown equipment or lead to a demand for safe shutdown (a plant trip). It is uncommon for a fire PRA to look for ways that a fire in non-safety related areas of the plant might lead to unexpected plant conditions. It is effectively assumed that the fire is just another cause for the failure of non-safety related cables and equipment of that location so that the experience would be reflected in internal events analysis random failures.

The event trees, fault trees and the list of initiating events developed in the internal events PRA analysis are commonly used in fire PRAs to establish which components are risk significant and to quantify core damage frequencies for various fire scenarios. To make the event trees and fault trees manageable, simplifying assumptions are made in the internal events analysis based on the combined likelihood of a given sequence of events. As a result many event sequences may be screened out from the event tree and fault tree models based on a perceived low likelihood of occurrence. These screening assumptions may not be valid for all fire scenarios.

For example, overcooling of the reactor (an overcooling transient) may occur if several diverse events take place simultaneously (typically a combination of random equipment failures and operator errors). The required sequence of events is often found to be a very unlikely in the context of an internal events PRA. Hence, overcooling transients may not be represented in the final plant sequences quantified in the risk study. The Oconee fire incident demonstrates that the assumption of independence among nominally diverse events may not be valid when fire is involved as a potential common cause source of equipment failures and/or operator error. At Oconee the switchgear failure caused two reactor coolant pumps to trip while feedwater control was lost due to failure of the Integrated Control System (ICS). The fire may also have affected the control room operators (smoke got into the control room and it took close to an hour to extinguish the fire), who did not pay close attention to cold leg temperature drop and allowed the reactor to cooldown at a rate greater than what was specified in the technical specifications. This implies that fire PRAs may need to more carefully examine the simplifying assumptions used in the development of the internal events plant response models to ensure that those assumptions are appropriate to the fire analysis as well.

5.0 CONCLUSIONS

This study has reviewed a select set of fire incidents that have occurred at nuclear power plants around the world in order to glean insights relevant to fire PRA practices, methods, and assumptions. The objectives of the review were to:[11]

– identify key fire risk and fire PRA insights from serious U.S. and international nuclear power plant fires, and

– develop recommendations for PRA improvements and areas for further investigation.

Indeed, insights have been gained relevant to fire PRA methodologies, assumptions and data. The overall conclusions of this study are provided in Section 5.1. Conclusions and recommendations related to specific topical areas are discussed in Section 5.2. The incident review process also provided some insights about the quality and usefulness of fire incident reports. Comments regarding this matter are provided in Section 5.3.

5.1 General Insights

This review has provided numerous insights regarding the validity, accuracy and applicability of fire PRA methods, data and scope. The review has confirmed many of the assumptions made and conclusions reached in a typical fire PRA including the commonly held perception that fires can challenge plant safety. It was found that in many situations fire PRAs apply conservative assumptions. However, the incidents also included behaviors and chain of event sequences that have not been considered in past fire PRAs. In general, in the judgement of the authors, the identified analysis omissions would not seriously compromise the overall conclusions of a complete and quality fire PRA as currently applied to U.S. plants.

It appears from the incident review that, in general terms, there are substantial differences in the progression and outcome of fire incidents between Western and Soviet-design plants. These differences are likely a reflection of differences in design, construction and maintenance practices and materials selection, particularly as related to cables and electrical systems. Indeed, it would appear from the incidents reviewed that, historically, the likelihood that a fire might substantially challenge plant safety appears much lower for U.S. plants than for Soviet-designed reactors. (As noted below, the Soviet-designed plants have undergone significant fire safety upgrades.) As a result, the fire PRA omissions identified in this review would have a more substantial impact on a PRA conducted for a foreign reactor design than they would on U.S. fire risk assessments.

This review identified six fires that have seriously challenged nuclear safety at an operating reactor. In the US, the only such fire incident was the 1975 Browns Ferry fire. Since that time, many plant improvements specifically aimed at enhancing the fire safety of U.S. plants have been implemented. These improvements derive primarily from implementation of the 10CFR50 Appendix R requirements that were a direct result of the Browns Ferry fire. The lack of any fires that have significantly challenged nuclear safety at any plant in the U.S. since 1975 is likely a reflection of these fire protection enhancements.

For the Soviet-designed reactors, this review identified four fires occurring between 1978 and 1988 that presented equal or perhaps greater safety challenges than the Browns Ferry incident. (Two additional fires that occurred during the final phases of plant construction would have challenged nuclear safety had the plants been in operation at the time of the fires.) In each of these incidents, the post-fire recovery efforts benefitted from reactor design features that allowed a substantial time (several hours) to recover core cooling functions before the onset of core damage. It is also noteworthy that no major fire events in Soviet-designed plants since 1988 were identified. Since the mid-1980s substantial effort has been made to upgrade fire safety at plants in Russia and other countries with Soviet-designed reactors. This includes the application of fire retardant coating on cables, upgrading of fire barriers, improved fire suppression systems, and improved protective gear for plant operators and fire fighting personnel. As with the U.S. improvements, this may be a significant contributing factor to the lack of fires leading to a significant nuclear safety challenge since 1988 for the Soviet-designed plants.

The sixth seriously challenging fire event took place at the Narora plant in India in 1993. Narora is substantially different from either U.S. or Soviet designs. It can be argued that of all the fires reviewed, this incident led to the most serious nuclear safety challenge. None of the fires reviewed actually led to any reactor core damage.

The review has identified important lessons in conducting fire PRA and points to areas where improved fire PRA methods and data may provide added benefits. Some refinements in fire PRA methodology may be appropriate. The incidents have demonstrated that smoke propagation can impact the effectiveness of the operators and fire fighters. Current fire PRA methods remain weak in their treatment of smoke effects. Turbine building fires and fires involving non-safety related areas of the plant are generally screened out in the initial stages of a fire PRA. Reviewed incidents indicate that complications from such fires (e.g., smoke propagation and operator error during plant shutdown) may lead into event sequences otherwise considered as very unlikely. There is a potential that such sequences, which are typically screened out in the internal events analysis, may not be picked up in a fire PRA.

The review has also identified some gaps in current fire PRA methodology. In particular, current methods do not address the possibility of multiple initial fires, secondary fires and multiple initiating events. Several fire incidents involved multiple fires ignited at different locations of the plant due to a single root cause (multiple initial fires). In a few cases, additional fires ignited due to damage caused by the original fire (secondary fires). Current fire PRA methodologies do not include an explicit provision for identifying such fire scenarios. Also, a fire incident may be a part of an event involving several distinctly different hazards (or initiators). For example, several incidents involved a turbine blade ejection incident leading to a fire, and/or involved a fire concurrent with substantial plant flooding. These types of events are not included in the scope of a typical fire PRA.

5.2 Specific Methodological Insights

Based on this review several specific methodological insights were gleaned. Several empirical observations were also made relating to the strengths and weaknesses of current fire PRA methodologies. These insights and observations are summarized below. The insights are categorized by the elements of a fire PRA analysis (see Section 2.4).

Fire Initiation

– Fires may occur concurrently at different locations within the plant. Fires may occur simultaneously as the result of a common root cause (multiple initial fires) or as the result of the damage caused by an initial fire (secondary fires). Current PRA methodologies are generally capable of addressing concurrent fires. That is, it is possible to postulate multiple fires and assess the cumulative impact of damage from each fire. However, no basis has been established for predicting under what conditions such fires might occur. Some additional examination of such events may be warranted to assess their potential risk importance (frequency and consequence). If such events are found to be potentially risk important, then some additional methodological development would also be needed.

– Electrical faults have led to self-ignited cable fires, even in the case of relatively low power (220VAC) circuits. Current PRA methods are capable of dealing with such fires. However, much uncertainty remains regarding relevant phenomena and the potential for creating a self sustaining fire. Therefore, the underlying assumptions and methods of analysis warrant further review in particular in the areas of occurrence frequency, the impact of various circuit characteristics (e.g., voltage level), how cable type influences the possibility and rate of fire growth, and methods for partitioning the general fire frequency to specific cables, fire areas, or fire scenarios.[9]

Fire Propagation

– IEEE-383 qualified cables may sustain combustion and propagate the fire given a sufficient exposure source. This confirms the need to model propagation of such fires in a fire PRA.

– Certain of the fires at Soviet-designed plants readily propagated along both horizontal and vertical cable trays. Nominally similar initial fires in U.S. plants were seen to propagate less readily, and none (including Browns Ferry) led to comparable physical fire extent or damage. It would appear that the potential for rapidly growing cable fires was higher for Soviet-designed plants than for U.S. plants, likely as a result of cable material selection and construction practices. (As discussed above, conditions at the Soviet-designed plants have

[9]Self-ignited cable fire analysis methods are being addressed separately under Task 3 of this program (JCN Y6037).

changed substantially since the fires identified in this review. Various fire protection upgrades have been implemented that will likely reduce the fire hazard substantially.)

- In the Soviet-designed plants a number of fire incidents involving inter-compartment fire spread were identified. In almost all such cases, faulty fire barrier elements or a lack appropriate fire barrier penetration seals facilitated the propagation of fire and smoke to adjacent compartments. For U.S. plants, only the Browns Ferry fire involved inter-compartment fire spread, and that case involved an incomplete penetration seal. This confirms the importance of fire barriers to fire safety, and illustrates that plant specific conditions dictate the possibility of fire spread to adjacent compartments. Such factors are typically considered in a quality fire PRA as a part of plant walk-downs.

- In at least one case room-to-room fire propagation was observed due to the spread of hot gasses only (i.e., in the absence of a direct flame spread path). In this case the fire spread may have been the result of the fire-induced failure of an energized cable. Electrical arcing leading to ignition of secondary fires as a result of cable failure has been observed in testing[26], but is not considered as a mechanism for fire spread in current fire PRAs. Consideration of this effect would require modification of the computer fire models used to predict cable fire growth behavior.

<u>Fire Detection and Suppression</u>

- For long-duration fires, four factors were observed that influenced the duration of fires before suppression: a delay in initiating the fire fighting activities, use of ineffective extinguishing media during initial attacks on the fire, the initial severity of the fire, and inaccessibility of the fire. Current methods for treating fire suppression in a PRA would not fully capture all such effects. Some review of these methods may be warranted.[9]

- Poor decision making or distractions from ongoing events can delay the activation of the fire brigade, even for severe fires. The implications of this insight depend on which of the two commonly applied approaches to manual fire brigade response assessments is being applied in the fire PRA:
  - Use of a generic curve characterizing the probability of suppression versus time based on historical fire incident data inherently includes these factors, but these methods have not, in the PRAs which have used them, been adjusted to reflect to plant- or scenario-specific factors.
  - Methods that base the timing of manual fire fighting on fire brigade practice drill response times do not explicitly consider these factors.

Given this perspective, some additional refinement of manual fire fighting assessment methods may be appropriate.[10]

- Once fire fighting is initiated, plant personnel may still make repeated attempts to extinguish a fire using ineffective suppression methods (such as hand-held gaseous fire extinguishers). Various events illustrate a continued reluctance to use water on electrical fires. In fire PRA, it is often assumed that once initiated, manual fire fighting will be promptly effective. Some additional treatment of the possibility of ineffective or delayed fire brigade response may be warranted.

- Reduced visibility caused by smoke can seriously affect fire fighting effectiveness. Current fire PRAs do not explicitly model smoke propagation. Hence, the plant specific conditions that may lead to smoke impacting fire fighting activities are not considered in a typical PRA analysis.

- The availability of automatic fire detection and suppression systems can be compromised by the fire itself, or by human errors prior to the fire event. Plant specific conditions contribute to such situations. Plant walk-downs are one vehicle by which these conditions may be identified. However, current PRAs would generally not include explicit consideration of these factors. Generic fire protection system reliability estimates may inherently include such failures, but would not account for the relevant plant-specific factors.

- Significant equipment losses may occur early in a fire (e.g., well before fire control or final fire extinguishment), but may also occur after a prolonged time. Hence, it is important for fire PRAs to consider a range of possible fire durations including long duration fires (i.e., in excess of one hour). That is, it is important to correctly characterize suppression time distributions. PRAs that fail to consider long duration fires, and as a result limit the assumed extent of fire damage, may miss significant fire risk contributors.

- Related to the preceding insight, fire damage can occur despite successful operation of fixed fire suppression systems. Some fire PRAs assume that successful operation of a fixed fire suppression system will control the fire and prevent additional damage to critical cables and components. This assumption may not be valid, in particular, for a congested area (such as cable spreading room or cable vault area), where the fire suppression system may be blocked by large equipment (such as in the turbine building), or where the initial intensity of the fire is sufficient to overwhelm the suppression system (such as in a large oil fire).

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[10] Fire suppression analysis methods are being addressed separately under Task 2 of the USNRC Fire Risk Methods research program (JCN Y6037).

Conclusions

Equipment Damage

- A number of the fire incidents did include indications of spurious equipment actuations and other circuit effects as the result of fire-induced cable damage. This issue is the subject of current debate, in particular, with regard to the appropriate scope of the assessment and the conditional probability of spurious actuations or other circuit effects. Few fire PRAs have attempted a comprehensive treatment of fire-induced circuit fault effects beyond loss of function. Existing fire PRA methodologies can be adapted to address the possibility of spurious actuation of equipment.[11]

- Structural failures may occur in a severe fire, and this may cause additional damage. Such failures are of particular relevance to the turbine building where large quantities of combustible materials are present. Fire PRAs do not typically consider structural damage as a possible outcome of a severe fire. Some re-assessment of screening methods, and in particular as applied to the turbine building, may be warranted.

- Additional hazards may result from, or occur simultaneously with, a fire. This includes flooding (e.g., due to fire-induced expansion joint breaks), major equipment failures (e.g., turbine or transformer failure), pressure/shock effects (e.g., hydrogen release and deflagration) and shrapnel damage (e.g., turbine blade ejection or shrapnel caused by energetic electrical faults). Current PRAs seldom consider simultaneous occurrence of multiple hazards.

Impact on Plant Safety Functions

- Redundant safety equipment may be rendered unavailable through indirect fire effects. For example, operators may shut down operable equipment to facilitate fire fighting. This was noted in particular during fires in Soviet-designed plants where procedures call for de-energizing electrical equipment before attempting manual fire suppression. Hence, this appears to be a plant specific phenomenon (based on plant fire fighting procedures). Current fire PRA methodologies could be adapted to address such scenarios. For example, an analyst might assign an increased “random” failure probability for the redundant train to reflect this potential. However, a technical basis for incorporating such equipment losses has not been developed.

- In fire PRA, fires affecting non-safety related components are often screened out without a detailed review of the potential impact on balance of plant functions and the operator actions that may ensue. At least one event has demonstrated that such a fire may adversely influence operator actions and may cause entry into accident sequences nominally considered to be of

[11] Circuit analysis and the spurious operation of equipment is being addressed separately under Task 1 of the USNRC Fire Risk Methods research program (JCN Y6037),

very low likelihood (i.e., in the internal events analysis). Current fire PRA methodologies can address such scenarios. This may, however, require a more thorough review and assessment by the fire PRA analyst of the simplifying assumptions applied in the development and screening of plant accident sequences during the internal events analysis.

– The fire incidents included cases where fire effects (heat and smoke) prevented successful completion of attempted operator actions. However, the events also included cases where operators played a critical role in ensuring core cooling under very difficult conditions. PRA methods were generally seen to be conservative in this regard and would not have credited operator actions taken during some incidents that were, in fact, successful.

– Several of the reviewed incidents involved smoke from ex-control room fires entering the main control room. While only one case (Narora) required abandonment of the main control room, in various cases smoke was cited as having impacted operator effectiveness. Current PRAs commonly assume that fires outside the control room will not impact the reliability of operator actions that take place within the control room. These assumptions may be modestly optimistic.

5.3 Availability and Quality of Incident Data

The availability of quality information for a given fire was instrumental to achieving the objectives of this study. At practically all stages of this study, as more detailed information on each event became available, the number of relevant and interesting insights obtained increased. The most useful information was typically obtained from narrative descriptions of the fire, through discussions with knowledgeable individuals and through the reconstruction of the detailed time line or chain of events for each fire. This reinforces what is very well known among those who conduct accident investigations and accident analyses; namely, the details of an incident are extremely important and the recording or cataloging of incidents using a formatted reporting structure often masks information that at some later point may be of specific interest. This illustrates that in cataloging incident reports, it is extremely important to maintain the details of an incident to facilitate future analyses of the incidents rather than to rely only on pre-formatted or standardized incident reporting forms. Standard form-based reports often will delete any extended incident narratives. For example, only an extremely detailed incident reporting form (which is not typical of the fire events data bases currently available or under development) would capture such important insights as multiple and/or ineffective suppression attempts using hand held extinguishers before the application of water, subtle aspects of operator responses to the situation, or the difference between multiple and secondary fires.

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Appendix 1 - Analysis of San Onofre, Unit 1 Fire on March 12, 1968

A1.1 Plant Characteristics

San Onofre Nuclear Generating Station Unit 1, located near San Clemente, California, was a Westinghouse Pressurized Water Reactor (PWR) with a 436 MWe (net) rated capacity. It started commercial operation in 1968, was permanently shutdown in the 1980s, and has since been decommissioned. [ref. A1-3].

A1.2 Incident Progressions and Implications for Fire PRA

Two similar incidents involving self-ignited cable fires took place within a short time [Ref. A1-1]. On February 7, 1968, San Onofre 1 experienced a cable fire adjacent to a containment penetration and on March 12 of the same year another cable fire occurred in a 480-volt switchgear room. Although, the focus of this review is on the March 12 incident, because of the similarities between the two incidents and the short time difference, it was deemed appropriate to describe the first incident here as well.

At 4:45 p.m. on February 7, 1968, the unit was operating at 380 MWe and performing core depletion tests. All of the pressurizer heaters had been on for 96 hours when the operator noticed that the heaters were not actually operating. At about the same time, the control room received a 480-volt bus ground alarm and a loud noise was heard in the control room and the lights flickered.

At 4:47 a security officer reported a fire at the Southeast side of the containment. The reactor operator transferred the No.1 480-volt bus to the #3 480-volt bus which caused ground indications on both buses. The reactor operator then transferred the 480-volt buses back to their normal sources. The #1 480-volt bus ground cleared when the Group C pressurizer heater breaker was opened. (A clear indication of a ground fault on the heater power cables.)

At 5:10 p.m. the reactor and turbine (generator) were manually tripped. No spurious equipment operations were noted during the incident and there was no apparent effect on the reactor shutdown/cooldown efforts. Fire fighting was initiated immediately and the fire was very quickly reported to be under control at 4:47 p.m. (just two minutes from the first signs of the presence of fire). The fire was fought with CO_2 and Ansul [1] portable extinguishers.

On March 12, 1968, San Onofre 1 experienced another cable fire, this time in a cable tray in the No.2 480-volt switchgear room. At the time of the fire incident, the unit was operating at 380 MWe when, at 12:21 a.m., several alarms were received in the control room including: "Intake Structure Hi Level," "480-volt System Ground," "Station DC Bus Ground or Low Voltage," and

[1] Note that 'Ansul' is a manufacturer trade name rather than a fire suppressant. This is a quote from the applicable report and no further information on the nature of the fire suppressants used is provided.

"Hydraulic Stop Gate Trouble." These were followed shortly by a "Sphere Heating and Ventilating System Trouble" alarm.

At 12:25 a.m., the annunciator panels for the "turbine-generator first out, auxiliary, and electrical boards" were lost. An auxiliary operator reported smoke in the No.2 480-volt switchgear room.

At 12:27 a.m., operators observed blue arcing above the east door window of the No.2 480-volt switchgear room.

At 12:32 a.m., fire was observed in three cable trays above the east door.

The reactor was tripped at 12:34 a.m., and began unit shutdown actions at 12:37 a.m. The No.2 480-volt bus was cleared by over-current relay operation.

At 12:35 a.m., assistance was requested from the closest outside fire department, which happened to be a Marine Corps Fire Department.

At 12:45 a.m., 24 minutes after the first control room alarms were received, the Fire Department arrived on the scene. The electric motor driven fire pumps would not start. Therefore, the started the gasoline engine driven backup emergency fire pump (12:56 a.m.).

The fire was declared extinguished at 1:00 a.m., 39 minutes after the initial control room alarms.

During cooldown efforts following the fire, it was determined that the coolant boron concentration was decreasing instead of increasing as expected, and the cooldown was suspended for 3 hours and 40 minutes until the problem was diagnosed and fixed.

Post-fire investigation revealed that power and/or control circuits were affected for RHR suction and discharge valves, the CCW heat exchanger outlet valve, the South primary plant makeup water pump, and three annunciator panels. Damaged cables rendered the following equipment electrically inoperable:

- Safety injection recirculation valves
- West recirculation pump and discharge valve
- Electric auxiliary feedwater pump
- Safety injection train valves (West train MOVs)
- Refueling water pump discharge valve to recirculation system

The following equipment was lost due to the relay cutout of the No.2 480-volt bus:

- West RHR pump
- South transfer pump
- Boric acid injection pump
- Boric acid storage tank heaters & boric acid system heat tracing
- South primary plant makeup pump
- Flash tank bypass valve
- East and West flash tank discharge pumps

- Center component cooling water pump
- Several other MOVs

A1.3 Incident Analysis

While the first incident had only a minimal impact on the plant, a large number of components were rendered unavailable in the second incident. A sufficient number of components and systems remained available to allow for orderly shutdown and core cooling. At least one of the alarms received in the control room was apparently spurious. This is the "Intake Structure Hi Level" alarm. An operator reporting from the intake structure found no reason for this alarm to have sounded.

In terms of the fire cause, there are many similarities between the two incidents. The investigation concluded that the most probable cause of both fires was thermally and mechanically stressed cables, coupled with the use of individual fuses to provide for clearing of faults on each phase of the three-phase 340-volt circuits. It also appears that the cables were undersized for their design current loads under their actual installations conditions.

The initial fault is thought to have been a cable-to-cable, phase-to-phase hot short involving two separate power feeds from the same three-phase power bus. The fusing configuration allowed back-feeding of fault current through the un-faulted phases of each power feed which led to an even more severe over-current condition for the conductors. Figure A1-1 provides a schematic of the power circuit for the pressurized heaters. In that figure, I_{SC0} depicts the initial short circuit after cable failure and I_{SC2} is the subsequent short circuit current back-fed through the heaters. Note that the portion of I_{SC2} passing through the intact fuses is below the continuous rating of each fuse.

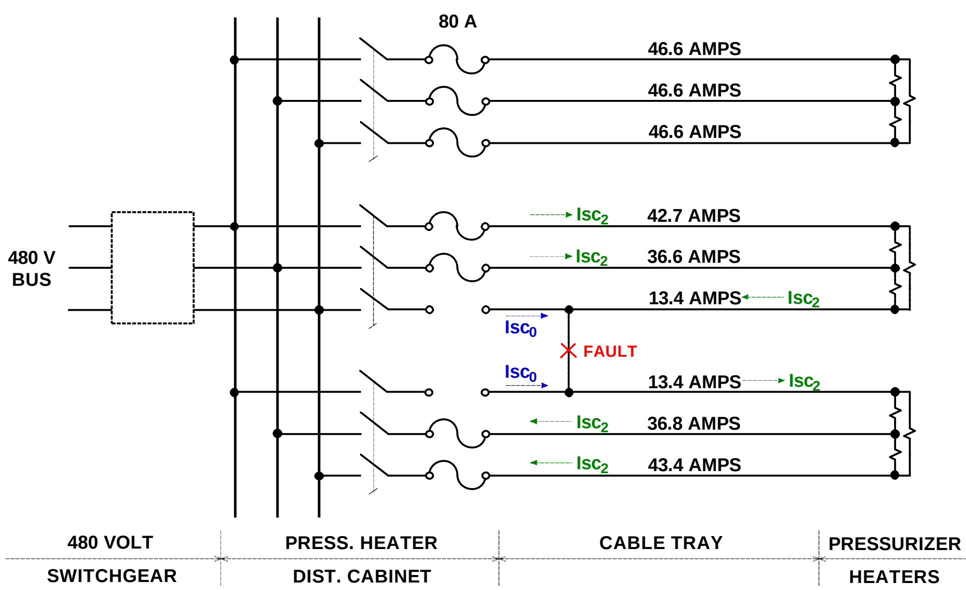

Figure A1-1: Schematic of Pressurizer Heater Circuits.

Both incidents involved self-ignited cable fires. They are important because they are the earliest fire incidents at a nuclear power plant where self-ignition of cables resulted in extensive equipment damage and loss of operability of equipment. While the first incident saw little or no fire spread, the second incident saw fire spread to three cable trays that were “totally burned for 15 feet.” Investigation of the incidents led to recommendations that urged industry to re-examine cable qualification and to raise the standards for establishing cable ampacity limits and for improving the flammability behavior of cables. Since the time of this fire, cable ampacity standards have improved substantially and now explicitly address cable tray applications. Cable ampacity standards are now widely recognized and applied. Further, a flammability standard was incorporated into IEEE-383, the general nuclear cable qualification standard [Ref. A1-2]. Most cables used in current U.S. reactors are required to meet this standard.

In both incidents, the fire did not cause complete loss of core cooling capability, core damage, radiation release or any injury to plant personnel or the public. The available sources do not discuss in detail fire fighting activities, occurrence of hot shorts (other than the initial cable-to-cable fault that initiated the second incident), the nature of other circuit failures or operator actions in response to the failures caused by the fire.

It may be argued that given the vast changes that have taken place since 1968 (improved ampacity standards, improved standards for cable flammability, enhanced fire protection features, etc.), some aspects of the San Onofre fire incidents are not applicable to fire PRA today since the conditions of that plant at that time were not representative of current conditions of nuclear power plants in the U.S. The one exception is the insight related to self-ignited cable fires. These incidents do illustrate that such fires can occur, can propagate, and can lead to severe consequences. However, this is likely only applicable to older plants in the U.S. since improved cable flammability standards have been in effect for the industry since 1975. In fire PRA is it common practice to assume that self-ignited cable fires are possible for older style “unqualified” cables, but that such fires are not possible for cables that pass the IEEE-383 flammability standard (“qualified” cables). The lack of any severe self-ignited cable fires after the San Onofre incidents provides important evidence supporting the validity of these assumptions.[2]

A1.4 References

A1-1 “San Onofre Nuclear Generating Station Unit 1, Report on Cable Failures - 1968,” Southern California Edison Company, San Diego Gas & Electric Company, publication date unknown, but circa 1968.

A1-2 “IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations,” ANSI/IEEE STD 383-1974.

A1-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

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[2]Note that self-ignited cable fires are being addressed separately under Task 3 under this project (USNRC JCN Y6037).

Appendix 2 - Analysis of Mühleberg Fire on July 21, 1971

A2.1 Plant Characteristics

Mühleberg is a single unit BWR type nuclear power plant located near Mühleberg, Switzerland. The unit has two identical turbine generators (A and B) rated at 162 MWe per generator for a total of 324 MWe for the plant. The plant started commercial operation in October, 1972. At the time of the incident, the plant was undergoing initial power ascension and pre-operational tests. Testing of the turbine-generators at 50% of rated power had been completed at the time of the incident. [ref. A2-5].

A2.2 Summary of the Chain of Events

The chain of events described in this section is based on References [A2-1] and [A2-2]. It was found that there are differences in the description of the chain of events between these two sources. Therefore, the authors of this report had to inject their own interpretation of the available information.

On July 21, 1971, about 21:18 p.m., the plant was in operation and the power level was being ramped up when the oil pressure in turbine B dropped and the feedwater pumps tripped on high water level in the reactor. The Reactor Core Isolation Cooling (RCIC) system initiated.

It was later determined that a loosened screwed-on pipe was the cause of an oil leak. The pipes and the screw joints had been inspected only 15 minutes before the incident and no oil leaks were reported. The turbine tripped. A partial scram took place initially, which was later followed by a full scram.

The leaking oil ignited and started a fire under the turbine. The exact cause of ignition is not known. It is suspected to be either sparks from a valve limit switch (the loosened pipe was near a valve assembly), hot surfaces of a fluorescent lamp, hot surfaces of valve housing or auto-oxidation caused by the oil soaking into the asbestos insulation on the valve housing. (The latter phenomenon was later shown to be plausible in laboratory settings.)

The exact time of fire ignition cannot be determined. The fire was discovered by a mechanic who was outside the turbine building and sensed a pressure wave. From this, one can infer that a form of deflagration or explosion may have taken place. Given a leak in a high pressure oil line, one plausible explanation is that as the leak developed, some quantity of oil was released as a fine mist which then ignited causing a minor explosion. However, neither of the available reports is clear on this subject. The mechanic telephoned the control room immediately. About 21:19, the local fire department was alerted. Given the timing of the oil pressure drop and reporting of the fire, it would appear that the fire was detected quite promptly.

At 21:24, three members of the operating crew entered the turbine building with breathing apparatus and discovered that the lights were out and dense smoke was filling the building.

At 21:32 the unit generator was tripped by the operators.

At 21:40 head count of the personnel was completed (all were accounted for).

At 21:43, about 24 minutes after notification, the local fire department arrived at the plant.

At 21:53, the fire brigade entered the turbine building wearing self contained breathing apparatus (SCBA).

The fire was initially confined to an oil fire beneath turbine B, but propagated into two cable trays also located underneath the turbine. Exhaust fans were used to remove the smoke from the building. As smoke started to clear an open fire was discovered on top of the oil tank. Initially it was thought that the oil tank had caught fire. However, it was soon discovered that the fire in the cable trays underneath the turbine had propagated horizontally to a cable duct above the oil tank through openings in the wall. The duct was located in the section of the building adjacent to the turbine.

At 22:02, the fire brigade, using a ladder from a ladder-truck, started spraying water on the ceiling of the turbine hall.

Fogging nozzles were used to fight the fire. Also, the exhaust fans had to be shutoff because of the potential for exposure to open flames.

At 22:15, additional plant personnel, who were trained in the use of SCBA, entered the turbine building and assisted in fire fighting activities.

At 22:56 it was noticed that the fire propagated upwards onto the upper parts of the turbine-generator set.

At 23:25 (about 2:07 hours after receiving first indications of an abnormal condition) the fire was brought under control.

At 00:30, on July 22, the fire fighter’s work was completed.

It must be noted that the fire did not damage any safety related cables and equipment. The operators managed to initiate and maintain shutdown cooling properly and without any major difficulties.

Figure A2-1 is a simplified layout drawing of the plant that shows the area where fire occurred. Note that the single lines extending between various items depict cable routes. Item 2 in that figure is the turbine-generator B, item 4 is the two motor generator sets, items 5 and 6 are the non-safety switchgear and item 7 is the cable “bridge” (as noted in Reference [A2-1]) between the reactor and turbine buildings.

Extensive damage was inflicted on the turbine building itself. It is estimated that 75% of the roof

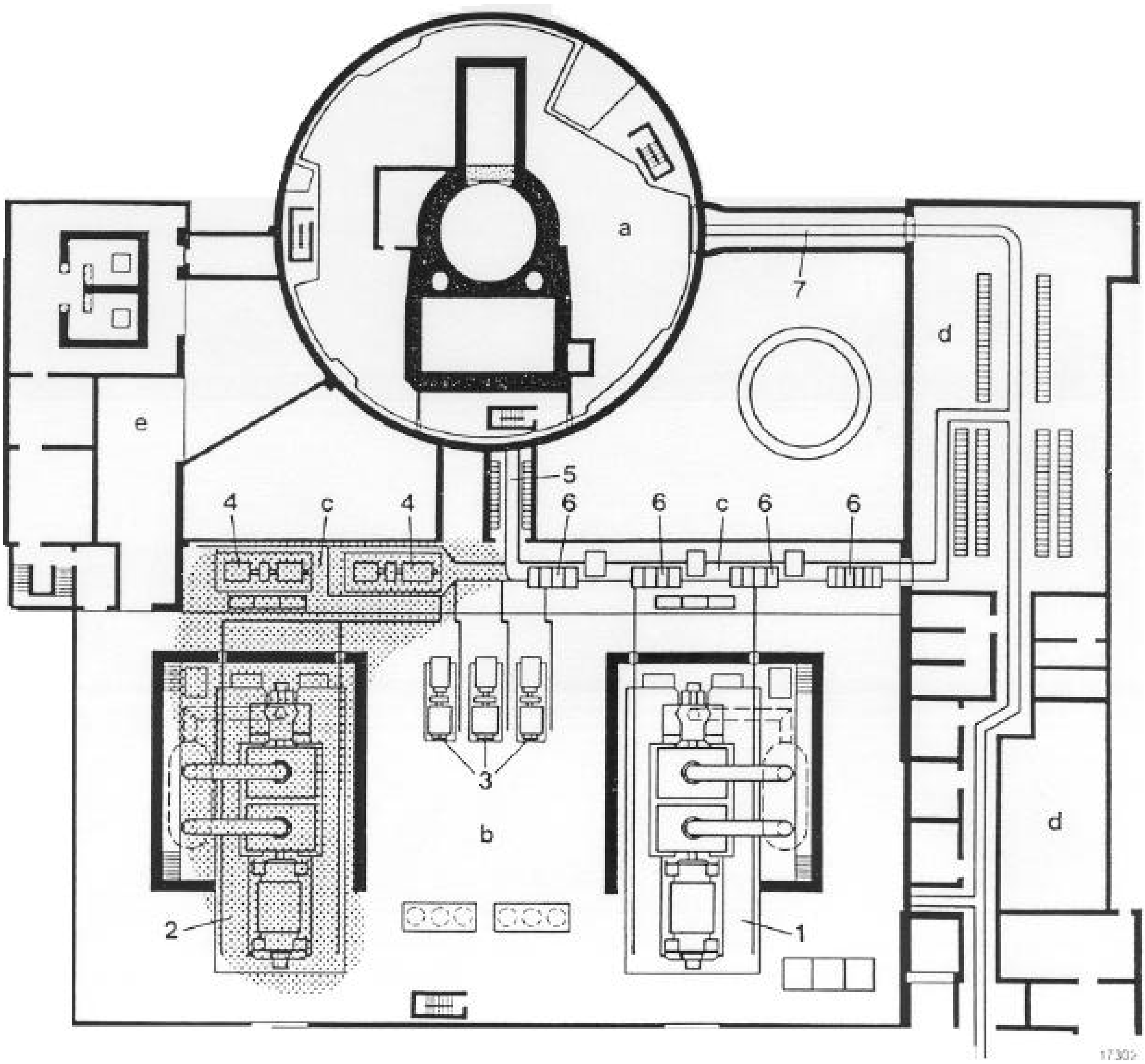

Figure A2-1 Location of Fire at Mühleberg (from Reference [2-1])

covering, 60% of the windows and 50% of the paintwork were severely damaged. Some of the purlins of the building were deformed, concrete surfaces near the turbine B, a number of gratings and wall insulation slabs were damaged. Aside from cables and electrical equipment, little direct damage was sustained by major mechanical equipment. Some peripheral items, insulation and piping were found to be damaged. However, the cables and electrical equipment sustained extensive damage. Turbine instrumentation, control panels, lighting equipment and 3000 kg of PVC cables were found to be severely damaged.

Indirect impact of the fire was considerably more extensive than direct heat damage. The hydrochloric acid vapors generated in the process of burning PVC cable insulation and interaction with moisture impacted a large set of equipment including in particular electrical devices (the switchgear equipment located in the turbine building as noted in Figure 2-1) and electronic devices. Although on the day after the fire the electrical equipment was sprayed with a neutralizing agent, the electrical and electronic equipment were still later found to be affected by the corrosive effects of hydrochloric acid. Ultimately some of the electronic equipment, pump motors, 380VAC motor control centers, and some of the mechanical and electrical equipment had to be replaced because of chloride deposits and corrosion.

A2.3 An Analysis of the Incident

The fire incident at Mühleberg is the first known large fire in a nuclear power plant occurring at a time when the reactor was already active (i.e., excluding construction fires). Although it did not impact any safety equipment, it caused extensive damage to a large set of equipment and cables. The fire was (apparently) detected promptly and reported to the control room by plant personnel. Fire fighting was initiated promptly and performed effectively.

This is one of few nuclear power plant fires where structural elements, especially the roof coverings, sustained some direct fire damage. In this incident the potential effects of a PVC cable insulation fire are clearly demonstrated. In a fire PRA, the impact of smoke on equipment is rarely modeled. Recent tests at Sandia National Laboratories [References A2-3 and A2-4] have demonstrated that electronic equipment may fail from exposure to smoke. At Mühleberg it is clearly demonstrated that a range of electrical and electronic equipment is susceptible to the effects of a corrosive smoke. However, from the available information it can be inferred that the smoke/corrosion damage was a slow process and susceptible equipment remained functional during the course of the fire. Such effects are typically assumed not to be risk significant since safe shutdown is assumed to be achieved (or failed) within a relatively short time period. This incident does not contradict these assumptions.

A2.4 References

A2-1 "Turbine Oil Fire in a Nuclear Power Plant", *Schadenspiegel*, 16th, March 1973.

A2-2 Von H.R. Lutz, "Der Turbinenölbrand im Kernkraftwerk Mühleberg", *Der Maschinenschaden*, pp. 96-102, Vol. 45, 1972.

A2-3 T. J. Tanaka, *Effects of Smoke on Functional Circuits*, Sandia National Laboratories, prepared for U.S. Nuclear Regulatory Commission, NUREG/CR-6543, SAND97-2544, October 1997.

A2-4 T. J. Tanaka, "Measurements of the Effects of Smoke on Active Circuits", *Fire and Materials*, **23**, 103-108, 1999.

A2-5 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix 3 - Analysis of Browns Ferry 1 and 2 Fire on March 22, 1975

A3.1 Plant Characteristics

Browns Ferry nuclear power plant is a three unit BWR located near Decatur, Alabama. At the time of the fire, Units 1 and 2 were in the very last stages of obtaining their operating licenses. Unit 3 was still under construction. Each unit is rated at 1,067 MWe. Units 1 and 2 have a shared control room and cable spreading room (CSR) while unit three is a separate unit. [Ref. A3!4].

There has been much written about the 1975 CSR and Reactor Building (RB) fire that occurred in Browns Ferry Unit 1. As a result, there is wide-spread knowledge throughout the international community regarding this incident. It is not our intent to repeat past discussions. The discussion that follows will focus on those events within this incident that have direct relevance to the objective of this study; namely, to develop fire PRA insights.

A3.2 Chain of Events and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A3-1] and [A3-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided. Unless otherwise noted, the event descriptions refer to events impacting Unit 1.

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
Prior to the incident	The power cables for two 480 VAC boards from opposite safety trains were routed during construction, erroneously, inside the same cable tray. (Regulatory Guide 1.75 which was in effect at the time disallows this practice.)	In a fire PRA, error in routing of cables is not taken into consideration. The actual discovery of such a construction error is rare. No other such incidents are known to the authors. Therefore, the assumption used in fire PRAs should generally be considered as acceptable.

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
Prior to the incident	Polyurethane foam was used at Browns Ferry to seal penetrations. Polyurethane is a flammable material. After filling a penetration with polyurethane, it was coated with Flamastic 71, a non-flammable fire retardant coating material. The combination had been tested and shown to meet fire resistant standards.	It is inherently assumed in a PRA that penetration seals are not a significant fuel source. Silicone foam is now the predominant seal material. Silicone is technically flammable, but it burns quite poorly. The use of polyurethane foam at Browns Ferry is not considered to have significant implications for current fire PRAs.
Prior to the incident	The plant was operating with some of its penetration seals incomplete. Depending on the seal, their integrity was violated (e.g., as a part of additional construction/maintenance activity), had not been fully leak tested and/or the intended Flamastic 71 coating was not applied. Also, the cable penetration seals for openings between the CSR and control room were still under construction.	In a typical fire PRA, the probability of a penetration being open is assumed to be about $1x10^{-3}$-$1x10^{-2}$ per penetration. The possibility of a large number of penetrations being incomplete is not considered likely. For a power plant that is several years into commercial operation this assumption should remain valid. Browns Ferry was a new plant just completing construction. Hence, this condition is not considered relevant to current fire PRAs for mature plants.
Prior to the incident	Workers were checking incomplete CSR - to - RB seals for leaks using candle flame to detect air flow (the RB was under negative pressure).	Introduction of an ignition source such as a candle into a plant is not considered in fire PRA. However, this practice would be explicitly disallowed at plants today. Hence, this aspect of the incident is not considered relevant to current PRA practice.
Prior to the incident	A CO2 suppression system was installed for the CSR, but during construction metal plates were installed under the breakout glass for manual system initiation device. This would have prevented manual activation of the system. Fire protection system inspections by TVA personnel had not discovered the presence of the plates.	This is one example about how certain fire protection features may not be available when needed. Fire PRAs may credit manual actuation of automatic systems, although this is not currently common practice. The overall failure probability currently assumed for fixed systems should cover such events.
~ -48:00	On or about March 20, 1975 two fires had occurred in the CSR because of candle flame usage. In one case a dry chemical extinguisher was used. No reports were filed with the NRC or internally except for a log entry. The second fire was discussed in an operators' meeting.	Fire PRAs do not consider pre-cursor events. Fire initiation frequencies are based on reported fires. In this case, it is difficult to establish whether there were one, two or three fires in the CSR.
Prior to the incident	Units 1 and 2 were operating at 100% power generating 1098 MWe.	

Time (rel. to ignition) (hr:min)	**Event Description (Note 1)**	**Fire PRA Implications**
00:00 (fire ignites)	At about 12:20 on March 22, 1975, a fire ignited on the polyurethane foam inside a cable penetration between the Unit 1/2 CSR and the Unit 1 RB. The ignition source was a candle that was being used to check for existence of air currents. The foam was exposed to open air at that time and was used as a penetration seal.	See note on use of candles above.
--	The workman who was using the candle tried to put out the fire by beating on it with his flashlight and later with some rags. The fire continued to burn.	The workman did not promptly report the fire.
--	The same workman applied CO2 from a portable CO2 extinguisher. The fire was not affected and continued to burn. After attempts by the CO2 extinguishers failed, portable dry chemical extinguisher was used. This also failed to put the fire out.	Repeated ineffective attempts to manually suppress a fire are not typically modeled in a fire PRA. It is commonly assumed that manual fire fighting, once initiated, will be effective within a very short time.
00:15	At about 12:35, the fire was reported to the control room. Operators initiated the fire alarm and announced the fire over the public address system.	The time to control room notification is generally considered as the time for fire brigade activation. In this incident, the workmen at the fire location made several attempts to put the fire out before reporting the fire. Therefore, there was no delay in initiating the fire fighting efforts, although there was a 15 minute reporting delay, and as noted above, initial fire fighting efforts were ineffective. A typical PRA does not distinguish between the local detection of a fire, control room notification, and activation of the fire brigade.
--	The Unit 1 operator making the fire announcement, "walked the control panel" looking for abnormalities (from Ref. A3-1).	Operator confusion due to erroneous information on the control board is often discussed in relation to fire PRA, but it is not explicitly modeled under current methods. The behavior of this operator is interesting to note because it means that the operator was cognizant of potential impact of a fire on cables and electrical circuits and was looking for abnormalities. Given that this was on of the first major fires at an operating plant, this awareness on the part of operator is laudable. For PRAs today one should expect that a control room operator would be aware of the possibility of abnormal indications on the control board and would not fully trust the board.

Time (rel. to ignition) (hr:min)	**Event Description (Note 1)**	**Fire PRA Implications**
--	Fire had propagated through the penetration into the RB side of the wall. The existence of the fire on the other side of the wall was not immediately recognized, but was later detected by other plant personnel who observed smoke in the RB.	Room to room fire spread is commonly considered in fire PRAs. However, the mechanism of spread (ignition within an incomplete penetration seal) is rather unusual. Given a mature industry, such a mechanism is unlikely to be manifested today.
--	Attempts were made from the RB side of the wall to extinguish the fire. The fire was located 20-30 feet off the floor. Fire fighters had to use ladders and in-place scaffolding to reach the fire. Both CO2 and dry chemical portable extinguishers were used. Dense smoke and limited availability of breathing apparatus further complicated the fire fighting effort.	Physical difficulties in fighting the fires is not explicitly modeled in fire PRAs. Also, the condition and availability of fire fighting equipment (i.e., proper clothing, breathing apparatus, ladders, etc.) are not modeled explicitly. A general model is used that probabilistically includes those conditions that may hamper proper fire fighting. It should also be noted that current rules for training and equipping fire brigades are far more stringent than the rules in place in 1975. Hence, some aspects of this event (i.e., lack of adequate equipment) may not be relevant to current risk assessments.
~00:20	After initial attempts to extinguish the fire by portable extinguishers (about 15 minutes) proved to be futile, the manual fire fighting efforts were stopped.	See note above regarding ineffective manual suppression efforts.
~00:20	On the Unit 1 control panel, a "Reactor Low Level Auto Blowdown Permissive" alarm was received on the Panel (9-3) that contains the Emergency Core Cooling Systems related controls and instruments. A second alarm was received "Core Spray, RHR Pumps Running". A third alarm "Core Cooling System Diesel Generator Initiate" was received. Alarms kept coming, indicating that RHR, Core Spray, HPCI, and RCIC pumps were all running. The automatic depressurization alarm came on and the ADS timer started. The operator, based on normal conditions of the reactor displayed on Panel 9-5, tripped these pumps. The recirculation pumps started running back, thus reducing reactor power.	The various alarms and activation of the ADS timer is an indication that equipment was spuriously actuating. In this case, spurious actuation of the ADS would have caused rapid depressurization of the reactor into the suppression pool. The operators apparently reacted properly to the conflicting signals being received in the control room, and took actions to isolate equipment that had apparently spuriously started.

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
00:25	The automatic CO2 system was discharged into the CSR.	Plant personnel apparently discovered and removed the metal plates that would have prevented operation (see note above) manually recovering the fixed suppression system.
00:28	About 12:28pm, the RHR, CS and HPCI initiated again. On panel 9-3, several lights (in random pattern) brightened and then went dim. Operators tried to shutdown the RHR and CS pumps.	These may be indicative of additional spurious operations of plant equipment although whether these were simply indications or actual operations remains a point of debate that cannot be resolved here.
00:40	At 12:50, on Unit 2 control panel 9-7 (turbine control panel) two annunciations were received about a delta-P on steam jet gas ejector filter and off-gas air flow. Because of the fire, the operator considered the alarms as erroneous.	This is a further example of how a control room operator did not fully trust the control panel indications knowing that a CSR fire was underway. In fire PRA, explicit models are not generally used to examine possible operator diagnoses of the specific information displayed on the board.
00:31	At 12:51pm, operators manually scrammed the reactor from 704 MWe power level.	It is not entirely clear why operators delayed the scram for 15 minutes after learning of the fire. In a fire PRA a scram immediately upon a report of an unsuppressed CSR fire would typically be assumed.
--	Diesel generators C and D had started and had tied into their respective control boards. Diesels A and B were idling and ready to tie in.	
00:33	At 12:53pm, operators tripped the turbine generator and two feedwater pumps. Operators checked that all control rods had inserted and started mid-range monitors. One feedwater pump was kept running to maintain reactor level and a turbine by-pass valve was left open to allow use of the condenser as a heat sink.	
--	1A and 1B 250VDC , 1A and 1B 480VAC MOV boards, 1A and 1B 480 VAC shutdown boards, 120V Unit Preferred Power, Shutdown Bus No.1 and both reactor protection buses were lost. The only remaining bus at this time was 1C 250V Reactor MOV board that provided power to four relief valves.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
00:36	At 12:56, the operating main feedwater pump tripped. It seems that the operators did not realize this until a few minutes later when the MSIVs tripped.	From the chain of events it can be inferred that the control board became very active and it is possible that the operators missed certain events. Loss of main feedwater is a major change in reactor condition and would have been noticed in a short time. However, this can be regarded as a case where operators were too busy or were distracted by the impact of the fire on the control board, and did not properly track developments in the reactor cooling system.
--	HPCI and RCIC started automatically because of loss of reactor level after the scram. 7Operators turned these systems off.	
--	On the Unit 2 control panel, operators noticed malfunctions on ECCS panel 9-3 and feedwater panel. Unit 2 RB fans were switched to low by the operators.	Typical fire PRAs consider the impact of a fire only on a single unit, even if that fire occurs in a common or shared plant area. In this case, the second unit also experienced some difficulties and was shut down. Simultaneous demand for multi-unit shutdown may introduce unique equipment demands that may not be covered by current fire PRAs.
00:40	At 1:00pm Unit 2 control room operators observed several annunciations regarding DC power and that one reactor protection M-G set had tripped. They proceeded to scram the Unit 2 reactor and initiate shutdown cooling. Unit 2 operator confirmed that all rods inserted.	
00:41	At 1:01pm Unit 2 turbine was tripped from the control room.	
00:43	At 1:03pm the Unit 2 Main steam isolation valves (MSIVs) closed. The Unit 2 Reactor Protection System (RPS) was noticed to be inoperable, all three main feedwater pumps were tripped by the control room operator, and the MSIVs closed because of RPS malfunction.	
--	Control room operators for Unit 1 stated that RCIC could not be started because the valves were not functioning and HPCI would not start from control panel 9-3. Upon closure of MSIVs, reactor pressure increased and the relief valves opened.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
--	The flow of the control rod drive (CRD) pump for Unit 1 was increased to beyond 100 gpm (this was the only high pressure pump available to inject water into the reactor with a 130 gpm capacity).	The operators used the CRD pump to overcome a loss of high pressure coolant pumps. This action was not a part of their operating procedures. This innovative approach provided a time bridge for later recovery of the core cooling capability (a condensate booster pump) and likely saved the plant from core damage. Innovative approaches beyond operating procedures are not typically credited in fire PRAs. If a procedure is not written for a specific action, little or no credit is given to the possibility that such actions will be taken. This approach, given an incident such as Browns Ferry fire, can be regarded as conservative.
--	Attempts were made to restore power to electrical boards. 480 V shutdown board was restored from the control room . Attempts were made to restore power to a RCIC valve, but the valve had a "dead fault" and could not be operated.	
00:49	At 1:09 p.m., the Athens, Alabama fire department was called.	
00:50	At about 1:10 p.m., attempts to put the fire out from RB side was stopped. These efforts had apparently been reinitiated at some point in the event.	See note above about ineffective manual suppression.
00:50	At 1:10pm, Unit 2 RCIC was initiated to supply water to the reactor. HPCI was also initiated in recirculation mode to relieve steam from the reactor. Reactor water level was controlled via RCIC. The CRD pump was verified to be operating. The relief valves were operating automatically.	
--	Smoke and CO2 entered the Control Room through unsealed floor penetrations when the CO2 was discharged into the CSR pressurizing the room. Scot Air Packs were used by some operators, but those could only sustain air for about 5 minutes. The operators went about their business without breathing apparatus.	Smoke in the control room would be commonly assumed in fire PRA to hamper control room efforts. In this case, it would appear that the smoke and CO2 were an annoyance, but not particularly debilitating.

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
00:55	Between 12:55 and 1:15pm, Unit 1 operators noticed that nuclear instrumentation and about half of the control rod drive position indications were lost. Only four of the eleven remotely operated relief valves were available. Condensate and condensate booster pumps were operable as well.	
--	An air hose was brought into the control room to supply fresh air.	
01:00	At 1:20pm, on the Unit 2 side, manual control over all relief valves was lost. However, the relief valves continued to operate automatically maintaining reactor pressure at 1020psig. RCIC and CRD pumps were supplying water to the reactor.	
01:00	At 1:20pm, Unit 2 diesel generator "D" tripped. Loss of power to a 480V shutdown board occurred, which led to loss of all 480 V shutdown and reactor MOV boards for about 45 minutes.	
01:10	At about 1:30pm, it was realized that high pressure injection via the CRD for Unit 1 could not maintain the water level in the reactor. Decision was made to depressurize the reactor to enable the use of condensate pumps.	
--	The operators and management decided that if the condensate pumps (working pressure 350 psig) could not be used, the RHR service water could be lined up to take water from the river and inject at 150 psig into the reactor. To do this, two valves had to be manually opened that were located at an area of the RB where the smoke was not so dense.	This demonstrates how operators would work together to plan out the use of available options under fire conditions. In fire PRA, as mentioned above, innovative recovery approaches are not generally credited. Also, if an area could be affected by smoke, little or no credit is given to the possibility of manual recovery actions (see further note below).
--	Operators ascertained that two out of three condensate pumps and one out of three condensate booster pumps were available. The bypass lines around demineralizers and heater were opened.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
01:20	At about 1:40pm, blowdown of Unit 1 was initiated using 4 remotely operated relief valves that remained operable from the control room. As the valves were being operated, the operators watched the water level in the core to ensure that it did not drop below top of active fuel. The condensate and condensate booster pumps provided water to the reactor. The water level increased.	
--	Control over feedwater pump bypass valve was lost. It was left in the open position. This led to an increase in reactor water level, which reached above the measurable scale (i.e., +60 inches).	
--	An operator was sent to the feedwater pump bypass valve location to partially close the valve and was instructed to remain there to make valve adjustments as directed from the control room.	
01:40	At about 2:00pm, the fire chief from Athens Fire Department recommended use of water to extinguish the fire. This was rejected by plant personnel on the scene.	Application of water was delayed due to electrical concerns. It remains unclear to this day whether or not this was a correct decision given the circumstances. Water application was delayed for several hours, but once applied the fire was quickly suppressed (see further notes below). As noted above, some fire PRAs commonly assume that manual fire fighting will be initiated promptly and once begun will be effective in a very short time.
01:40	At about 2:00pm, the "C" 4kV bus was lost. Restoration attempts were not successful. Problems were also noticed in transformer TS-1B which serves 480 volt Shutdown Board 1B.	
01:40	At about 2:00pm, Unit 2 lost preferred power because Unit1 and 2 preferred power boards were tied together. The buses were separated and Unit 2 regained its preferred power.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
01:40	From 2:00pm until the fire was extinguished, several attempts were made to restore torus cooling. However, despite several attempts and some success in opening valves locally, reactor shutdown cooling and torus cooling could not be established because of dense smoke in the RB.	Fire conditions at the location of valves in the RB prevented operators from completing attempted valve alignment actions. In a fire PRA, manual actions in a smoke filled room would not be credited. This event does illustrate that fire effects can prevent manual actions under sufficiently harsh conditions.
01:50	At 2:10pm, a Unit 2 relief valve stuck open, which caused the reactor to start depressurizing.	
01:55	At 2:15, Unit 2 relief valve manual control was restored. A decision was made to continue depressurizing Unit 2 reactor.	
02:10	At 2:30, all but one of the Unit 2 level indicators were lost.	Transient electrical failure is difficult to explain. In fire PRA, credit is typically given to spurious electrical signals to clear after about 30 minutes because of additional failures and short to ground.
02:10	At 2:30pm, the Unit 2 RHR pump D was paced in torus cooling mode.	
02:25	At 2:45pm, the following equipment was inoperable: All ECCS, MSIVs, seven of the manually controlled eleven Relief Valves, Reactor Closed Cooling Water System, and Diesel "C". Also, some instrumentation was unavailable: torus temperature and level, drywell temperature, jet pump flow, reactor flange temperature, all neutron instruments, computer, CRD instrument panel, etc.	
02:40	At 3:00pm, Unit 2 RHR drain pump was initiated to control torus water level.	
02:40	At 3:00pm, Unit 2 reactor pressure was at 200psig, which allowed the use of condensate booster pump.	
02:50	At 3:10pm, TVA's Central Emergency Control Center in Chattanooga was activated.	
02:55	Between 2:00 and 3:15pm the water level was above the measurable range. At about 3:15 it dropped below the upper setpoint of +60 inches.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
03:10	Between 2:30pm and 3:30pm several unsuccessful attempts were made to manually open a suction valve on an RHR pump.	
03:40	By 4:00pm, the automatic CO2 system was setoff three times in the CSR. At this time, fire in the CSR seemed to be contained	
03:40	About 4:00pm the MOV board 1A was restored.	
03:40	At 4:00pm, a Unit 2 main steam drain line was opened into the condenser that caused difficulty in maintaining vacuum in the condenser.	
04:00	About 4:20pm, the fire in the CSR was declared as extinguished.	This scenario demonstrates that use of hand held fire extinguishers and automatic fire suppression systems may not to be immediately effective and may take several hours to control and extinguish the fire. The possibility of ineffective fire fighting efforts is considered in some fire PRA methods probabilistically while other methods assume prompt and effective suppression. Current probability curves for time to control a fire gives a very low probability to the possibility of several hours of delay.
04:10	Between 2:00pm and 4:30pm, the RHR valves 74-73 and 74-71 were opened manually in the RB.	
04:10	At about 4:30pm, an RHR service water valve was partially opened to the RHR heat exchanger, to provide RHR cooling. At this time power was restored to the valve.	
04:10	At about 4:30 p.m., fire fighting at RB side of the fire was resumed. The fire continued to burn.	
~05:10	Between 5:30 and 6:00 p.m., from TVA headquarters in Chattanooga, permission was given to use water to fight the fire.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
05:10	About 6:00pm, the four operating relief valves were lost. It was later found that a solenoid valve that controls the air to the valves had failed closed because of fire damage.	Such late failure demonstrates that fire damage can continue to occur for a long time after the fire growth and burning rate has reached a steady state, and the zone of influence of the fire may have reached its maximum. In a fire PRA, the fire duration is practically never modeled to last more than two hours. However, since it is assumed that all the cables within the zone of influence are damaged, effectively late failures are modeled conservatively.
06:10	At about 6:30pm, the RHR drain line was opened manually to direct torus water into the condenser hotwell.	
06:10	At 6:30pm, Unit 2 conditions were considered as stabilized.	
06:20	At about 6:40, Plant Superintendant gave the permission to use water on the fire.	A large delay in fighting a fire is not generally modeled in a fire PRA. Current probability curves for time to control a fire gives a very low probability to the possibility of several hours of delay.
06:20	From 6:40pm untill 9:30pm, reactor pressure increased from 300 psig to 600 psig. Condensate pumps became ineffective. The operators reverted back to using the CRD pump.	
~06:40	At about 7:00 p.m. two men entered the fire areas and directed water on the fire using a fire hose located outside the fire area. These men had to wedge the hose in position because of poor breathing apparatus condition had to leave the area.	
06:40	At 7:00pm, Unit 2 vacuum pumps were restored to establish vacuum in the condenser.	
06:55	At 7:15 p.m., two men entered the fire area and found no evidence of burning. Spraying continued.	
07:25	At 7:45, the fire was declared as completely extinguished.	

Time (rel. to ignition) (hr:min)	Event Description (Note 1)	Fire PRA Implications
--	As the smoke cleared and reliance on breathing apparatus lessened, various valves were approached in the RB, the position of the valves were checked, control power to motor operators, pump controls, etc. was established using temporary jumpers.	
07:40	At 8:00pm control of Reactor Water Cleanup valves were restored.	
09:30	At 9:50pm, control over the four previously operable relief valves were restored by field operators by rearranging the air supply to the flow control valve that supplied air to the valves.	
09:30	From 9:50pm reactor depressurization was resumed and from 600 psig, by 10:20, it reached 350 psig allowing the condensate booster pumps to pump water into the reactor.	
10:10	At 10:30, Unit 2 diesel generator D was restored.	
10:25	At 10:45pm, Unit 2 RHR shutdown cooling was established using RHR pump B.	
13:10	At 1:30am on March 23, torus cooling was established.	
15:50	At 4:10am on March 23, shutdown cooling was established.	

Note 1: All failures and reactor related information refers to Unit 1 unless noted otherwise. All Unit 2 entries are specifically noted.

Equipment Damaged

A total of 1600 cables were damaged. Of these, a large number were safety related. The number of damaged safety related cables can be categorized by Unit as: 482 from Unit 1, 22 from Unit 2, and 114 common to both units.

Damaged Areas

A small area in the CSR and a large area within one compartment in the Unit 1 RB. Dense smoke propagated throughout the RB.

Impact on Core Cooling

While the fire did present severe operational challenges, adequate core cooling was maintained at all times. At no time during the fire did all core cooling function stopped. Fuel cladding, the containment and the torus were not adversely affected by the fire.

Radiological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were only minor injuries to plant or external personnel because of smoke inhalation and other minor injuries.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A3.3 Comparison of Fire PRA Elements and the Incident

In this section, the chain of events in the fire event is compared against a typical fire scenario as developed in a fire PRA expressed in terms of a list of scenario elements. Entries are made only if specific and relevant information was available. No attempt was made to postulate a possible progression of events beyond the available reports unless it was deemed to be essential in reaching a specific insight. Such cases are specifically noted.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Presence of combustible / flammable materials	A readily combustible material (polyurethane foam) was used as a penetration seal. The design required that a fire resistant coating be applied to the penetrations, but the coating was not in place at the time of the incident. Also, there were a significant amount of control and instrumentation cables in intimate contact with the seal.	With few exceptions (e.g., hydrogen), it is unusual to find a highly combustible material in safety areas of a nuclear power plant. In a fire PRA it is typically assumed that highly combustible materials (in this case polyurethane) are either absent or protected. Silicone is currently the preferred fire seal material, and silicone in not nearly as combustible. Hence, the use of polyurethane would be considered very unusual today.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Presence of an ignition source	A candle flame was used by the construction crew as part of an accepted procedure to check for penetration seal leaks.	The presence of an open flame in a safety-related plant area is not considered in current PRAs. Such practices are widely prohibited by plant procedure. This, and the two small fires that preceded this fire, are the only known fires in a power plant to have been ignited in this way. PRA practice is not contradicted by these related incidents.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Electricians using open flame candle to check for leaks in penetration seals caused the open polyurethane foam in one of the penetrations to ignite. Because of the negative pressure in the RB, the fire was drawn into the penetration and spread to the RB. Several ignitions had occurred previous to this event. On March 20, 1975 two fires had occurred in the CSR because of candle flame usage.	The precise fire scenario that occurred at Browns Ferry (a candle igniting a fire inside a penetration seal) is not explicitly modeled in fire PRAs. However, the typical cable fire scenarios that are modeled do consider the possibility of self-ignited cable fires, in particular, for plants with older cables that are not certified as low-flame-spread. This is nominally consistent with the conditions observed at Browns Ferry. Hence, the potential for, and impact of, fires at this location would likely have been identified in a fire PRA.
Fire growth within the combustible or component of original ignition	Because of the readily combustible nature of polyurethane foam and air flow from the CSR into the RB, the fire spread through the penetration seal rapidly.	In fire PRA, the initial fire ignition source is modeled by an established "pilot fire." In this incident, the rapid propagation of the fire through the polyurethane can be considered as the pilot fire. Again, while this particular pilot fire would not be considered, a properly modeled self-ignited cable fire would lead to the same consequences and would be considered.
Fire propagates to adjacent combustibles	The polyurethane fire ignited cables inside, and adjacent to, the penetration. The fire then propagated horizontally and upwards through all the cable trays that passing through the affected penetration. Cables were damaged over a distance of several 10's of feet. The fire also propagated downward a few feet along vertical cable trays next to the wall.	The cables used in Browns Ferry were rated as fire retardant based on the standards of the time. Nonetheless, they did support a self-sustained and propagating fire that burned for several hours despite repeated attempts at manual suppression with hand-held fire extinguishers. In fire PRAs, the comparable ignition source would be a self-ignited fire as noted above. Most assessments of such fires assume only limited potential fire growth. This experience my belie those assumptions at least for older style cables.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
A hot gas layer forms within the compartment of origin (if conditions may allow)	Although, the available source used in this analysis do not indicate the presence of hot gas layer, since the fire occurred near the ceiling of a RB compartment, there should have been a hot gas layer that perhaps facilitated the horizontal fire propagation.	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	In effect, two compartments were simultaneously affected by this fire. Because of negative pressure in the RB side of the wall, the flames were drawn through the partly open penetration seal. Dense smoke propagated through the entire RB, making it very difficult to take manual actions to overcome valve operability problems.	Fire propagation to adjacent compartments is considered in fire PRAs using mainly qualitative methods. This would typically include some probability that penetration seals might fail allowing for passage of fire from one compartment to another. The possibility of flames being drawn through negative pressure path to other compartments is not typically modeled explicitly. While current fire PRA methodologies can identify and treat room-to-room fire scenarios, the specific mechanism of spread noted in this case in not explicitly considered.
Local automatic fire detectors (if present) sense the presence of the fire	None of the sources indicate presence or activation of automatic fire detectors. Since personnel were present when the fire occurred, fire detection was instantaneous, although the fire in the RB was not immediately recognized.	Manual detection is commonly credited in fire PRA. However, there is a continuing weakness in these methods in that the actual time between initiation and detection is typically not known unless personnel happen to be present when the fire starts.
Alarm is sounded automatically in the control room, locally and / or other places	See above. In this case the alarm was announced manually by an operator over the plant PA system.	
Automatic suppression system is activated (if present)	At the CSR side, the operators eventually activated the fixed CO2 system. This certainly affected the progression of the fire at the CSR side. Fire did not propagate past a short distance from the penetration and there were little or no smoke in that room. There was no fixed suppression for the RB	In this case operators had to perform some (apparently minor) recovery actions to activate the CO2 (removal of a blocking plate inside the actuation mechanism left over from construction). Manual recovery of a fixed suppression system may be credited under some recent PRA methods (e.g., the EPRI *Fire PRA Implementation Guide*)

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Personnel are present in the area where fire occurs	Personnel and construction crew were present in the CSR. In fact they were the cause of the fire.	PRAs don't explicitly consider personnel as a source of fire, although such events are inherently included in the fire events data base. Personnel are commonly credited for detection if an area is commonly or continuously manned.
Control room is contacted or fire alarm is sounded	The control room was contacted about 15 minutes after the fire was ignited. The delay is attributed to lack of proper knowledge of the crew involved with initial stages of the fire about the requirement in the emergency response plan to sound the fire alarm immediately upon discovery.	This event echos other similar events (e.g. Waterford 1995) where there was some delay in declaring that a fire was present even given that some plant personnel were aware of the fire. It is commonly assumed that a fire alarm will be sounded immediately upon any personnel detecting any fire anywhere in the plant. These assumptions may be optimistic.
Fire brigade is activated	There was no designated plant fire brigade at that time. Plant personnel tried unsuccessfully to put the fire out and ultimately called the local fire department.	Regulatory requirements for plant fire brigades have changed substantially, in large part as a result of this fire. This event is not considered relevant to current fire PRAs.
Fire suppressant medium is properly applied	Overall, fire suppression activities were not especially successful. Initial discharges of hand-held extinguishers at both sides of the wall were unsuccessful. In the CSR, the fire was controlled by a combination of manual extinguishers and activation of the fixed CO2 system. On the RB side, repeated manual suppression attempts proved to be futile and at best prevented the fire from spreading unchecked. Plant management resisted suggestions of the off-site fire department to use of water due to concerns that water might lead to additional equipment losses. This decision was reversed about 7 hours after ignition and the fire was put out quickly using water.	Two fire suppression scenarios unfolded in this incident, one in the CSR and one in the RB. The CSR fire fighting efforts were ultimately effective based largely on the fixed CO2 system. In a fire PRA, the CO2 system would likely have been credited because the penetration seals would have been assumed to be intact. For the RB fire, given the location of the fire close to the ceiling and lack of a fixed fire suppression system, the time to control the fire would likely have been assumed to be relatively long in a full-scope fire PRA; probably on the order of 30-45 minutes. However, it would also have been assumed that once on the scene, effective fire fighting (i.e., water) would have commenced immediately. The probability versus fire duration curves recommended by current fire PRA methods give a very low probability to fire durations of 7 hours. The delay in activating effective fire fighting strategy for the RB would likely not be captured in a typical fire PRA.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Automatic fire suppression system is activated	There were no automatic suppresion systems available. As noted above, there was a fixed manual CO2 system in the CSR that was activated.	
Fire suppressant medium is properly applied to where the fire is.	As discussed above, several attempts by hand-held extinguishers were unsuccessful. However, no additional failures were noted after water was applied to the fire and the fire fighting efforts did not cause any additional failures because of mishandling of equipment or hoses.	See notes above.
Fire is affected by the suppression medium	As discussed above, on the CSR side, the fixed CO2 system was effective. However, on the RB side, only water was effective at suppressing the fire.	See notes above.
Fire growth is checked and no additional failures occur	The fire growth on the CSR side was checked to a few feet from the penetration. On the RB Side, the fire propagated was partly controlled by repeated application of fire extinguishers, but continuing damage was noted for at least six hours.	The RB fire cannot be considered to have been brought under control until water was finally applied to the fire. Fire PRAs commonly assume that fire control will prevent further damage. This incident does not contradict this assumption, but the failure to initiate effective fire suppression in a timely manner would not be captured in a typical PRA.
Fire is fully extinguished and fire brigade declares it as out	See the discussions above. Some difficulty was encountered in using hose fittings between the plant and local fire department.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Primarily cables were damaged in this fire incident. There was also some damage to aluminum conduits and to some aluminum coated pipe insulation, but this was not risk significant. No structural failures were noted. Numerous cables were damaged in both open cable trays and inside conduits.	The cable damage that was observed would likely be captured in a fire PRA. Cables are the most commonly considered fire damage target in fire PRAs. There were no particular events at Browns Ferry that would contradict current PRA practice in this regard.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Cable failure impacts equipment outside the fire location	Several systems were affected on both the Unit 1 and Unit 2 sides of the plant. Many electrical circuits were affected, including loss of various electrical busses. There is debate over the precise way the control circuits and associated equipment were affected (i.e., whether or not spurious actuations actually occurred). Although plant design had incorporated separation of redundant trains, in several cases redundant trains were affected because of routing error, use of conduits to meet the separation criteria and common circuit elements. In the case of the latter, indicating lights of control circuits were not considered as safety-related and their cables were therefore not subject to separation criteria. The following systems and equipment affected: Unit 1 - RCIC, ADS, CS, RHR, HPCI, electrical distribution and Standby liquid control. A more limited set of equipment and systems was affected on Unit 2.	Many systems were rendered unavailable by the fire. Such losses are commonly identified in fire PRAs. The construction errors that contributed to some of the redundant train equipment losses would not typically be captured in a fire PRA unless "hand-over-hand" cable tracing were undertaken, and this is rare. Rather, the plant would be assumed to have been constructed per design. The potential for, and impact of, spurious equipment operations due to cable failures is a topic of current debate. In some fire PRAs, it is assumed that spurious actuation of equipment is possible while others neglect this possibility. The current debate focuses on the likelihood of various cable fault modes, the likelihood of both single and multiple spurious actuations, and the duration of postulated cable hot shorts that might lead to spurious operations. There is evidence that some spurious actuations did occur during the fire. It appears quite clear that at least one, and probably more, spurious alarms were received in the main control room, likely due to faults in instrument cables. However, the available information does not provide conclusive evidence supporting or disproving typical fire PRA practice regarding spurious equipment operations. (Refer to Reference A3-3 (the Task 1 Letter report for this program) for more discussion of these aspects of the fire.)
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Unit 1 was impacted by a number of sequential equipment losses as described in Section A3.2 above. Unit 2 also experienced several failures. However, the failures were much less significant than those impacting Unit 1, and core cooling conditions were stabilized in about 6 hours after fire ignition.	The equipment failure experienced for Unit 1 would likely have been captured in a fire PRA. The operator's use of non-procedure based recovery actions would likely not be credited in a fire PRA. With regard to unit 2, it is typical in a fire PRA to assess the impact of a given fire on one unit only. In this case, both units were impacted, and this would not likely be captured in a typical fire PRA.

Fire Scenario Element/Issue	**Incident - Browns Ferry, March 22, 1975**	**Fire PRA Insights**
Operators in the control room receive messages and respond to the information displayed on the control board or received verbally from the plant	Numerous alarms and seemingly erroneous indications were received on the control board. It seems that the operators were well aware of the potential impact of a fire on the control circuits. Overall the control room operators made several correct decisions regarding core cooling strategies and use of available resources to ensure that the core remained covered, and do not appear to have been mis-led by the erroneous signals and alarms.	Given the extensive impact of the fire on the indications and control on the control board, the operator performance in this incident was laudable. In a fire PRA it would be assumed that the probability of operator error would have been increased by the fact that smoke and CO2 did get into the control room, and by the numerous erroneous indications. No credit is generally given to operators using methods that are outside set procedures to ensure core cooling. These assumptions, given the chain of events at Browns Ferry, are certainly conservative.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	See the discussions above.	See the discussions above.
Structural failures (if occurred) may jeopardize availability of equipment	No structural failures other than melting of the polyurethane inside the penetration and some damage to pipe insulation was reported.	
Water when sprayed over electrical equipment may fail the exposed equipment	There is no evidence of such an event. Once water was applied to the RB fire, there was no reported additional failures.	
The cooling effect of CO_2 may adversely impact equipment	There is no evidence of any such damage despite use of the CO2 system to fight the CSR fire.	It is not clear whether or not any nominally vulnerable components were located in the CSR so the implications remain unclear.
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The incomplete nature of the penetration seal clearly impacted the fire development. Had the penetration seal been complete and intact, the fire would likely not have been so easily ignited. Some separation requirements had not been met during construction. The CO2 manual actuation device had been rendered inoperable during construction.	The aggravating factor in this case (i.e., exposed polyurethane) is not generally modeled in fire PRAs. It is assumed that the plant is under normal operating condition and all initial construction related tasks are completed. Of course, some probability is assigned to the possibility of a poor penetration seal. However, the presence of a highly combustible material because of an exposed seal is generally not questioned.

A3.5 Incident Analysis

The Browns Ferry fire was actually a relatively modest fire in classical fire protection terms. The fire remained confined to a relatively small part of two adjacent rooms and did not present a significant challenge to plant structures. However, the fire led to loss of numerous and redundant plant safety systems. While core cooling functions were never totally lost, the fire did present a significant challenge to plant operators in their attempts to stabilize Unit 1 in particular.

In many ways, the Browns Ferry fire is quite typical of the "classical" fire PRA risk scenario. That is, a relatively modest fire that occurred at a cable "pinch-point" and compromised a substantial set of plant equipment and systems. In general terms it is expected that a full-scope PRA of the as-built Browns Ferry Plant would have identified the potential vulnerability associated with fires in the impacted area, and would have identified these areas as significant fire risk contributors. Specific aspects of this fire incident that would be captured in a typical fire PRA include the following:

- the potential for a fire at this location, albeit most likely in the form of a postulated self-ignited cable fire rather than as a result of personnel actions,

- the lack of fire detection leading to a potential delay in detection of, in particular, the RB fire,

- the potential for spread of fire from room-to-room, albeit the mechanism for failure would be assumed to be random failure of the penetration seal rather than the fact that the seal was incomplete at the time of the fire,

- the lack of fixed suppression in the RB meaning that manual fire fighting would be required,

- the complications associated with manually fighting the fire in the RB given its inaccessible location,

- the potential for initial failure, and subsequent recovery, of the fixed CO2 system in the CSR

- the potential for substantial fire spread in older style cables,

- the potential safety system equipment losses due to a fire involving the cables located in the area of the fire,

- the potential for loss of multiple instrument trains and the potential for spurious alarms and erroneous control signals in the MCR, and

- the fact that operators would attempt various manual recovery actions, and that some of these actions would be successful while others would fail due to fire effects.

Other aspects of the fire would not however be captured in a typical fire PRA. In some cases, these aspects of the fire are not considered relevant to a current fire PRA due to the sweeping changes that have been implemented since, and in response to, the Browns Ferry fire. These would include the following:

- The possibility that an open flame would be introduced into a safety-related area is widely precluded by current plant procedures. This would not be considered a credible ignition scenario in a typical fire PRA.

Other aspects of the fire incident that also would not be captured in a typical fire PRA, but that are considered relevant to current PRA practice are the following.

- The failure of the person who initiated (and hence first detected) the fire to promptly alert control room personnel would not typically be captured in a fire PRA. It is commonly assumed that plant personnel will immediately report any fires that occur. See further discussion below.

- The failure of manual fire suppression efforts using hand-held extinguishers despite prolonged and repeated attempts would not be captured in a typical fire PRA under some methods of analysis. See further discussion below.

- The seven-hour delay in the application of water to the RB fire would not be captured in a typical fire PRA under some methods of analysis. See further discussion below.

- The fact that construction had not fully complied with the design leading to redundant cables being co-located in the same raceway would not be detected in most PRAs. This might be found but only if hand-over-hand cable tracing was performed as a part of plant walkdowns. Cable tracing is a very intensive effort and is only performed for critical cases or where there is virtually no available cable routing information. In cases where routing is unknown, but cable tracing is not performed, a conservative assumption would typically be made. This was not the case here because cable routing information was available and would have been assumed to be correct. There is little prospect that future PRAs would be able to capture such construction errors. This illustrates one area of PRA analysis uncertainty that is not easily resolved.

- The potential for a single fire to impact equipment for, and force a simultaneous shutdown of, two sister units is not captured in typical fire PRAs. This has been raised as a potential area of concern for some of the IPEEE fire analyses. However, common practice is to analyze fires as impacting a single unit only. Fire

PRA methods could be extended to explicitly cover multi-unit issues. This is not an especially difficult prospect, but does imply development of appropriate analysis guidance and may involve development of some specific analysis tools.

Note that three of the last five points highlight issues of detection and suppression effectiveness that are not reflected in current fire PRAs. In this case, there was a delay in initial reporting of the fire, ineffective efforts to fight the CSR fire, a delayed recognition of fire in the RB, repeated and prolonged but ineffective efforts to suppress the RB side fire. These events are echoed by other events included in this review. The implications are dependent on the method of analysis being applied, and there are currently two commonly applied methods. The topic of fire duration analysis is covered in detail in the body of this report.

References

A3-1 Regulatory Investigation Report, Office of Inspection and Enforcement, Region II; Subject: "Tennessee Valley Authority, Browns Ferry Unit 1 and 2, 50-259 / 75-1 and 50-260 / 75-1, Fire in Cable Spreading Room and Reactor Building on March 22, 1975; prepared by Charles E. Murphy, signed July 25, 1975.

A3-2 "Recommendations Related to Browns Ferry Fire", report by Special Review Group, U.S. NRC, NUREG-0050, February 1976.

A3-3 J. LaChance, S.P. Nowlen, F. Wyant and V. Dandini"Circuit Failure Mode And Likelihood Analysis," A Letter Report to the USNRC, Sandia National Laboratories, USNRC JCN Y6037, Final Report, March, 2000 (this report, while unpublished, is available through the USNRC public document room).

A3-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix 4 - Analysis of Greifswald, Unit 1 Fire on December 7, 1975

A4.1 Plant Characteristics

Greifswald is a Soviet design plant located on the Baltic coast in the former East Germany (GDR) [Ref. A4-3]. The plant site included five VVER-440 reactors of which four, units 1 through 4, are "of the first generation V-230 type." All five units are now permanently shut down and undergoing decommissioning. Unit 1 began power operations in December, 1973. This discussion is based on two relatively limited references [Ref A4-1, A4-2].

A4.2 Chain of Events Summary

On December 7, 1975 at 11:08 a cable fire broke out in or near a 6kV Unit 1 switchgear. The cause of the fire was cited in one report [Ref. A4-1] as "(a) high short-circuit current (that) flowed for several minutes following an electrician's switching error, and the subsequent failure of the automatic breaker." The fire apparently burned for approximately 92 minutes destroying "a large number of electrical cables."

One report [Ref. A4-2] cites that "the fire caused virtually a station black out." The fire damage apparently caused a loss of power to all six of the unit's main coolant pumps, and there was no steam-driven pump available. Hence, the plant was reliant on natural circulation and "steam relief through safety valves on the steam generator secondary side" for reactor core cooling. After several hours (at least five hours) in this cooling mode, the secondary side water inventory was depleted, and reactor temperature and pressure began to rise. This led to automatic opening of the pressurizer safety valves. The valves did not re-seat properly and reactor coolant continued to escape (effectively a loss of coolant accident situation). As a result reactor pressure decreased and ultimately reached the low pressure pump head pressure. This allowed the operators to supply water to the reactor by activating low pressure emergency cooling pumps.

Secondary side cooling was apparently restored by routing a spare power cable from an alternate source (apparently from Unit 2) directly to one auxiliary feedwater pump.

The available reports state that the core did not sustain any damage, and that while some "increased discharge of radioactive material into the atmosphere" resulted, "it was below proscribed limits."

A4.3 Incident Analysis

There is insufficient information available about the Greifswald fire to provide a meaningful analysis of the incident. However, from little information that is available, it is clear that in this incident plant safety was affected significantly. It does appear clear that for some period of time all active means of cooling the reactor core were lost, and that non-proceduralized manual recovery actions were needed to recover the plant.

The loss of plant safety functions that resulted from this fire incident is typically modeled in a fire PRA. All high pressure core cooling capabilities were lost in this incident. This led to a demand for the pressurizer safety valves to open to relieve primary pressure. However, since the valves failed to reseat a small LOCA occurred. This is the only known fire incident where a LOCA occurred as an indirect result of the fire. The failure of pressurizer safety valves to re-close should be considered as an independent failure event. In fire PRAs it is common to include independent failures and the possibility of pressurizer safety valves failing to close is included in the event trees. Hence, this aspect of the event should also have been captured in a fire PRA.

Based on the available sources, there is no information available on the severity of the fire itself, how the fire was attacked, the actual extent of fire damage realized, how operators responded to the incident, nor why the fire burned for as long as it did (about 92 minutes). It would appear from the reports that a lack of redundant train cable separation was the primary factor contributing to the severity of fire impact on plant operations. The available reports cite that many plant improvements were being made in part in response to this incident. As noted above, the plant is now permanently shut down.

A4.4 <u>References</u>

A4-1 "ASSET team to visit Greifswald" and "German DR releases details of 1975 Greifswald fire," *Nuclear Engineering International*, April, 1990, pg. 6.

A4-2 Frigyes Reisch, "Lessons from Greifswald incidents," *Nuclear Engineering International*, June 1990, pp. 42-43.

A4-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix 5 - Analysis of Beloyarsk, Unit 2 Fire on December 31, 1978

A5.1 Plant Characteristics

Beloyarsk is nominally a four unit nuclear power plant site located near Ekaterinburg, Russia, which was part of the former Soviet Union at the time of the fire described here. Beloyarsk Unit 2 was a 146 MWe LWGR-1000 type nuclear power plant[A5-5] that began operations either in 1967[A5-4] or in December 1969[A5-5]. It shared its turbine building (TB) with Unit 1, which was a 102 MWe LWGR-1000 type[A5-5] nuclear power plant. Both units have been permanently shut down, Unit 1 in 1983 and Unit 2 in 1990.[A5-4,5] A third unit on site continues to operate,[A5-4,5] and a fourth unit was under construction but has been suspended[A5-5]. (Units 3 and 4 are of the BN-600 design type.)

A5.2 Incident Summary

At 01:50 on December 31, 1978, Unit 2 was operating at 100% power when plant personnel noticed a fire in the Unit 2 side of the TB. The fire was caused by a break in a lubricating oil piping system. The oil apparently had spilled onto hot surfaces (the turbine itself or steam pipes) and caught fire. It is not known how long the fire had been burning when detected. The off-site fire brigade was immediately notified, and three fire-fighting teams arrived at the plant within about 6 minutes. The oil fire was already quite severe and had already caused the roof of the building immediately above the fire to collapse. About 960 m^2 of the TB was severely damaged.

From the TB, fire propagated into the adjacent control building via open cable penetrations and other openings. In the control building, the fire propagated upwards inside cable shafts and caused fires on several different elevations. It propagated through open cable penetrations and leaking or open doors and hatches into various adjacent areas. Reference [A5-1] states that the flames propagated vertically at about 0.7 m/s in the cable shafts between cable floors. From the available information it is not clear what factors led to such rapid propagation of the fire. A large number of control and power cables were damaged. The fire also propagated into the control panels of the Main Control Room (MCR) and caused damage there. At one point an oil-filled transformer also ruptured and the oil caught fire igniting additional cables in the area. The cause of this secondary fire is not known (possibilities would include direct fire exposure or electrical faulting).

Fire fighting continued, without a break, for approximately 22 hours. Fire fighters worked in harsh environments that included heavy smoke and a −47°C outside temperature. Ultimately, the attack on the fire involved 35 fire brigades and a total of 270 fire fighters including 150 fire fighters trained in using Self-Contained Breathing Apparatus (SCBA).

Seventeen hours after discovery of the fire, it was declared to be under control. The fire was considered completely extinguished about 22 hours after detection.

A5.3 Detailed Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in detail and in chronological order as best as can be inferred from the available sources [Ref A5-1 through A5-3]. If the precise timing and the order of an event is not known, the time of occurrence is not specified (i.e., all cited times derive from the available reports). However, the chain of events is presented in a logical chronological order based on the available information and the judgement of the authors of this report.

Whether or not an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided. Note that the times reported in the first column are relative to the time that the fire was first detected. The time of fire ignition is not known precisely.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	The unit was operating at 100% power level.	
During the incident	The outside temperature was -47ºC.	While the available sources have provided little information, the extremely low outside temperature must have impacted the effectiveness of the fire fighters. It would likely impact fire fighters' trip from their remote stations to the plant. The impact of weather conditions on the effectiveness of fire brigade activities is not considered in fire PRAs.
00:00	A fire was noticed at 01:50 on the Unit 2 side of the TB. The exact time when ignition had occurred is not reported. The fire was caused by a break in the lubricating oil piping system. The oil apparently spilled on hot surfaces (the turbine itself or steam pipes) and caught fire.	This event starts as a typical TB fire scenario that involves the turbine lubrication oil system. The fire initiation portion of this event is routinely considered in fire PRAs.
00:00	The fire brigade was immediately notified by the plant manager. Three off-site fire fighting teams were sent to the station under the direction of the chief of security. At the same time, the dispatcher of the fire brigade called other fire stations near the Beloyarsk area and informed the local managers of the situation at the plant.	Most fire PRAs, at least in the U.S., assume that fires will be handled by on-site fire brigades. Practices in Russia are, however, quite different from the U.S. in that primary fire fighting is provided by the off-site militarized fire brigade. The potential need to call on an off-site fire brigade, a backup plan at all U.S. plants, is not considered in fire PRAs.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	Because of the rapid growth of fire, the plant personnel were unable to take any actions to fight the fire before the arrival of the fire brigade.	From this statement one can infer that there was a delay in initiating the fire fighting activities. The causes of the delay are not clear, but one can presume that a lack of personnel fire fighting training and/or plant procedures were involved. In any case, it seems that this delay had a significant impact on the outcome of the fire.
00:06	At 01:56, when the first teams of fire brigades, under the command of RTP-1 (rank of the person in command), arrived on the scene, the TB roof near #2 turbine-generator had already collapsed and the flames were visible from outside through the windows.	The time from ignition to collapse is no clear, but is certainly very short (probably on the order of 10 minutes). This implies a very rapid fire growth and very severe fire. The causes of rapid fire growth and such severe impact on the roof is not addressed in the available sources. Fire PRA methodologies do not typically consider the possibility of roof collapse.
--	The fire propagated from the TB into the Control Building via open cable penetrations and other openings. In the Control Building, the fire propagated through open cable penetrations and leaking or open doors and hatches into cable tunnels, electrical rooms and cable shafts. The fire in cable shafts spread rapidly upwards. It is estimated that the flame propagated vertically at the speed of 0.7m/s. A large number of control and power cables at elevations 12.35m and 16.40m were damaged. The fire propagated into the control panels of the Main Control Room and caused damage there.	The potential for room-to-room fire spread is considered in a typical fire PRA, but for US plants this is rarely found to be a dominant contributor to fire risk. While analyzed, such propagation is considered unlikely in US plants. This scenario is similar to other fire events at Soviet plants where a fire propagates through the cable trays and open penetrations. There was apparently less attention paid to sealing openings in plant barriers during the construction of soviet plants than would be typical of U.S. plants. Many such openings are apparently left open. Hence, the apparently unchecked fire spread from room to room seen in this incident cannot be considered as directly applicable to US plants. However, it is also possible that the TB roof collapse might also breach otherwise intact fire barriers so, while arguably not directly applicable, this combination of collapse and potential room-to-room fire spread has some relevance to U.S. plants as well.
--	The installed foam system at the fire location could not be activated because the cables for the system were damaged. A portable foam system was not used because the fire area was filled with smoke and the personnel could not reach the fire location.	In a typical fire PRA, the routing of the cables for fixed fire suppression systems is not addressed. This event demonstrates that there can be a dependency between the fire and the availability of the fire suppression systems. Also this statement is an indication that smoke can adversely impact fire fighting activities.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:15	At 02:05 the assistant chief of the fire brigade (RTP-2) arrived and took command of the fire fighting activities. After examining the situation at -3.6m, 0.0m, 8.0m and 12.35 m elevations, he determined that cable shafts #3 and #5 were affected and that the fire was spreading upwards. The upper elevations (above 12.35m) of the Control Building were filled with smoke. This included the Unit 2 Control Room and Cable Spreading Room. The commander gathered those plant personnel who were available to help in the use of a portable foam suppression system. Two portable foam systems (GVB-600 type) were brought to elevation 12.35m and a third was installed at elevation 16.40m.	It should be noted that at this point the fire has progressed in scope well beyond those fires that are commonly modeled in a fire PRA. A typical fire PRA for US plants would assume that possibility of a fire propagating to so many areas and being this severe would be vanishingly small. Again, there is no evidence from this event to suggest that this assumption is flawed given the close attention paid to fire barrier elements in the US.
--	Severe disturbances of the plant systems were caused by the fire and control of the plant was made extremely difficult. There was apparently some fire damage some control room panels. Lack of separation of cables from redundant trains led to the common mode failure of a large number of system trains.	Multiple safety systems and a large set of reactor instrumentation must have been lost. This is one of few fire incidents where multiple safety trains were damaged. It is stated in one of the sources that "reactor was saved mainly by good luck".
00:38	At 02:28 RTP-3 arrived and took over the command of the activities. He divided the fire fighting effort into three fronts. The first front was to fight the fire in the TB and try to prevent the spread of the fire into the cable tunnels. The second front was to fight the fire in the Control Building and extinguish the fire at and above elevation 12.35m. The third front worked at 16.40 m elevation of the Control Building was instructed to extinguish the fire at this elevation.	
00:50	The fire commander at the local headquarters was informed of the fire at 02:40. A busy inter-city telephone system was caused delays in informing various fire stations and headquarters.	Problems with local communications would not be considered in a typical PRA. However, since fires are also commonly assumed to be handled by on-site personnel (see note above), this would not be a significant factor in any case.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	Transformer oil had spilled and had ignited with fire spreading to nearby cables. The fire was burning at elevations 0.0 m and 8.0 m. Additional fire fighter teams were called in. The positioning of the fire engines and method for fire fighting was determined per established fire fighting procedures.	From this statement it may be inferred that a transformer failed causing a secondary fire. The failure cause is not clear and may have been due to direct exposure to flames or excessive heat, or due to electrical faults impacting the transformer. In fire PRAs, the possibility secondary fires is not postulated.
--	The operators had to work in heavy smoke conditions. One report states that at one point the operators were half-unconscious because of smoke inhalation. Operators, despite all the difficulties, managed to start one train of reactor emergency cooling system.	In fire PRA, no credit is given to the possibility of operators functioning in a compartment filled with smoke. With substantial smoke in the control room, abandonment would be assumed. This incident demonstrates that this PRA assumption is conservative.
02:07	At 03:57 RTP-4 arrived with a team of senior officers from the general territory of the plant. At this time, the fire had propagated to elevation 20.0 m of the Control Building and the foam systems at lower elevation could not control the fire properly. It was decided to create a command center for fire fighting. Plant Administration considered activating the automatic foam system to reduce the intensity of the fire. For this they issued electrically safe gloves to the fire fighters and engaged the electric power to the automatic foam system.	
--	A newly arrived fire engine provides three additional foam dispensing points at elevation 12.35m (GVB-600 type foam system).	
02:30	At 04:20 RTP-5 arrived on the scene, took over the command and made some changes to the fire fighting activities. He specifically instructed the third team to fight fire at elevation 20.0m from #2 stairwell. He put together two additional teams. The fifth team was instructed to inspect, with plant administration, the cable tunnels.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	Per the instruction of fire commander, RTP-5, an additional 100 fire fighters were called in from Sverdlovsk. This included fire fighters who were trained in using self contained breathing apparatus (SCBA). They also brought 40 tons of foam capacity with them.	
17:05	At 18:55, the fire was declared as under control.	
21:40	At 23:30, fire was declared as completely extinguished. The fire fighting was conducted without break at areas where the room temperature was as low as -47^{o}C. The fire fighting involved 35 brigades and a total of 270 fire fighters including 150 who were trained in using SCBA.	This is one of the longest duration fires in the history of the nuclear power industry world-wide. Fire duration considered in fire PRAs is typically under one hour and the probability of such a long duration fire is considered to be very small.

Equipment Damaged

- One of the turbine generators of Unit 2
- At least one oil-filled transformer
- A large amount of electrical cables in the TB and control building
- Control panels apparently including some panels in the main control room

Damaged Areas

About 960 m^2 of the TB roof area above one of the turbine generators for Unit No. 2 was damaged and collapsed. Cables and control panels were damage in the Control Building at elevations 12.35 m, 16.40 m and 20.0 m. The cable spreading room, the control room and cable shafts were affected by this fire.

Impact on Core Cooling

A large number of safety related equipment were affected by this fire, but some core cooling functions remained available at all times.

Radiological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

25 people were exposed to smoke or extreme cold weather conditions and apparently suffered minor injuries.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A5.4 Comparison of Fire PRA Elements and the Incident

In this section, the chain of events in the fire incident is compared against the elements of a typical fire scenario. Entries are made only if specific information was available relevant to each element. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in reaching a specific insight.

Fire Scenario Element/Issue	**Incident - Beloyarsk, December 31, 1978**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubrication oil, cables and other insulating materials were the combustibles consumed in this fire.	Turbine halls are widely recognized as containing unique and potential severe fire hazards.
Presence of an ignition source	Hot surfaces on the turbine and/or steam pipes served as then ignition source for the oil	
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Turbine Lube oil pipes broke and spilled oil. The turbine and/or steam pipe hot surfaces caused the oil to catch fire.	Oil leaks and spills are common sources assumed in the analysis of a TB.
Fire growth within the combustible or component of original ignition	The fire grew rapidly into a large fire.	The rapid fire growth is somewhat unique to turbine building fires, but would be assumed in most fire PRAs.
Fire propagates to adjacent combustibles.	The fire propagated to electrical cables and via the cables, it propagated to other compartments, including cable shafts in the Control Building. From the cable shafts it propagated upwards to several floors of the Control Building. At one point in time, a transformer failed and spilled its combustible oil that also caught fire.	While room-to-room fire spread is considered, the extensive propagation seen in this incident is not typically modeled in a fire PRA. The characteristics of the cables and openings among compartments were certainly a key contributor in this event. The same factors in the U.S. plants are quite different from those in Soviet plants. This experience may not be directly relevant to US plants.

Fire Scenario Element/Issue	Incident - Beloyarsk, December 31, 1978	Fire PRA Insights
A hot gas layer forms within the compartment of origin (if conditions may allow)	The TB roof above the fire collapsed within a few minutes. From this one can infer that hot gases accumulated underneath the roof and caused the failure of structural elements of the roof.	Collapse of structural elements is not modeled in fire PRA. (Collapse within such a short time is unusual in any case.) In most areas combustible loading is low, and this assumption should be valid. A TB typically houses large quantities of oil and other combustibles; therefore, the same assumptions may not be applicable.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	The fire propagated to adjacent compartments by burning along cable trays. Open penetrations and doors allowed the fire to spread to the cable shafts in the Control Building. The fire burned in the shafts for several hours and ignited fires at elevations 0.0 m, 8.0 m, 12.35m, 16.40m and 20.0m. It severely affected the control room.	This is one of few fire events where a large portion of an important area of the plant (in this case the Control Building) is affected by the fire. In a typical fire PRA, the extent of damage caused by a fire is confined to at most a few adjacent compartments. However, it must be noted that particular attention is paid to fire barriers in the US, and a typical PRA would confirm the integrity of fire barriers as part of a plant walkdown. Hence, it is likely that a PRA would have identified the lack of penetration seals as a significant contributor to plant fire risk.
Local automatic fire detectors (if present) sense the presence of the fire	The fire was detected manually by plant personnel.	
Alarm is sounded automatically in the control room, locally and / or other places	The alarm was promptly sounded upon detection and the fire brigades called out.	
Automatic suppression system is activated (if present)	The available information sources mention that automatic suppression systems activated as designed. However, given the extent of manual fire fighting that had to be done, the automatic systems must have only partially helped the situation.	It would appear that a fixed manual fire suppression system near the fire origin could not be manually activated because the fire had already damaged system cables. Fire protection system cables are not typically traced as a part of a fire PRA.
Personnel are present in the area where fire occurs	The fire was detected by plant personnel. It is not clear how long before that the fire had ignited.	Manual fire detection is commonly credited in fire PRA.
Control room is contacted or fire alarm is sounded	See note above.	

Fire Scenario Element/Issue	**Incident - Beloyarsk, December 31, 1978**	**Fire PRA Insights**
Fire brigade is activated	The fire brigade was called immediately after the discovery of the fire and it took them about 6 minutes to arrive on the scene. In the course of the fire, several other units were called in from a wide area around the plant. A number of senior officers of the fire service got involved in commanding the fire.	In Russia, fire brigades are not located on-site. In this event, plant personnel chose not to attack the fire until arrival of the first fire brigade although the reasons for this decision are not given. In most fire PRAs, fire are assumed to be handled by on-site personnel. Fires growing sufficiently large to require off-site support are not commonly modeled.
Fire suppressant medium is properly applied	Fire suppressant used in this event were water and foam. Large quantities of water and foam were applied to different levels of the Control Building and the cable shafts.	There are no records of erroneous application or misapplication of the suppressant.
Fire is affected by the suppression medium	It took a long time for the fire to be brought under control. The factors influencing the long fire duration are deemed to be, the fact that multiple plant areas were impacted, the inaccessibility of some fire areas, propagation of smoke and the intensity of the fire.	
Fire growth is checked and no additional failures occur	The fire was declared under control after about 17 hours from ignition..	This fire was of very long duration and well exceeds the fire durations typically considered in a fire PRA.
Fire is fully extinguished and fire brigade declares it as out	The fire was declared as completely extinguished about 22 hours after ignition.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	The roof immediately the fire collapsed. About $960m^2$ of TB roof was severely damaged. A large number of cables, at least one transformer, and some electrical panels were damaged by the fire.	Much of the plant systems damage would have likely been identified in a fire PRA analysis of the control building in particular.
Cable failure impacts equipment outside the fire location	This fire involved extensive loss of cables and their associated systems.	The equipment losses appear typical of what might be assumed in a fire PRA.

Fire Scenario Element/Issue	Incident - Beloyarsk, December 31, 1978	Fire PRA Insights
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	The safety of the plant was severely affected. The available sources do not provide much information about this issue. However, clearly the operators had difficulty in controlling the reactor. Reference [A5-1], states that it was "pure luck" that there was no core damage resulting from this event.	Certainly, multiple safety trains were affected in this fire event. It is not clear whether the control room experienced a complete loss of vital instrumentation. It would appear that some core cooling capability remained available throughout the event.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	No information on operator actions is available.	
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Clearly the operators had to work under extremely difficult conditions. No further details could be gleaned from the available sources.	The operators appear to have remained in the main control room despite conditions that would almost certainly be assumed to force abandonment in a fire PRA.
Structural failures (if occurred) may jeopardize availability of equipment	The available information does not clarify whether the collapsed TB roof caused any damage to equipment that may had been needed for safety of the reactor.	
Water when sprayed over electrical equipment may fail the exposed equipment	No information.	
The cooling effect of CO_2 may adversely impact equipment	There were no CO2 systems cited.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	No information.	

A5.5 Incident Analysis

This event is illustrative of a very severe turbine hall fire. The lack of separation between redundant cables and extensive fire spread led to numerous common mode failures making the control of the plant extremely difficult. The conditions for the control room operators were further aggravated by direct control panel damage (fire spread from below into the control room panels) and smoke in the control room. At one point the operators were severely affected by smoke inhalation. Operators, despite all these difficulties, remained in the control room and managed to start one train of a reactor emergency cooling system. The required operator actions and the locations where those actions took place (e.g., it is inferred that some local actions were required) are not described in the available documents. Reference A5-1 states that it was only fortuitous that core damage did not take place.

There was apparently a fixed foam extinguishment system at the original fire location (in the TB), but the system could not be activated because the cables for the system were damaged by the fire. It is not common practice to trace fire protection system cables, so this potential might have been missed in a fire PRA. It would appear that US standards are largely mute on the protection of fire protection systems from fire damage.

A large number of fire fighters gathered from a wide area around the plant and fought the fire from several fronts. Several senior officers from the region joined the force at various times through the incident, and each arriving official of higher rank took over the command of the fire fighting operation. At least four changes of command took place. This apparently added some confusion and uncertainty to the fire fighting efforts, but reports are not clear in this regard. In the US, the overall lead would likely remain with plant personnel, rather than being transferred to off-site personnel.

This incident started as a typical TB fire scenario involving the turbine lubrication oil system. Hence, the fire initiation portion of this incident is routinely considered in fire PRAs. However, the fire grew out of control for some time and ultimately spread to much of the control building. In some, but certainly not all, fire PRAs, total loss of equipment in the TB is considered. However, the complications that followed after the fire propagated to other parts of the plant can be attributed to plant specific conditions (lack of seals for fire barrier penetrations) not typically found in US plants, and therefore, not typically addressed in US plant fire PRAs. The lack of fully sealed fire barriers had a profound impact on the propagation of the fire into different compartments. In fire PRAs, the status of fire barriers is routinely examined as part of a plant walkdown.

An important aspect of this incident is the collapse of TB roof; especially the short time it took for the fire to lead to such catastrophic failure. The roof collapse is attributed in part to the delay in initiating fire fighting efforts as well as to the apparent rapid fire growth. The plant personnel did not attempt to fight the fire, but rather, waited for the fire brigade to arrive (this is consistent with their training, fire brigades in Russia are an off-site function and the fire service is actually a branch of the Russian military). Other potential factors, for example structural design characteristics of the roof, fire protection (or the lack thereof) for the structural elements, and/or extremely cold outside temperature, are discussed in any of the available reports. In fire PRA, the possibility of structural failure is typically not modeled. This assumption may be appropriate for areas where the combustible loading is low. However, for TB fire scenarios, where combustible loading is generally high, the possibility of structural failure may exist but is not typically considered. The impact of such failure on safety related functions is a plant specific issue. Although in a typical PRA structural failure of the TB is not modeled explicitly, only under special conditions such a collapse may impact safety functions.

This incident has some similarities to other fire incidents at Soviet-design plants where a TB fire propagated into other parts of the plant through open or leaking doors and penetrations. This incident demonstrates the importance of quality fire barriers and the sealing of barrier openings. In fire PRA, it is typically assumed that fire barriers are properly designed and installed. Some nominal failure probability (such as 0.01 per demand) is commonly assumed in order to assess the potential risk contribution of room-to-room fire spread. In the U.S. there has also been considerable regulatory interest in recent years associated with fire barriers. This has likely contributed to a high reliability for primary fire barriers in U.S. plants. This incident demonstrates that it is important to verify the integrity of critical fire barriers as part of the fire PRA effort to ensure that realistic information is employed in the analysis. As it is noted above, barrier status is routinely examined in a typical fire PRA as part of plant walkdown.

This is one of the few fire incidents identified where fire fighting proved to be extremely difficult. While the available discussions of fire fighting are not extensive, it is clear that the efforts were influenced by a number of complicating factors. The fixed foam suppression system in the TB was disabled before it could be activated because of fire damage to cables. The routing of the cables for a fixed fire suppression system is generally not addressed in fire PRAs. This incident demonstrates a potential dependency between the fire and the availability of fixed suppression systems. Such dependency will be minimized in most US plants by the use of diesel (or gas) driven fire pumps, and the widespread use of wet-pipe sprinkler systems that are not dependent on electrical actuation or control. It would appear that the US fire suppression system standards are largely mute on this subject. Hence, there appears to be no basis for a general assumption that US systems would be immune from similar failures.

Fire fighting was done in heavy smoke conditions and with an extremely low outside temperature. Because of the extensive spread of the fire, it was fought from at least three separate fronts. Such complications are not typically considered in fire PRAs. Indeed, fire PRAs rarely postulate fires of this magnitude or duration. Often, for TBs it is assumed that the entire building is engulfed in fire. If this fire scenario cannot be screened out as risk insignificant, a detailed analysis of potential fire scenarios may be conducted. For those detailed analyses, in fire PRAs the time to extinguish a fire is typically assumed to be on the order of few tens of minutes. This incident demonstrates that it can take extended times, in this case over 17 hours, to control the fire.

Multiple safety systems and a large set of reactor instrumentation appear to have been lost in this incident. The details of what was lost and how the operators managed to provide core cooling and reactor control is not provided in any of the available reports. This is one of few fire incidents where multiple safety trains have been damaged. The operators clearly worked under very harsh conditions due to the presence of smoke and fire in the Main Control Room. In addition to cable failures, there was also direct control panel damage in the Main Control Room. Despite these adverse conditions the operators managed avoid core damage. In a typical fire PRA, if the control room is filled with smoke, it is assumed that the operators will become ineffective and, if an alternate (reserve) shutdown panel is not used, core damage will certainly occur. This incident illustrates that operators can be effective even under harsh conditions.

A5.6 References

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Appendix 6 - Analysis of North Anna, Unit 2 Fire on July 3, 1981

A6.1 Plant Description

North Anna is a two unit nuclear power station located near Mineral, Virginia. Both units are 893 MWe Westinghouse design, pressurized water reactors. Unit 2, where this fire incident occurred, started commercial operation in December 1980 [Ref. A6-3].

A6.2 Chain of Events Summary

On July 3rd, 1981, at 07:23, Unit 2 was at 17.9% power level when an internal fault in one phase of the "B" main transformer led to catastrophic failure of the transformer and fire (Reference [A6-1]). A ceramic insulation shifted and the side of the transformer ruptured. Transformer oil sprayed from the opening over the transformer and the outside wall of the turbine building.

The fire caused the feeder breakers from a Reserve Station Service Transformer to two station service buses to trip open. The voltage transient caused by this event led to several bi-stables in the Solid State Protection System to drop out, resulting in a high steam line flow signal. Since the reactor coolant temperature was low, this led to a safety injection signal.

The fire brigade was activated immediately. The local fire departments were also contacted for assistance (at 07:25). The deluge systems on the B and C transformers activated. However, the fire was too severe for the capability of the system and the fire continued to burn. It took the fire brigades about one hour to bring the fire under control.

A6.3 Incident Analysis

Although this incident is considered a severe fire in classical fire protection terms, it affected only non-safety components. Hence, in a fire PRA it would be considered as risk insignificant. Fire scenarios impacting only non-safety components are commonly screened out in the early stages of a fire PRA. The occurrence of the spurious safety injection signal, although in this case initiated by failures caused by the fire, would also be possible due to other types of equipment failure. In other words, such a fire is considered as one of many possible causes for the actuation of safety injection signal. Hence, in a more general context this fire incident should be captured within the bounds of an internal events PRA rather than in the fire PRA.

Despite the low potential risk impact, the incident provides an interesting insight about fixed fire suppression system capabilities. It demonstrated that a fixed fire suppression system can be overwhelmed even when the fire initiates in those components that the system is intended to protect. In other words, it shows that effectiveness of the suppression system may be an important factor. In fire PRAs it is assumed that the fire protection systems are designed and installed properly and if actuated they can control the fire caused by the protected components.

However, this insight is mitigated for many PRA applications because large oil-filled transformers are commonly located in outdoor switch-yard areas rather than within the plant structures. The main concern of a fire PRA is focused on safety related cables and equipment and the areas where such components are present. The are typically internal plant areas, and quite commonly, the characteristics and quantity of combustible materials make the possibility of overwhelming the fixed suppression system very unlikely. Therefore, the assumption regarding adequacy of suppression systems is not called into general question by this incident. However, the issue of effectiveness of the suppression system, as discussed in Reference [A6-2], must be taken into account for all scenarios. This incident makes it clear that it is not sufficient to consider the reliability of the suppression system alone. Reference [A6-2] provides methods for incorporating effectiveness of these systems.

A6.4 References

A6-1 Licensee Event Report (LER) - 339-81-055, Virginia Electric and Power Company, North Anna Power Station, Unit 2, Docket No. 50-339, July 15, 1981.

A6-2 N. Siu and G. Apostolakis, "A Methodology for Analyzing the Detection and Suppression of Fires in Nuclear Power Plants," *Nuclear Science and Engineering, 94*, 213-226(1986).

A6-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix 7 - Analysis of Armenia NPP fire on October 15, 1982

A7.1 Plant Characteristics

The Armenia Nuclear Power Plant (ANPP) is a two unit VVER 440/230 power plant located outside Yerevan, the capital of Armenia.[A7-5,6] At the time of the fire, Armenia was part of the former Soviet Union. Unit 1 began operation in 1976 and was shut down permanently in 1989. Unit 2 began operations in 1979 and continues to operate.[A7-6] The two units shared turbine building where four turbine-generators (two generators per unit) are located. Each reactor has a separate reactor compartment with six steam generators per unit. The capacity of the steam generators is such that, after a reactor trip, no makeup water or core injection is necessary for over 5 hours. This feature played an important role in the fire incident under review. The two units do not share any systems. The ultimate heat sink is provided by natural draft cooling towers. The diesel generators are located in a separate building away from the main reactor and turbine buildings. There were three diesel generators for each unit at the time of the incident.

Each unit has a separate main control room – Control Room 1 and Control Room 2 ! responsible for reactor control. The connections to the power grid are controlled from a separate Central Control Room located on the site. The power and control cables are run through several cable galleries (cable tunnels and cable shafts). At the time of the fire incident, the cables from both units and from redundant trains of the same system could be found in the same cable galleries. (Since the fire incident, routing of the cables has been modified to minimize the co-location problems of the original design and fire retardant coating have been applied to the cables). The cables were laid in horizontal cable trays with no fire retardant materials protecting them. Cable insulation, per Soviet test standards, was rated as 0.5 hour fire resistant. It is not clear if this rating has any direct correspondence to U.S. fire rating standards.

A7.2 Incident Summary

On October 15, 1982, at 09:55, fires ignited along a power cable at seven different points in two separate compartments (cable galleries). The fire primarily impacted Unit 1. The impact on Unit 2 was much less severe than Unit 1. The fire rapidly established itself and spread to other cables and cable trays in both compartments. Ignition occurred because of a short circuit in the terminal block of a 6 kV power cable to a service water pump. This short was manifested as an overload current when an operator attempted to start a pump.

Local automatic fire detectors sensed the presence of the fire within 1 minute of ignition. (The ignition time is assumed to be the moment that pump switch was manipulated by the operator.) The detectors sounded an alarm in Control Room 1 and in the Central Control Room. The cable galleries were equipped with an automatic foam fire suppression system. However, the system initially did not activate because the controls for the system were set to the manual mode. The system control cables were damaged by the fire before this could be corrected and therefore the system could not be activated for the entire course of the fire.

The fire brigade was called within 5 minutes of fire ignition. The procedures for fighting electrical fires stipulated that no fire fighting activity can be initiated inside a compartment that contains electrical equipment or cables and is darkened by smoke until the power is turned off. The brigade, therefore waited and did not start fire fighting activities until about 10:15, 20 minutes after fire ignition. The initial brigade attack was made using fire hoses and water streams.

As noted, the initial fire was ignited in two separate compartments. Fire also propagated to an adjacent cable shaft. Smoke rapidly filled the compartments of fire origin and propagated to other rooms, including the Unit 1 main control room, because of open cable penetrations, doors and hatchways.

About 10:05, 10 minutes into the fire, the main circulating pumps of the primary loop for Unit 1 were lost. This initiated emergency protection signals. Indications were received on the control board that the neutron flux (reactor) period was less than 20 seconds. The 0.4kV and 220VDC safety buses were then lost. The turbine stop valves closed and within 2 minutes the generators were disconnected from the grid. Eventually, a large number of components were lost due to the fire.

At about 12:10, 2 hours and 15 minutes into the fire, short circuits were experienced that led to secondary fires and a complete station blackout. The investigation team later concluded that the mechanical impact of the water stream caused short circuits in the control cables related to the main unit turbine generators. As a result, the main breakers of the two generators for Unit 1 (i.e., G-1 and G-2) closed spuriously and connected these two turbine-generators to the grid. This caused several short circuits. The turbine-generators failed due to electrical and mechanical overload. Turbine Generator 2 experienced a short at its power outlet. As a result of the generator failure and the shorting, hydrogen escaped and exploded and an oil fire was ignited near Turbine 2 that engulfed the oil storage tank. Close to 300 m^2 of the turbine building was eventually affected by this secondary fire. In addition to the turbine generators, the startup transformer was also affected (overloaded) by the inadvertent connection of the turbine generators to the grid. This transformer exploded and caught fire as a result of the overload.

At 12:30, ANPP personnel started laying temporary cables for connecting a diesel generator to the “house” loads. At 12:45, the Unit 1 control room lost all instrumentation and control over the reactor. By 15:13, the power to two high pressure injection pumps (emergency core cooling pumps) was restored using spare cable runs outside the buildings from a diesel generator to the motor windings of the pump. This re-established the core cooling capability.

At 16:00 the fire brigade considered the fire under control and at 16:58 fire was declared to have been extinguished. The total fire duration was just over seven hours.

A7.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in detail and in a chronological order as best as can be inferred from the available sources (References [A7-1] through [A7-4]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included within the chronological order of events based on the available information and the judgement of the authors of this report. If a specific time is cited, this is based on one of the available reports.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	The automatic, fixed foam system in the cable galleries were switched from automatic to the manual mode.	This condition should be detected during a PRA plant walkdown.
Prior to the incident	Diesel Generator #1 was under maintenance at the time of the incident.	
Prior to the incident	Both Units were operating at 100% power level.	
00:00	On October 15, 1982, at 9:55 a.m., fire ignited at seven points along a 6kV power cable. The cause of the fire was attributed to a short circuit in the terminal block of a 6kV electric motor of the 2NTV-4 service water pump (Note 1). It is estimated that the current reached in excess of 10kA for an extended duration. The excessive current led to ignitions in seven places in two cable galleries (N59a and 60a) along the cable route. The cause of the short circuit was traced to an error committed by electrical shop personnel. They had failed to ensure that the terminal block and 6kV cable attachment were properly sealed. This was in violation of the specific written instructions on operation and maintenance of electric motors.	Electrical fires, including self-ignited cable fires for older style cables, are considered in fire PRAs. However, the simultaneous occurrence of fire ignition at several points is not postulated. Moreover, in this incident the fire started in at least two compartments. In fire PRAs done for plants in the U.S., the frequency of ignition of fires for a compartment is based on statistical analysis of fire events that have occurred in U.S. plants. Often, very small frequency is assigned to self-ignited cable fires. At ANPP, the ignition occurred in a 6kV power cable because of high current caused by a short in the power circuit. Certainly there are significant differences in the electrical circuit design between U.S. and Soviet power plants and in the fire performance rating of the power cables. Therefore, extrapolation of the insights gained from this incident to fire PRA for U.S. plants must be done with caution.
--	Both units were manually tripped from the control room.	The decision to trip both units was made quite early. PRAs often assume a plant trip will be initiated given any significant fire in the plant.
00:01	Local automatic fire detectors sensed the presence of fire within 1 minute of ignition.	This is consistent with typical assumptions used in a fire PRA.

Time (hr:min)	Event or Step Description	Fire PRA Implications
	The detectors sounded an alarm in Control Room 1 and Central Control Room.	
--	The fire rapidly established itself and spread to other cables and cable trays, including control cables. Some of the control cables laid inside metal boxes (possibly either junction boxed or enclosed raceways) were also affected by the fire.	In fire PRAs, the growth of cable or any other fire is established through modeling of the propagation process. Typically, the growth time is in several minutes. In this incident, the fire propagated rather rapidly. It is possible that the large amount of energy discharged by the short circuit into the cable caused the rapid initial growth of the fire. It should be noted that the fire resistance requirements of the cables used in the plant at that time may not have been as stringent as those currently applied in a U.S. power plant. Therefore, the rapid growth of fire may be partly relevant to U.S., plants, and in particular, older US plants.
—	Because of lacking or open fire doors and hatches and loose filling of cable penetrations, the fire propagated to adjacent areas. This included cable shaft N (at elevation +3.60m) and to four parallel cable galleries (elevation -3.60m).	In a typical fire PRA it is assumed that hatches, cable penetrations and fire doors are properly designed and installed. Therefore, the possibility of fire spread through hatches, cable penetrations and fire doors is assumed to be a low probability event. This incident demonstrates that if these devices are not properly installed, fire propagation to an adjacent compartment may be imminent.
--	Smoke rapidly filled the compartments of origin and propagated to adjacent rooms because the cable penetrations between rooms were not sealed. Smoke also got into Control Room 1.	Propagation of smoke and its impact on plant personnel is typically addressed in fire PRAs using conservative and simplified models. The possibility of smoke ingress into the control room from fires outside the control room is often not considered, unless there are clear indications that this could be possible.
--	The cable tunnels were equipped with a foam system. However, the system did not activate because the controls for the system were set to the manual mode. The system was never activated throughout the entire course of the event. The control circuit (cables) of the system became damaged by the fire.	The routing of power and control cables for the fire protection system is generally not established when conducting a fire PRA. Loss of a fire protection system because of the fire itself is seldom considered. In a typical fire PRA it is inherently assumed that the power and control cables associated with the fire suppression system are not in the compartment where the fire is postulated. U.S. standards appear to be largely mute on this subject.
00:05	The fire brigade was called within 5 minutes of fire ignition. (It may be noted that Soviet plants commonly rely on a fire brigade that is associated with the plant but resides off-site.)	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:05	At 10:00 a.m., smoke in feedwater area was noticed	
00:07	At 10:02 a.m., all main coolant pumps disconnected without an apparent reason. This initiated a level 3 scram (Note 3), which was immediately followed by a level 1 scram because of loss of power to reactor protection system.	
--	Tried to check status of condenser vacuum, but none of the related valves could be operated from the main control room.	
00:10	Lack of cable separation in the cables for the two units and between redundant trains caused numerous common cause failures. About 10:05, in Unit 1, a Type III Emergency Protection signal activated because of the loss of main circulating pump 1GCN-3. In a few seconds, a Type I Emergency Protection signal was received with indication that the following conditions are present: - Neutron capacity exceeded 20% - Neutron flux period less than 20 sec. - Loss of 380VAC control and 220VDC protective power systems	The available reports cite that the control room indications were not accurate, probably due to degradation and/or failure in the instrument cables. The reports imply that the Type I emergency protection signal was spuriously generated as a result of these instrument problems.
00:10	At 10:05 the turbine stop valves were closed	
00:11	At 10:06, the reserve transformer 1 was switched off. Lights went out. Telephone links to outside the plant were cut off. A large portion of instrumentation readouts and alarms in the Central Control Room and main control room 1 were lost. All Unit 1 6kV and 0.4kV buses except for the uninterrupted power coming from the AC/DC motor generator set were lost. From the accident investigation report, it is not clear how exactly these losses took place.	
00:12	At 10:08, diesel generators 2 and 3 started but would not connect to their respective buses. The two main generators were disconnected from the grid.	It must be noted that these actions would take place in the central control room. The central control room was not directly affected by smoke. Actions from multiple control points are seldom explicitly modeled in fire PRAs. Current human action methodologies however, can address such scenarios.
--	Diesel generator 2 disconnected because of local	

Time (hr:min)	Event or Step Description	Fire PRA Implications
	interlocks prevented it from connecting to the bus.	
--	Diesel generator 3 disconnected because of a hot short in its associated cable.	Note that the presence of hot short is specifically mentioned in incident description. This is one of few incident descriptions that the possibility of existence of a hot short is specifically mentioned. In fire PRA, such failure modes play an important role.
--	Plant personnel, for a short time, succeeded in activating one plant reserve transformer and bring power in for one emergency makeup pump and one service water pump.	
--	Thick smoke was spreading from the cable tunnels, switchgear rooms, and other areas of the control building. The control room was affected by the smoke and by the fire.	In a typical fire PRA, it is assumed that if the control room is filled with smoke the operators cannot continue to function.
00:15	At 10:10, plant fire brigade arrived at the scene.	
00:17	Ar 10:12, the local grid was disconnected from the electrical system.	
--	A large set of equipment was lost because of the fire. This included 400m^2 of cable areas and some switchgear rooms.	
--	The fire brigade started the foam pump, that started rotating but no foam was formed because of air trapped inside the pump. Personnel removed the air but could not restart the pump because fire damage took out the power to the pump.	Fire-induced loss of a fire protection system is not typically considered in a fire PRA.
--	Because the plant lost normal and emergency makeup, the operators closed all blowdown lines from the steam generator and reactor.	
00:20	At 10:17 a.m., large quantity of smoke was observed in the turbine building.	
00:20	Between 10:17 and 10:25, operators tried to remove hydrogen from the main generators but failed to complete the task. One report surmises that because of their excessive anxiety, the responsible operators erroneously closed a nitrogen feed valve (a manual valve) during the hydrogen transfer operation. As a result about 20% of the hydrogen was left in the generators.	This is an apparent example where a fire did lead to increased operator anxiety leading to an operator failure. In this case, the failure aggravated the fire situation because the hydrogen was not properly purged from the main generator.
00:20	The procedures for fighting electrical fires	Delay in initiating fire fighting activities

Time (hr:min)	Event or Step Description	Fire PRA Implications
	stipulated that no fire fighting activity can be initiated inside a compartment that contains electrical equipment or cables and is darkened by smoke until the power is turned off. The brigade, therefore waited and started fire fighting activities at about 10:15, 20 minutes after fire ignition using water streams. A part of the fire fighting activities were conducted from Control Room 1. The hatch to cable shaft was opened from the control room and water was applied from there.	because of procedural requirements is not generally considered in a fire PRA. In this case there is also the added complication of fire fighting activities (laying of hoses, personnel movement, opening of access hatches, etc.) in the control room itself. This particular configuration is unlikely to be encountered in a U.S. plant.
00:25	External fire brigades were alerted. The delay in summoning the external fire brigades was due to loss of telephone connections caused by the fire.	In a typical fire PRA, such circumstances as the need to call external fire brigades and difficulties in reaching them is not modeled explicitly. Such conditions are assumed to be included in an overall model that is based on statistical analysis of fire event data.
--	In total, 21 fire brigades arrived at the plant from Yerevan and other surrounding areas.	The transit time for the off-site brigades cannot be established. See the preceding note.
--	The plant experienced a station blackout because power cables were lost that affected the connections to both the diesel generators and to the offsite grid.	A fire-induced station blackout is a somewhat uncommon fire risk scenario for U.S. plants. However, fire PRA methodologies that do address possible spurious actuations and the resulting potential for loss of equipment, should include scenarios that would effectively lead to station blackout conditions..
--	Primary and secondary side pressures were controlled by the operators in the main control room by opening the valves at steam dump stations 1 and 2.	
00:35	At 10:30, a spurious signal started feedwater pump #1. This was considered as a spurious connection because the normal pump startup signal should have first initiated the lubricating oil pump. The pump rotated without lubrication. The control operators were unable to disconnect the pump. Electrical technicians achieved this from the bus powering the pump.	This is clearly an anecdotal account of a spurious actuation caused by an apparent control cable hot-short failure leading to a start signal generated between the control room and the MCCs. It is also interesting that the fault bypassed starting of the lube oil system and, had the pump not been secured, an unrecoverable failure of the pump would have followed. The fault also blocked or bypassed the normal stop command functions in the control room. Although such a scenario would be considered in a fire PRA that includes spurious operation, the fire incident reports seldom provide sufficient information to allow an in depth understanding of the chain of events leading to the spurious actuation.

Time (hr:min)	Event or Step Description	Fire PRA Implications
01:10	By 11:05, substantial smoke had entered the main control room. Additional difficulties with plant control arose because of the smoke inside the control room and lack of alternate control provisions.	There is relatively little information on this aspect of the event, but it is clear that operations in the main control room were hampered significantly.
01:33	At 11:28, steam generator #3 safety valve opened.	
01:35	At 11:30, a total loss of instrumentation occurred in the main control room. The electrical connections to the turbine hall and central control room instruments and equipment were also lost.	This incident is one of few fire events where total loss of instrumentation took place (the so called "flying blind" scenario). In a typical fire PRA this scenario would be assumed to lead to core damage. Clearly, based on this and other fire incidents the PRA practice of assuming core damage under such circumstances is conservative.
--	A courier system was established between the main control room and other locations of the plant to send and receive information and instructions.	Operator actions outside of normal procedures would not typically be credited in a PRA.
01:47	At 11:42, plant personnel succeeded in establishing a temporary cable between the main and central control room. (It is inferred here that this refers to a voice communication cable was strung between the control rooms to facilitate the interaction between the two control rooms.)	In fire PRAs, loss of communication between different centers of the plant is typically not considered as an important element of a fire scenario. However, it must be noted that often, it is conservatively assumed that in case of a severe fire damage to main control room controls and instrumentation, the operators will abandon the control room and take control over the plant from other locations. The probability of success of this mode of operation is genrally modeled conservatively.
01:50	At 11:45, the power supply if neutron flux monitoring system was lost.	
--	The 0.4 kV uninterruptible power bus was lost because of a short in the DC power system.	
02:05	By 12:00, for both units, the electric power for the primary side of the units was gone. There was no indications in Unit 1 main control room. Unit 2 main control room had lost its lighting. Temporary telephones had to be used for communication and the operators in Unit 1 main control room were working in darkness and smoke filled room. The only instrumentation that was available to	

Time (hr:min)	Event or Step Description	Fire PRA Implications
	Unit 1 plant personnel was the primary pressure readings from 3 manometers at local stations.	
02:10	At 12:05, it was discovered that turbine generator 1 was rotating at 1000 rpm. The generator was vibrating and smoke was coming out of its bearings.	
02:15	At about 12:10, short circuits were experienced that led to secondary fires. The investigation team later concluded that the mechanical impact of the water stream caused short circuits in the control cables related to the generators. As a result, the main breakers of the two generators for Unit 1 (i.e., G-1 and G-2) closed spuriously and connected these two turbine-generators to the grid. The turbine-generators failed due to electrical and mechanical overload. Turbine Generator 2 experienced a short at its outlet. As a result of these failures hydrogen escaped from generator #2 and exploded (as noted above 20% of the hydrogen was left behind during the failed purge operation). An oil fire occurred at Turbine 2 that engulfed the oil storage tank. Close to 300m^2 area of the turbine building was eventually affected by this fire.	The impact of water, and especially mechanical impact of water on cables and shorts caused by that is not considered in a typical fire PRA. It is interesting to note that these shorts occurred more than 2 hours after the ignition. Fire PRAs do not commonly consider damage beyond at most a few 10s of minutes. Secondary fires are not modeled in a fire PRA. In this incident, the secondary fires were very large (two substantial oil fires) and caused significant damage to the turbine building and may have aggravated the loss of offsite power.
--	Because of inadvertent connections to the grid, the Caucauses region power voltage dropped and several high voltage lines disconnected.	
02:21	At 12:16, in addition to the turbine generators, the startup transformer (Note 2) was affected by the connection to the grid. Because of overload, it exploded and caught fire.	This incident points out that secondary fires may occur at more than one location and can have catastrophic impact on equipment.
02:25	Starting about 12:20, personnel tried to establish nitrogen flow into generators #2, but failed because of low nitrogen pressure. The fire brigade started fighting the fires in the turbine building and at the transformer.	
02:35	At 12:30, ANPP personnel started laying the temporary cables for connecting a diesel generator to the “house” loads.	In a typical PRA, the possibility of recovery actions that are beyond the established and written procedures is assumed to be very unlikely. In this case, after over 2 hours these efforts ultimately led to success as noted below.
02:50	At 12:45, control of Unit 1 from the main control room panels was completely lost. The	Under current designs this would lead to abandonment of the control room and use of

Time (hr:min)	Event or Step Description	Fire PRA Implications
	smoke in the control room was reportedly "unbearable", forcing all remaining operators to don masks.	alternate shutdown. At this time there was no specific remote shutdown capability available. For such a condition, the fire PRA analysts would assume that core damage would occur.
03:05	At about 13:00, plant personnel succeeded in connecting a temporary power cable from diesel generator #4 to Unit 1's emergency makeup pump #1 and start the pump (a high pressure emergency core cooling pump). This allowed water injection into the primary loop of Unit 1. The pressure of the reactor was monitored from a local manometer. The coolant apparently discharged through the relief valves into tank B8/1.	
--	During the next four hours, operators wearing breathing masks went to the upper levels of the turbine building to manually open the steam dump valves of the steam generators. (It must be noted that it is not clear if this action was commenced before or after the temporary power to the emergency makeup pump was connected.)	Operator actions in a fire impacted area would not typically be credited in a fire PRA.
03:25	At about 13:20, the turbine building and transformer fires were brought under control in about two hours after they started.	
04:05	At about 14:00, one of cable spreading room walls was broken open to provide access for fire brigade to fight the fire at elevation 5.4m under the main control room.	
05:18	At 15:13, per Reference A7-2, the power to makeup pump #4(1APN-4), was restored using a spare cable run outside the buildings from a diesel generator to the motor windings of the pump.	This was a non-proceduralized action that would not have been credited in a typical fire PRA.
06:05	At 16:00 the fire brigade considered the fire under control.	
07:03	At 16:58 fire was considered as extinguished.	
07:05	At about 17:00,a feedwater pump was also powered using a temporary cable setup that established makeup to the steam generators. This was possible only after the fire in the turbine building was extinguished.	This event illustrates operator actions in a fire impacted area shortly after extinguishment of the fire. This would not typically be credited in a fire PRA.
07:05	At about 17:00, the main control room power was re-established using Unit 2 sources and	Recovery of lost control room functions would not typically be considered in a fire PRA.

Time (hr:min)	Event or Step Description	Fire PRA Implications
	instrumentation was restored. The instrumentation had to be re-calibrated and repaired to provide correct readings in the main control room.	
10:45	At about 20:40, neutron flux instrumentation was restored.	

NOTES:

Note 1 - Reference [A7-1] identifies the pump as "Boron Make-up Pump" and the cause of the fire as "Failure of electrical protection occurred and caused overheating of cable and motor".

Note 2 - Reference [A7-2] identifies the transformer in plural as "Service Transformers". It is assumed that it refers to the transformers that bring offsite power to the unit and if there were more than one such transformer, all were apparently affected by the fire.

Note 3 - In Soviet designed reactors, apparently there are three levels of scram. In a level 3 scram a portion of the control rods start moving in. A level 2 scram normally occurs based on a timer 10 minutes after level 3 scram is initiated and initiates the insertion of the rest of the rods. A level 1 scram is full rod drop that would normally occur 10 minutes after initiation of level 2 scram. Note that each of these time delays can be bypassed to speed the process of reactor shutdown in an emergency.

Equipment Damaged

- Numerous Power cables
- Numerous Control cables
- Turbine generator number 2
- Start-up transformer
- Off-site communications
- Off-site power
- Diesel generator power supply cables

Damaged Areas

The control building and the turbine building experienced severe damage. An area of about 300m^2 in the turbine building was affected by the fire there, mainly damaging Turbine Generator 2. Inside the control building, about 400m^2 of cable routing areas were affected by the fire. Smoke entered practically all parts of the control building, including the control room. At the time, the plant was not equipped with a reserve control room or an explicit alternate shutdown capability.

Impact on Core Cooling

Although the plant experienced a station blackout for a long time, core cooling was maintained via natural circulation in the primary loop and the water remaining in the steam generators. While all active means of core cooling were lost for some time, at no time during the fire did core cooling stop. This is due to the large secondary side capacity for passive reactor cooling. Fuel cladding, the primary envelope and the containment were not adversely affected by the fire. At about 5 hours after the fire, water was injected directly into the steam generators by installing a spare cable from a diesel generator to a feedwater pump directly.

Rediological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There was smoke inside the control room. However, there were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A7.4 Comparison of Fire PRA Elements and the Incident

In this section, the chain of events in the fire event is compared against a the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in reaching a specific insight.

Fire Scenario Element/Issue	**Incident - ANPP, Oct. 15, 1982**	**Fire PRA Insights**
Presence of combustible / flammable materials	The primary fuel was cables in at least two cable galleries. The fuel loading was high due to the presence of stacks of cable trays along the walls. Secondary fires involved both turbine and transformer oil.	
Presence of an ignition source	There were no open ignition sources. This was a self-ignited cable fire. Ignition occurred because of a short in a 6kV power circuit and excessive (more than 10kA) current in the cables.	This verifies that a propagating self-ignited cable fire is possible, although clearly the fire rating of the cables impacts this potential. The fire rating of the cables was cited as 0.5 hour per Soviet standards. No correspondence to U.S. standards has been established.

Fire Scenario Element/Issue	**Incident - ANPP, Oct. 15, 1982**	**Fire PRA Insights**
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The fire was caused by a current overload due to an error committed by electrical shop personnel. Ignitions were noted in seven places and in two compartments (N59a and 60a).	The root cause of the self-ignited cable fire is operator and maintenance crew error. Self-ignited cable fires are commonly considered for older US plants that contain cables not certified as low flame spread per current standards. Simultaneous, multiple ignitions in more than one compartment is not considered in current fire PRAs.
Fire growth within the combustible or component of original ignition	The fire presumably propagated to adjacent cables within the ignition tray and established itself very rapidly. The high overload current and the implied electrical energy release at the points of shorting likely contributed to this rapid growth behavior.	This points out that even a self-ignited cable fire can establish itself and propagate rather rapidly. Of course, it depends on the characteristics of the combustible materials (in this case cables) present in the compartment. In a typical fire PRA fire growth is estimated using a computer model of fire propagation process. These models typically predict fire growth in terms of several 10s of minutes. In this incident the fire propagation took place rapidly. Current models do not consider the potential for electrical heating effects to enhance fire growth behavior.
Fire propagates to adjacent combustibles	Fire was ignited in two separate compartments. The fire clearly propagated, apparently rather quickly, to adjacent cable trays and along those trays to the enclosure boundaries.	The propagation of fire took place rather rapidly.
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information avaiable	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke filled the compartments rapidly and propagated to adjacent rooms including the main control room for Unit 1. Fire also spread to these adjacent compartments, most likely through poorly sealed cable penetrations.	This room-to-room spread can be largely attributed to missing or poor cable penetration seals, and open doors and hatchways. This condition would not be typical of a U.S. plant as significant regulatory attention is paid to the quality and integrity of fire barriers. In a typical fire PRA the possibility of fire propagation through fire doors and penetration is assumed to be very unlikely. The quality of penetrations is commonly verified during walkdowns conducted as part of fire PRA preparation.

Fire Scenario Element/Issue	**Incident - ANPP, Oct. 15, 1982**	**Fire PRA Insights**
Local automatic fire detector (if present) senses the presence of the fire	Local automatic fire detectors sensed the presence of fire within 1 minute.	These systems operated quickly and as designed and would be credited in a fire PRA.
Alarm is sounded automatically in the control room, locally and / or other places	Fire detector alarms sound in both the Control Room of Unit 1 and Central Control Room	
Automatic suppression system is activated (if present)	An automatic fixed foam suppression system was installed in the areas of fire. The system did not activate because the control setting was on manual and the control circuit became damaged by the fire.	The mis-positioned control switch would perhaps be detected during plant walkdowns as a part of the PRA. However, the control and power cables for automatic suppression systems are usually not traced. This event points that those systems that require control and power circuits may become unavailable from the fire itself. This also impacts methods that credit manual recovery of a failed suppression system (e.g., the EPRI *Fire PRA Implementation Guide*).
Personnel are present in the area where fire occurs	There were no personnel in the areas where fire ignited.	
Control room is contacted or fire alarm is sounded	The control room became aware of the fire within one minute of ignition through fire detectors.	
Fire brigade is activated	The plant fire brigade was called within 5 minutes of ignition. The external fire brigade was not immediately called because telephone connection to the off-site .	Most fire PRAs for US plants assume fires will be handled by the on-site fire brigade. The potential problems with notification of an off-site brigade would likely not be considered.
Fire suppressant medium is properly applied	The procedures for fighting electrical fires stipulated that no fire fighting activity can be initiated inside a compartment that contains electrical equipment or cables and is darkened by smoke until the power is turned off from those cables and equipment. The brigade, therefore, delayed initiation of fire fighting activities until about 10:15, or 20 minutes after fire ignition. Water hoses were used to fight the fire.	In a fire PRA it is generally assumed that fire fighting activities begin as soon as the fire brigade is assembled. This event points out that other circumstances may delay the fire fighting actions.

<u>Fire Scenario Element/Issue</u>	**<u>Incident - ANPP, Oct. 15, 1982</u>**	**<u>Fire PRA Insights</u>**
Fire suppressant medium is properly applied to where the fire is.	The fire brigades applied water streams from various angles, including through a hatch inside the control room. The fire brigade did apply the water stream properly. However, because the electrical circuits remained energized, some of the circuits, at about 12:10p.m., experienced short circuits. Some of the short circuits led to secondary fires in other parts of the plant. The mechanical impact of the water stream is cited as causing short circuits in the control cables related to the turbine-generators. As a result, generator G-2 was re-connected to the off-site grid and leading to a severe secondary fire. There was also a secondary fire and explosion at a transformer.	This event is evidence of the spurious actuation of equipment (re-connection of the generator to the grid). However, the details of exactly how the actuations took place is not known. The use of water was also cited as a contributing factor in some of the short circuits, but how this was determined is not clear. Given the severity of the fire, many short circuits would be anticipated in any case.
Fire is affected by the suppression medium	The fire was ultimately brought under control, but only after an extended time.	There is no indication that ineffective fire fighting methods were attempted.
Fire growth is checked and no additional failures occur	The fire was eventually brought under control at about 16:00, nearly eight hours after ignition.	The fire burned longer than fires typically postulated in a fire PRA. However, the ready spread of fire from room-to-room certainly contributed to the extended fire duration and complicated fire fighting activities.
Fire is fully extinguished and fire brigade declares it as out	The fire started at 09:55 and it took the fire brigade until 16:00 to control the fire and 16:58 to declare the fire as completely extinguished for a total duration of about nine hours.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Extensive damage occurred to cables in the compartments where fire was initiated.	
Cable failure impacts equipment outside the fire compartment	A large set of equipment was lost because of the fire. By 12:45 the control over Unit 1 was completely lost. The Unit experienced a station blackout. For some time all active core cooling functions were lost though natural circulation remained available throughout the incident.	Given the lack of redundant train separation, and lack of quality fire barriers, the potential extent of systems loss would have likely been identified in a fire PRA.

Fire Scenario Element/Issue	**Incident - ANPP, Oct. 15, 1982**	**Fire PRA Insights**
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Both units shut down because of the fire. Emergency core cooling systems were activated. This may have occurred because of a short. Unit 1 did loose all active cooling functions, but core cooling remained available via natural circulation provided by the large capacity of the steam generators. Several spurious actuations are specifically noted in this incident. Both generators connected to the grid, on diesel generator disconnected from its emergency loads, and one main feedwater pump was activated without initiating the lubricating oil system.	This is attributed in the available reports to inaccurate reading of the reactor core conditions. Neutron flux and other reactor related instrumentation indicated conditions that may not have been the actual conditions of the reactor). This was likely because many of the instrument cables were degraded and/or failed by the fire. Instrumentation faults leading to automatic actuations are not typically considered in fire PRAs. This illustrates that inadvertent actuation of a system is possible from a fire impacting control cables. However, there are no indication about the specific nature of circuit failures.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	Control room operators attempted to control the core cooling and reactivity control systems. They remained inside the control room the entire length of the fire event. Smoke and fire effects in the control apparently did hamper operator performance.	This event points out that the operators may remain active under extremely adverse conditions. In this case the control room was directly affected by the fire through the cable shaft and by the presence of smoke. In a typical PRA it is assumed that if the control room is filled with smoke, the operators become incapable of acting properly from the control room.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Control of the reactor from the control room was lost. Recovery was achieved when a temporary cable was pulled from the diesel generator building to an emergency core cooling pump Power to the pump was restored and core cooling was resumed at about 15:13 hour, just over seven hours after the fire started.	Recovery actions in a fire PRA do not generally include actions outside those cited in written procedures. This incident, similar to the Browns Ferry and several other incidents, points out that the operators can be very innovative in devising methods to provide power and core cooling and reactor control functions.
Structural failures (if occurred) may jeopardize availability of equipment.	No information	
Water when sprayed over electrical equipment may fail the exposed equipment	The reports do attribute some cable shorts and one spurious actuation to the water spray from hoses and the resulting movement of the cables.	The basis for this assertion must be questioned. Given the fire severity, many short circuits would be expected, and there is no clear way to assure that the water hose streams were actually responsible for the observed faults.

Fire Scenario Element/Issue	**Incident - ANPP, Oct. 15, 1982**	**Fire PRA Insights**
The cooling effect of CO_2 may adversely impact equipment	Not applicable.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The automatic foam system was switched to manual at the time of the fire preventing it from actuating automatically.	See discussions above.

A7.5 Incident Analysis

The ANPP incident is considered one of the most severe fire accidents of the nuclear power industry both in classical fire protection terms and in the context of nuclear safety. The fire itself was severe and spread to several plant areas. All of the safety related systems for Unit 1 were disabled for several hours. Core damage on Unit 1 was prevented because the steam generators had the capacity to absorb reactor heat for several hours through natural circulation. This allowed plant personnel sufficient time to run temporary power cables from the diesel generator building to a high pressure injection pump motor in order to recover active cooling functions.

The root cause of the event is attributed in the available reports in part to human error in that the operator apparently failed to follow proper procedures in his attempts to start a pump. However, from the information available at this time the exact set of errors cannot be specifically identified. The reports also state that the ignition was caused by a short circuit in a 6 kV power system and failure of the protective devices to function properly. In addition, the apparently poor fire resistance characteristics of the cables and lack of separation between redundant trains allowed the fire to propagate rapidly and disable a number of important plant systems. Finally, the lack of quality fire barriers allowed the fire to propagate from room-to-room complicating fire fighting efforts and causing further damage.

The event also demonstrates that self-ignited cable fires are possible. In fact, in this case, the main cause for cable ignition was not attributed to cable damage or degradation (as is seen in other events in Soviet-designed reactor sites), but simple overloading of the cable. Reports estimate that the cable were subjected to more than 10 kA fault current. Presumably, due to the high energy potential (voltage and current) of the cables, and the flammability characteristics of the cables, the fire established itself rapidly in two separate compartments and propagated to other cables and cables trays, including cables inside metal boxes (probably either junction boxes or enclosed raceways).

In a fire PRA, fire propagation timing is estimated using mathematical models of the burning process. These models typically predict tray-to-tray fire propagation times for multiple tray configurations on the order of several tens of minutes. In this incident, however, propagation took place much more rapidly than what is typically predicted. Factors that contributed to the rapid fire spread likely include a relatively poor fire performance of the cables themselves and the fact that a high energy electrical discharge along the length of the cable was probably occurring. The characteristics of the cables at ANPP are presumed to be significantly different from those typically found in a nuclear power plant in the U.S. In particular, since 1974 the U.S. industry has applied the flammability standards of IEEE-383. Therefore, a direct comparison to U.S. plants may not be appropriate.

This event also demonstrates that multiple fires in different compartments may occur simultaneously. In this case the initial fire started in two different compartments and at several points within each compartment. In fire PRAs, simultaneous occurrence of fire ignition at several points is not postulated.

Severe secondary fires involving turbine generator lube oil and one transformer in the turbine building were also experienced. The turbine fire was apparently caused when a cable fault spuriously re-connected the generator to the off-site power grid leading to failure and an oil spill. The transformer fire was also apparently caused by cable faults leading to an explosion of the transformer and release of the transformer oil. Fire PRAs universally assume that only one fire occurs at a time.

In a typical fire PRA it is assumed that hatches, cable penetrations and fire doors are properly designed and installed. This is verified in most PRAs as a part of the plant walkdowns. At most, a random failure probability (on the order of 0.01 per demand) is assumed to reflect the possibility of a barrier being degraded at the time of a fire. Therefore, the possibility of fire spread through hatches, cable penetrations and fire doors is assumed to be of very low probability and is typically found to be risk insignificant. This incident demonstrates that if these devices are not properly installed and maintained, in case of a fire, smoke ingress, and perhaps fire propagation to an adjacent compartment should be expected. The experience at ANPP is not considered typical of U.S. plants because significant regulatory attention has been paid to ensuring the presence, quality and integrity of fire barriers in the U.S.

The propagation of smoke and its impact on plant personnel is typically addressed in PRA using conservative and simplified models. If it is concluded that smoke may enter a certain compartment, no operator actions in that compartment would be credited. In this incident, smoke did enter the control room and did have some impact on the operators. Nonetheless, the operators, despite the smoke and ongoing fire fighting activities, remained inside the control room and remained functional.

Furthermore, in a typical PRA, recovery actions that are beyond the established and written procedures are generally assumed to be very unlikely and of low reliability. In this incident, core damage was averted because operators acted outside of their procedures and routed a temporary cable between a diesel generator and the motor of a high pressure injection pump. At the point where significant smoke had entered the control room, a typical fire PRA would have assumed control room abandonment. Subsequent to abandonment only procedure-based actions that were possible outside the fire effected areas would have been credited. In this case that would have almost certainly imply a very high conditional core damage probability.

The routing of power and control cables for the fire protection systems is generally not established when conducting a fire PRA. Loss of a fire protection system because of the fire itself is seldom considered. This incident demonstrates that the fire suppression system may be lost due to the fire itself. Also, in a typical PRA, the unavailability of automatic suppression system is taken to range from 0.02 to 0.05 per demand (2-5% failure rate). It is not clear whether this unavailability includes the possibility of the system being left in the manual actuation mode by the operators or maintenance crew, as was the case in this incident.

Fire fighting activities were delayed by about 10 minutes because of procedural requirements to de-energize electrical equipment before entering a fire area containing electrical cables and equipment. In a fire PRA, the timing of fire brigade actions is typically based on the time that it takes for the brigade to arrive on the scene, ready with equipment. Delays in initiating fire fighting activities because of procedural requirements are not generally considered in a fire PRA. This incident also reiterates that it is possible to have a fire duration on the order of several hours.

The impact of water, and especially mechanical impact of water, on cables and the potential that this might lead to electrical shorts is not considered in a typical fire PRA. In this incident, shorts attributed to the hose streams occurred more than 2 hours after the ignition of fire. The basis for the assertion that the hose streams caused the problems must, however, be questioned. Given the severity and duration of the fire many short circuits would be expected in any case. Regardless of the cause, these shorts caused secondary fires. Such fires are not modeled in a fire PRA as noted above. In this incident, the secondary fire was also very severe and caused significant damage to the turbine building and contributed to the loss of offsite power. Furthermore, with the loss of the start-up transformer in addition to the generator oil fire, this incident demonstrates that secondary fires may occur at more than one location and can have catastrophic impact on equipment.

During this incident four apparent spurious actuation events were noted. In one, breakers spuriously actuated (closed) connecting both of the turbine generators to the power grid. The generators subsequently operated as motors causing further damage and secondary fires involving one of the generators. In the second, a main feedwater pump spuriously actuated apparently due to faults in the associated control cables. The fault bypassed the normal start logic, and allowed the pump to run without the associated lube oil pumps also running. The fault also bypassed or defeated the control room start/stop controls and attempts to stop the pump from the control room failed. The pump was shut down by electrical technicians who de-energized power from a local power bus. In the third case, a cable fault caused breakers for one of the diesel generators to open disconnecting the generator from its emergency loads. Attempts to recover the loads failed. The fourth case is associated with faults in the control room instrumentation circuits. Reports cite that instrumentation readings received in the control room were suspect (neutron capacity, neutron flux period and status of certain power busses). These false readings are cited as the cause for initiation of a Type I Emergency Protection Signal, apparently earlier in the shutdown sequence than would normally be expected (see note 3 at the end of the table in Section A7.3).

In each of the above cited spurious actuation events, there are no indications in the accident investigation reports about the specific nature of the cable failures that might have led to the observed system behaviors. The problems appear to be primarily associated with control and instrument cables, rather than power cables. In particular, a spurious pump start might result from cable-to-cable hot shorts in the power cables. However, in the case of the spurious feedwater pump start, the electrical technicians stopped the pump by isolating it from its power source. Because the pump did stop when its power source was cut, this implies no other power source was involved, and one can thereby infer that it was a control circuit fault that led to the actuation. In fire PRAs the treatment of spurious actuations due to cable faults is a current area of methodological debate. In particular, the likelihood that multiple spurious operations might be observed in a single incident remains a point of debate. This event and the Browns Ferry (1975) fire are the only two incidents identified in this review (or known to the authors) where there are clear indications that multiple spurious actuations did occur as a result of cable failures. For further discussion of spurious actuations in fire PRA, see the body of the report (Section 4.4.1).

A7.6 References

A7-1 Heikki Aulamo, Jouko Martilla and Heikki Reponen, “The Full Stories on Aremenia and Beloyarsk”, Nuclear Engineering International, July 1995.

A7-2 Correspondence between Mardy Kazarians and Ms. Marika Sarkisova of Armenian Nuclear Regulatory Agency, 1999.

A7-3 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A7-4 Soloviev.P.S. “Accidents and incidents in nuclear power plants”, Obninsk,1992.

A7-5 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A7-6 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 8 - Analysis of Rancho Seco Fire on March 19, 1984

A8.1 Plant Description

Rancho Seco was a 913 MWe Babcock and Wilcox design, pressurized water reactor located near Clay Station, California. The plant started commercial operation in April, 1975 and was permanently shut down in 1989. [Ref. A8-2].

A8.2 Chain of Events Summary

The plant was operating at 85% power on March 19, 1984 and had been experiencing problems with the automatic level control of the de-foaming tank and hydrogen side drain regulator tank of the main generator. The drain regulator tank level control was switched to manual mode, requiring direct operator level control. Operators apparently failed to provide adequate attention to level control and this allowed the main generator seal oil pressure to decrease. This in turn allowed hydrogen to escape from the generator. At 21:50 hydrogen gas exploded and started a fire (Reference [A8-1]).

The fire was detected immediately by plant personnel in the area. It was extinguished by the fixed automatic carbon dioxide system within 14 minutes. Nonetheless, significant damage was observed due to the fire. The fire damage happened in a relatively short time frame and is attributed primarily to the initial explosion and early burning.

A8.3 Incident Analysis

This fire is one of few turbine building fire incidents in the U.S. that has caused significant damage. The incident demonstrates the unique nature of the turbine building fire hazards, in this case a hydrogen gas leak and explosion, and the potential for fast developing fires that may cause damage despite effective operation of fire suppression systems. Fire PRAs do consider the risk contribution of turbine building fires. However, this incident illustrates that some special attention to more severe fires than might be reasonably postulated in other plant areas may be warranted for turbine building analyses. In this particular incident, the impact on plant operations and safety systems was apparently minimal, but the operation impact potential is a plant specific factor. That is, the presence (or absence) of safety significant equipment in the turbine building is plant specific.

In several of the other incidents reviewed here gaseous suppression agents have proven ineffective at extinguishing fires effectively. In particular, hand-held gaseous (CO2) fire extinguishers have been used unsuccessfully to fight a number of fires (e.g., Waterford 1995, Browns Ferry 1975). In this case, the system was a fixed gaseous discharge system that functioned as designed and suppressed the fire rather quickly. It would appear that the system intervened before the fire could spread to any other fuels (such as cables). More extensive damage would likely have occurred without the quick response of this system.

A8.4 References

A8-1 W. Wheelis, , "User's Guide for a Personnel Computer Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SNL/USNRC, August 1986.

A8-2 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix 9 - Analysis of South Ukraine, Unit 2 Fire on December 15, 1984

A9.1 Plant Characteristics

The South Ukraine Nuclear Power Plant (SUNPP) is located near Nikolaiev, Ukraine.[A9-4] The site has three operating units and a fourth unit "under construction."[A9-5] Each unit is a VVER 1000 type reactor. At the time of the fire, Ukraine was a part of the former Soviet Union. Unit 2 was in the last stages of construction when a fire inside the containment destroyed a large quantity of cables. Fresh fuel was loaded and the main vessel was closed off, but the reactor had not been activated at the time of the incident.

A9.2 Chain of Events Summary

On December 14, 1984, at 07:55 the operators for Unit 2 started to pressurize the containment in order to test its integrity and leak-tightness.[A9-1,2] On December 15, at 04:30, the containment was at an over-pressure of about 0.36 mPa.

At 09:00, operators noticed that one train of temperature instrumentation was not working. The temperature instrumentation trains were inspected outside the containment and no damage was noticed. At 10:47, the status of the pressurizer heaters was investigated. It was discovered that there was no resistance on power feed to 17 out of 28 heaters.

At about 11:40, plant personnel were checking electrical panels and noticed that several relay coils had caught fire. At the same time, plant personnel noticed that the pressure in the containment had increased from 0.36 to 0.38 mPa and no external causes could be identified for this phenomenon. The plant manager ordered the pressure in the containment to be dropped, and called out the fire brigade, surmising that the pressure rise may have been due to a fire inside the containment.

At 12:00, operators started to reduce the containment pressure using a 300 mm (approximately 12") diameter pipe specifically designed for this purpose. Operators noticed a burning smell and observed smoke in the air coming from the containment. However, the fire detector panel did not indicate the presence of fire inside the containment. Regardless of this observation, the plant personnel started setting up hoses to fight a fire.

At 12:10, the fire brigade arrived on the scene. On the control panels of 1st and 2nd safety trains operators noticed that containment pressure was not indicated properly. This was attributed to a short in the associated instrumentation circuit. The indicators on the panel for the 3rd safety train were not operating because of a "burned out" fuse (possibly another fire-induced fault but not clearly established in the reports).

At 13:20, the pressure in the containment reached atmospheric level. Plant personnel and fire brigade members entered the containment and discovered a fire in compartment A305/I,2. They attacked and suppressed the fire almost immediately.

At 13:45, the fire annunciator panel was realigned to properly indicate fire conditions. About this time, operators also noticed that the temperature in containment compartments A-503/I and A-505/I had reached 150ºC. An automatic suppression system apparently providing coverage for these areas was not functional at that time (it was switched to "manual" mode). Hence, the two compartments were approached by fire fighters with fire hoses.

At 17:00, all of the compartments where fires had occurred were inspected and the fire was declared as extinguished. The actual fire initiation time is not known. Most likely it started between 04:30 and 09:00 on December 15th. It was determined that the fire started inside containment in the cable tunnel for the second safety train. At 09:00, the first indications of abnormalities were noted. Assuming ignition at or shortly before 09:00, the fire duration was then approximately 10 hours.

The factors that influenced the occurrence and propagation of the fire were determined to be as follows (as cited in the available reports):

- The power cables passing through the containment penetrations were energized and powering the pressurizer heaters.
- Pressurization of the containment caused the wires inside the penetration to move and touch off a short circuit.
- Penetrations included un-isolated (un-insulated) wires or electrical feeds-throughs,
- At the time of the incident, the penetration area was wet; thus, causing a short between open wires.
- Pressurization increased the oxygen concentration (partial pressure) in the containment
- Arcing from cable to cable ignited a fire in compartment A305/2.
- Hot gases escaped into A305/1 from A305/2 through an opening between the two compartments and started the fire there.
- Long exposure to hot gases and flames damaged the seal in the ceiling at 22.8m elevation and allowed propagation of the fire to 2nd safety train cables in the upper elevation. This caused the fire to propagate into the cable shafts of the reactor building and the annulus at 32m elevation.

A9.3 <u>Incident Analysis</u>

The precise causes for fire ignition and extensive spread is not known. It is postulated that the fire started in an electrical penetration. In particular, it is suspected that pressurization of the containment caused the wires inside the penetration to move causing a short circuit and, presumably, an overload. Moisture in the area of the penetration may also have been a factor. Available reports state that the fire apparently started because of poor cable conditions and the mechanical damage that the cables had sustained inside the penetrations.

This conclusion is supported by observations made by plant personnel prior to the actual fire. That is, before this fire incident, a series of events and conditions were observed that can be regarded as pre-cursors to fire ignition. For example, arcing was noticed among cables in a cable tray. In another case evidence of severe heating was noticed in the cables. Therefore, it can be concluded that pressurization of the containment was merely the "trigger action" that caused pre-existing cable damage to be manifested as a fire. In any case, it would appear that short circuits in or near the penetration assembly led to cable current overloads and a self-ignited cable fire. In a typical fire PRA, such specific conditions leading to fire ignition are not modeled explicitly. Rather, the likelihood of fire ignition is established from statistical analysis of similar incidents in nuclear power plants across the industry. The specific conditions of a plant, at least at this level of detail, are seldom taken into account in estimating fire ignition frequencies. In a fundamental sense, the current PRA practice would capture the potential for self-ignited cable fires, albeit, the specific mechanism leading to onset of the fire would not be modeled.

With regard to detection, the detection mode in this fire incident is interesting. The fire detection system apparently had apparently been disabled in some manner or had an inherent deficiency. Operators correctly suspected a fire inside the containment based on the rising pressure and other observations. This can be cited as a rather astute observation on the part of the plant operators. Had the containment not been under pressure, manual fire brigade response would not have been delayed as long, and it is likely that the fire would not have progressed as far as it ultimately did.

The existence of the fire was verified only after depressurization started (based on the presence of smoke and odors in the exhaust stream). In fire PRA, the fire detection system is generally analyzed using industry-wide generic unreliability numbers. Special conditions that may lead to failure of the detectors to properly recognize the presence of fire may get addressed during a plant walkdown. However, current fire PRA methodology documents do not provide well defined guidance on how to determine conditions under which detectors may fail.

This is one of few major fire incidents that occurred inside containment. In fire PRAs it is generally assumed that containment fires are not risk significant. Containment structures are commonly screened with minimal detail in the early stages of a fire analysis. This incident neither negates nor supports that assumption from an operational perspective. It does, however, demonstrate that it is possible to experience a severe fire inside containment. Hence, some additional attention to screening bases for the containment may be appropriate.

The fire propagated via cables into cable shafts and the annulus. Hot gases had escaped from the compartment where the fire is presumed to have started through an opening into an adjacent room and started a fire there as well. Long exposure to hot gases and flames had also damaged a seal in the ceiling allowing the propagation of fire to a compartment at an upper elevation. An important insight from this incident is that the spread of fire to certain of the adjacent compartments was apparently caused by the spread of hot gases alone. Apparently, no direct paths for fire (flame) spread were identified that could have allowed fire spread into certain of the fire compartments. It is postulated in this review that fire-induced failure of energized cables due to the hot gas exposure may have provided the ignition source. This is conjecture, but is consistent with observations made during small-scale fire testing by Sandia National Laboratories.[A9-3] In fire PRAs, the possibility of propagation to other compartments is deemed to be unlikely unless large quantity of combustibles are present in direct proximity to a propagation path (such as a cable tray penetrating a fire barrier). This incident appears to show that cable fires can generate sufficient heat to propagate fire to adjacent spaces without a direct path for flame spread along a continuous fuel element. It must be noted that the combustion characteristics and qualification testing standards of the cables in Soviet-designed plants are not known to the authors of this report. It is possible that they are quite different from the U.S. cables and therefore, extrapolation of the conclusions from this incident to U.S. plants should be done with caution.

In this incident the fire suppressions system was switched to the manual mode and did not actuate. Had the system actuated early in the fire it is quite likely that the fire damage would have been much more limited. The system was never actuated during the incident, but the available information does not indicate the reasons for the operators not activating the systems manually. This either indicates the system was totally inoperable at the time of the fire, was rendered inoperable by the fire, or an error of omission on the part of the operators and fire fighters. It is reasonable to assume that while waiting for the containment to de-pressurize, fire fighters would have checked the status of the containment fire suppression systems. However, no clear discussion of this is provided in any of the available reports. Even late actuation of the suppression system would have likely reduced fire damage.

The observation of burning relays in panels outside containment indicates that shorts occurred in the power and/or control cables and caused the relay coils to overheat and catch fire. This can be regarded as simultaneous and/or secondary fires, albeit, in this case these secondary fires did not propagate. Fire PRAs do not consider multiple concurrent fires. This incident demonstrates the possibility of such incidents.

This incident is considered a severe fire because a large area of the plant was affected. More than 16 km of cables were burned in this fire. Ultimately, multiple safety trains were affected. If the plant had been in operation at the time of the fire, such a fire could have caused a severe safety concern.

It should also be noted that since the time of this fire, a number of plant improvements have been made. In particular, in cooperation with the U.S. Department of Energy (DOE), efforts are underway to improve “the safety of day-to-day operations at the plant. DOE projects are supporting the development of full-scope simulators to enhance operator training (1995-ongoing), performing in-depth safety assessments (1995-ongoing), and providing safety parameter display systems (1996-ongoing).”[A9-5]

A9.4 References

A9-1 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A9-2 Soloviev.P.S. “ Accidents and incidents in nuclear power plants”, Obninsk,1992.

A9-3 Nowlen, S.P., *An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables*, NUREG/CR-5546, USNRC, May 1991.

A9-4 *1999 World Nuclear Industry Handbook*, Nucl. Eng. Int., 1999.

A9-5 *Soviet-Designed Nuclear Power Plant Profiles*, USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 10 - Analysis of Zaporizhzhya, Unit 1 Fire on January 27, 1984

A10.1 Plant Characteristics

Zaporizhzhya is a six unit nuclear power plant site located near Energodar, Ukraine.[A10-4,5] All six units are of the VVER-1000 design. At the time of the fire described here, Ukraine was a part of the former Soviet Union. Plant construction on Unit 1, begun in 1980, was in its last stages when a severe cable fire occurred on January 27, 1984. As a result, the plant's initial operations were delayed until late 1984 (November[A10-4] or December[A10-5]). The plant began commercial operations in April 1985.[A10-4] At the time of the fire, some of the cable penetration seals were not installed yet, and there were other penetration seals that had been reopened for inspection. The other units at the site began operations between 1985 and 1995.

A10.2 Chain of Events Summary

On January 27, 1984, Unit 1 was in the last stages of construction and apparently the reactor was not activated yet. At 17:15, a fire was reported at elevation 13.2m of the Control Building. It was later postulated that a failure in the terminal box No. 114 had caused the fire. The features of the box and the nature of the initiating fault are not clear from the available information. The reports postulate that a loose item had fallen into the box.

The fire propagated via cables coming out of the terminal box and into a cable shaft where it started to burn its way up the cable risers. The fire eventually spread through practically all elevations of the control building. In response to the fire, the operators tripped the electrical system, including the DC power system.

All attempts to put the fire out in the initial stages failed. Two operators even tried to crawl under the smoke and approach the fire with hand held extinguishers, but they had to pull back because of the heavy smoke. Plant personnel and off-site fire brigades were summoned to support fire suppression efforts. Using a stairwell for positioning themselves, the fire brigade sprayed water at different points of the Control Building. However, since the fire brigade personnel were not familiar with the building layout, and because of the heavy smoke in the building, they were ineffective at fighting the fire in some locations, and the fire continued to propagate. In the end, over 115 fire fighters participated in the fire fighting effort.

Until 19:25, about 2 hours after ignition, the fire had remained confined to the cable shaft. At this point fire barriers failed and the fire propagated into areas adjacent to the cable shaft on four separate elevations (16.0, 19.0, 21.0 and 24.0 m). At elevation 16.0 the deluge system was activated (it is not clear whether this was done manually or automatically) and that controlled the fire on that level. The fire on elevation 20.0 m was stopped by the sprinkler system on that level. Although by 21:00 the fire at elevation 16.0 was declared extinguished, the fire continued to propagate to elevations 19.0 m and 24.0 m. On elevation 19.0 m, the fire was stopped by a sprinkler system. Despite the impact of fixed suppression systems at different elevations, the fire continued to propagate and by 21:40 it reached elevations 28.3 m and 41.0 m.

At 24:00 the fire was declared as out and the fire pump was stopped. However, at 01:15 on January 18, plant personnel noticed a cable fire at the 20.4 m elevation. This was apparently a re-ignition of the previously suppressed fire on this level. The fire pump was restarted and fire water was sprayed inside the impacted cable shafts and in cable chase areas. The fire fighting continued for another 11 hours and finally after more than 17 hours from the discovery of the fire, the fire was declared as completely extinguished.

A10.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A10-1] and [A10-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On January 27 1984, Unit 1 was in the last stages of construction. Some of the cable penetration seals were not installed yet and there were other penetration seals that were reopened for inspection. At this stage of construction, the automatic fire suppression system and fire detectors inside cable trays and cable shafts were not yet activated. The dry-pipes of the deluge system for cable trays and cable shafts were temporarily connected to a fire water system that required manual activation.	Construction often presents unique fire hazards and construction phase fires are often discounted in fire PRAs. In this case, the fire appears to offer valuable lessons despite the fact that the plant was still under construction. It does not appear that the fact that construction was ongoing had a significant impact on the fire's progression. In particular, it would appear that despite reports of incomplete fire barrier penetration seals, the fire did remain confined to the initially impacted cable shaft for two hours or more before spreading to adjacent areas.
00:00	At 17:15, a fire was observed at elevation 13.2 m of the control building. It had started in or near terminal boxes No. 112 and 114. As a result of incident investigation, it was concluded that the fire may have been caused by a short in 112-114 terminal box at elevation 13.2m. The short circuit may have started in a cable (it was suspected that something had dropped inside the terminal box).	This event can be classified as a self ignited cable fire. In fire PRAs for U.S. plants, the possibility of occurrence of self ignited cable fire is considered to be very unlikely. It is also interesting that the reports cite that the fault likely started inside the box and that the fire propagated to the cables outside the box. However, the condition of the cable penetrations into the terminal box are not known.
--	The fire propagated into a cable shaft	Vertical cable risers are recognized as a potential fire hazard in fire PRAs.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	As soon as the shift supervisor received news about the fire, he ordered the control room operators to initiate isolation of electrical devices.	Plants in the former Soviet Union typically require by procedure that power be isolated before fire fighters attack fires in electrical equipment. Since the plant was not in operation this likely had little or no real impact.
00:20	At about 17:35, a supervisor and his assistant crawled under the smoke towards the fire on elevation 13.2m and tried to extinguish the fire with hand held extinguishers. Their attempts were futile. Because of the heavy smoke, they had to retreat to safety.	In this case, the fire brigade had already been notified of the fire and called out. Hence, the attempts by operators to extinguish the fire would not have delayed the later response by trained fire fighters. However, the event illustrates that early intervention by un-trained or ill-equipped personnel may not be successful.
00:23	At 17:38 fire brigade arrived at the plant.	In a U.S. plant the primary fire brigade is on site, and a more rapid response would typically be assumed.
--	A fire pump was started manually.	
00:45	By 18:00, using the stairwell for positioning themselves, the fire brigade sprayed water at different points of the control building. However, since the fire brigade personnel were not familiar with building layout and because of the heavy smoke in the building, they failed to be effective and fire continued to propagate. At this time fire fighting was taking place from the cable spreading room for the 3rd train, half of the 2nd train cable shafts and the 2nd train cable spreading room.	
01:45	Until about 19:00, the fire fighting activities were neither systematic nor effective. It is stated in one report that the fire fighters often did not know whether the water they were spraying was directed at the fire or not.	The potential for fire fighters to spray water indiscriminately is recognized, but typically discounted in fire PRAs. Such behavior could lead to collateral damage to electrical equipment. In this case, a lack of adequate pre-fire planning and lack of fire brigade coordination were clearly contributing factors. The fact that primary fire brigades in US plants are made up of plant personnel would reduce the likelihood of similar behavior in the event of a fire.
02:10	Starting 19:25, plant personnel started from the lower elevations systematically looking for actual fires, so that fire fighting activities would be focused on actual fires.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:10	Until 19:25, the fire remained confined to the cable shaft and affected the cables there up to elevation 16.3 m. However, at this point propagation to adjacent areas apparently began.	Fire resistant construction of the cable shaft boundaries was the main reason for the fire to remain confined up to this point. Despite reports of incomplete barrier seals, the fire did apparently remained confined for up to two hours.
--	At elevation 13.2, the fire brigade fought the fire manually. At elevation 16.0 the deluge system was activated and that controlled the fire.	
02:15	By 19:30, the fire resistant barriers of the cable shaft failed and the fire propagated into new areas. It was discovered that the fire had propagated to elevation 20.0 m where it was stopped by the sprinkler system.	This is a case where a fire barrier may have been overwhelmed by the fire. In fire PRAs for U.S. plants it is common to assume that fire barriers will last for their full fire duration rating (typically three hours) and that fire of a duration that would exceed the rating are very low likelihood.
02:25	At 19:40, the chief engineer ordered the operators to trip 6kV boards BA, BB and BD (associated with safety trains 1 and 2) from the control room.	
02:45	At 20:00 plant personnel tripped the electrical system, including the DC power system at elevation 41:00m.	
03:45	By 21:00, the fire at elevation 16.0 was declared extinguished.	
03:45	By 21:00 (approximately), the fire propagated to elevations 19.0m and 24.0m of the Control Building. On elevation 19.0m, the fire was stopped by the sprinkler system on that floor.	
04:25	By 21:40 the fire propagated to elevations 28.3m and 41.0m of the Control Building.	
06:45	At 24:00 the fires were declared out and the fire pump was stopped.	
08:00	At 01:15 on January 18, 1st and 2nd safety trains were lost.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
08:00	At 01:15, plant personnel noticed cable fire at 20.4 m elevation. The fire pump was restarted. Water was sprayed inside the cable shafts and in cable chase areas. The power system was tripped.	This is one of the few incidents where fire re-flash well after initial extinguishment has been reported (some cases of re-flash immediately following suppression attempts have been reported). The main cause of the re-flash is postulated to be deep seated fire in the cable bundles that got exposed to fresh air. The possibility of re-flash is not considered in a fire PRA, however, given the apparent rarity of such events this may not be a significant oversight.
17:50	The fire was finally declared as completely out by 11:10 on January 18, 1999. More than 115 fire fighters were involved in this effort.	

Equipment Damaged:

- An electrical junction box (source of the fire)
- Large quantity of electrical cables

Damaged Areas

- Cable shafts and a large area of the control building were affected by this fire.

Impact on Core Cooling

- Safety related equipment was affected by this fire. The plant was in the last stages of construction. From the available information, it is not clear whether or not core cooling function was necessary. Had the fire occurred during plant operations, the impact on plant operations would have been severe.

Radiological Release

- No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A10.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events of the fire incident is compared to the elements that make up a typical PRA fire scenario. Entries are made only if specific information was provided by the available sources. No attempt was made to postulate a possible progression of the chain of events no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element/Issue	**Incident - Zaporizhzhya, January 27, 1984**	**Fire PRA Insights**
Presence of combustible / flammable materials	Cables were the primary sources of combustible for this fire incident. Materials in the initiating junction box also played a role in very early fire behavior.	It is claimed that the construction companies had used non-fire resistant cables and plastic materials inside the electrical junction boxes that contributed to the fire. In fire PRA it is assumed that a plant is constructed per set specifications. The possibility of manufacturers' error in using the wrong materials is assumed to be very unlikely.
Presence of an ignition source	A failure or foreign object in the electrical panel is suspected to be the main cause for fire ignition.	This is, in effect, a self ignited cable fire since there was no external fire exposure source.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	See above.	
Fire growth within the combustible or component of original ignition	Fire apparently established itself quite readily within the junction box.	The fire grew outside the initial junction box and spread via cable entering the top of the box.
Fire propagates to adjacent combustibles.	Fire propagated to other cables and continued to propagate for a long time..	Fire spread was apparently slow but steady during the initial growth period though no specific estimates are available. There is conflicting information however regarding how quickly the fire actually spread, in particular, in the time between 2 and 4 hours after ignition.
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information is provided regarding hot gases. However, given that the fire occurred in various compartments and cable shafts, hot gases should have played an important role in the propagation of the fire from one compartment to the other.	Clearly, a very dense smoke layer did form in the compartment of fire origin that prevented initial attempts to attack the fire. Smoke formation is commonly recognized a potentially delaying effective fire fighting activities.

Fire Scenario Element/Issue	**Incident - Zaporizhzhya, January 27, 1984**	**Fire PRA Insights**
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	In part because of incomplete penetration seals, the fire had the opportunity to propagate into other compartments. Smoke had a major impact on the fire fighting activities. Attempts were made by the operators to crawl under the smoke and extinguish the fire. But their efforts proved to be futile. Outside fire brigade members, because they were not familiar with the plant, had difficulties in fighting the fire in smokey condition. From the information provided, it can be inferred that the entire control building was affected by smoke.	The actual role of the incomplete penetrations may be overstated in the available reports since the fire apparently remained confined to the initial area for up to two hours. Some penetrations may have been overwhelmed by the fire. Fire PRAs generally consider fires of sufficient intensity so as to overwhelm a fire barrier as highly unlikely. In a fire PRA, smoke movement is not explicitly modeled. These events demonstrates it is important to include some consideration of smoke spread as part of the fire PRA analysis and include the propagation paths and their impact on recovery actions and fire fighting.
Local automatic fire detectors (if present) sense the presence of the fire	From available information it is inferred that fire detectors were already installed but were not activated yet.	The fact that the plant was still under construction was a factor in this event that would not be typical of an operating plant.
Alarm is sounded automatically in the control room, locally and / or other places	n/a	
Automatic suppression system is activated (if present)	From the information provided, it is inferred that fixed automatic water systems were present and functional at least in certain parts of the Control Building. The sprinkler and deluge systems controlled the fire in at least one and possibly two locations.	
Personnel are present in the area where fire occurs	Personnel were present at all parts of the plant where fire had propagated.	This fire was manually detected.

Fire Scenario Element/Issue	Incident - Zaporizhzhya, January 27, 1984	Fire PRA Insights
Control room is contacted or fire alarm is sounded	The fire was reported to the control room promptly upon discovery, but time of initiation is uncertain.	
Fire brigade is activated	Plant and outside fire brigades were activated to fight this fire. A total of 115 fire fighters participated in this incident.	There was no apparent delays in calling out the fire brigade.
Fire suppressant medium is properly applied	Water streams were applied at several different locations. From the available information it is inferred that the automatic sprinkler and deluge system at certain locations were successful to control the fire for that area.	From one report it appears that fire fighters were initially spraying water somewhat indiscriminately and were not certain where the fire actually was. Such behavior is commonly considered and dismissed as unlikely in fire PRAs.
Automatic fire suppression system is activated	See above	
Fire is affected by the suppression medium	The fires were ultimately affected by the water systems. It was brought under control at several locations and was declared extinguished by midnight. However, the fire re-flashed and the fire fighters had to start the fire pump again and continued to fight the fire until 11:00 the next day, when it was finally announced as completely out.	Fire fighting was not very effective apparently due to uncertainty as to where the fire actually was (see comments above).
Fire growth is checked and no additional failures occur	The fire growth could not be checked for a long time. It was thought that the fire had been brought under control at several points in the path of its growth. While fire fighting efforts seemed to be at least partially effective, fire growth continued for several hours. Contributing factors include combustibility of the cables, configuration of the cables (vertical risers) and the shape and inaccessibility of the compartments.	This is an incident where despite all the efforts of the fire fighters, the fire remained unchecked for a long time. In fire PRAs, the possibility of a fire lasting for several hours, while fire fighting efforts are seemingly effective, is deemed to be very unlikely. That is, it is commonly assumed that once fire fighting activities begin, the fire will be quickly brought under control.

Fire Scenario Element/Issue	**Incident - Zaporizhzhya, January 27, 1984**	**Fire PRA Insights**
Fire is fully extinguished and fire brigade declares it as out	The fire was declared as out at midnight. However, it re-flashed inside a cable shaft. It took the fire fighters another 11 hours to completely extinguish the fire.	The possibility of re-flash is not explicitly modeled in fire PRAs. However, it can be argued that since the models used are based on actual fire occurrence data, it empirically includes the possibility of re-flash. This event points out that if one were to model fire suppression in great detail should include the possibility of re-flash in that model.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	A large number of cables were lost. The available information does not provide sufficient information about the type of electrical circuits, equipment and systems that were affected.	
Cable failure impacts equipment outside the fire location	Several kilometers of cables were replaced, electrical panels were replaced. Cable failure had certainly impacted equipment outside the fire areas. However, the available information does not specify which cables and equipment were affected. Because of the extensive damage, the fire delayed plant startup.	In this case because the plant was still under construction the operation impact was apparently minimal. However, from the severity of the fire as described in the available sources and given that the fire damaged a large set of cables, it is inferred that if the fire had occurred during power operation, core cooling capability would have been affected severely.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	All three safety trains were affected either directly or indirectly because of operators' decision to switch off 6kV bus to minimize the hazards during fire fighting.	From the information provided, it can be inferred that all three safety trains were lost in this fire incident. Thus, if the fire had occurred after reactor activation, core cooling would have been severely jeopardized.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	No clear information available.	
Operators attempt to control the plant properly and bring the plant to a safe shutdown	n/a	
Structural failures (if occurred) may jeopardize availability of equipment	n/a	

Fire Scenario Element/Issue	**Incident - Zaporizhzhya, January 27, 1984**	**Fire PRA Insights**
Water when sprayed over electrical equipment may fail the exposed equipment	No information on this phenomenon.	As noted above, the fire fighters did spray water somewhat indiscriminantly. However, there are no reports of any damage. Given that the areas contained primarily cables, this is not unexpected (i.e., cables should not be vulnerable damage as a result of wetting).
The cooling effect of CO_2 may adversely impact equipment	n/a	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The plant was under construction.	As noted above, construction is widely recognized as presenting unique fire hazards and construction fires are routinely dismissed in fire PRA analyses. In this case, in the judgement of the authors, the fire behaved much as it likely would have had the plant been in operation. The one possible exception is with regard to fire spread through incomplete penetration seals as noted above.

A10.5 Incident Analysis

The root cause of this fire incident can be attributed to an electrical fault leading to a self-ignited cable fire. While the actual nature of the fault remains unclear, the available reports cite that the most likely explanation is that a fire started inside a terminal box due to either an external object shorting across bare terminals or a self ignited cable fire. The fire then propagated from the terminal box to associated cables entering the top of the box and from there into a cable shaft.

Self ignited cable fires can be regarded as rare occurrences. It is common to assume that the potential for such fires is tied to the specific characteristics of the cables, cable manufacturing practices and cable installation practices. In fire PRAs for the plants in the U.S. it is assumed that self ignited cable fires are implausible if IEEE-383 qualified low-flame-spread cables are used. In the case of Zaporizhzhya, the qualification standards of the cables and terminal boxes is not clear. Hence, this incident neither refutes nor confirms these assumptions.

It appears that the fire propagated rather slowly at first, but steadily. Some of the information reported for the time period between 2 and 4 hours after detection indicates that the fire may have spread more quickly during this period, but the information is somewhat contradictory. The cable risers in the cable shaft where the fire began were the main path for fire propagation. In many regards, this fire followed a “classical” initiation and spread behavior as commonly assumed in a PRA fire scenario. That is, the fire started quite small, propagated to adjacent cables, propagated to nearby cable trays and cable risers, and then spread unchecked until suppression efforts were begun. Hence, in this regard, a fire PRA would have likely postulated the potential development of a fire in the impacted compartment, at least up to the point that other fire areas became involved.

Initial attempts by operators to fight the fire were unsuccessful because they did not have proper gear to deal with the smoke. Subsequent efforts by the fire brigade were also hampered by smoke because fire fighters could not clearly identify areas of active burning. The fire fighters were initially somewhat ineffective in their attacks due in large part to the heavy smoke buildup. Other contributing factors include a lack of adequate pre-fire planning and unfamiliarity of fire fighters with the plant. Ultimately the fire managed to propagate upward to practically all Control Building elevations. This incident demonstrates the potential impact of smoke on fire fighting activities. In fire PRA, the impact of smoke on the fire fighters is not generally modeled explicitly. It is commonly assumed that once fire fighters arrive on-scene, they will quickly and effectively control and suppress the fire. It is quite common to base manual fire suppression times on the response time of the fire brigade without explicit consideration of the conditions they might encounter upon arrival.

Lack of fire brigade training and pre-fire planning is another interesting insight of this incident. From the available sources, the importance of this factor is not clear. In fire PRAs conducted in the recent years in the U.S., the training of the fire brigade is often reviewed in some level of detail (see for example Reference 10-3). In this case, there are also reports that fire fighters were spraying water despite the fact that they had no clear idea of where the fire actually was burning. The potential for misdirected suppression is considered, but commonly dismissed, in fire PRAs. This incident illustrates that the potential for such actions does exist and provides some indication of the circumstances under which this might be anticipated. That is, for fire PRAs careful consideration of the training of on-site fire brigades is confirmed to be both appropriate and important. Furthermore, it would also be appropriate to consider the level of cooperation, coordination and pre-fire planning that goes into interactions with off-site fire brigades that might be called upon to support fire fighting efforts at the plant.

The available reports cite that incomplete and unsealed penetrations were a factor in the fire spread. However, from the available information, it can be inferred that at least some nominally intact fire barriers were overwhelmed by the fire. This is inferred from the fact that the fire remained confined to the cable shaft for over two hours before propagating to various adjacent spaces. Hence, it is likely that many of fire barriers were intact and confined the fire, but that continued burning eventually overwhelmed some elements of the barriers and allowed the fire to propagate to adjacent areas. In fire PRAs for U.S. plants it is common to assume that all fire barriers are properly designed and installed to withstand the fire threats likely to be experienced in most areas. Furthermore, cables are not generally considered a high-hazard fuel source, so the likelihood that a cable fire would overwhelm a rated fire barrier would be assumed very small. It would be common in such cases to assign a small random failure probability to the barrier, typically on the order of 0.01 per demand. The applicability of the experience here to U.S. plants is unclear because of likely differences in Soviet versus U.S. barrier qualification and monitoring practices.

This is one of the few incidents where a long-term fire re-flash has been reported. There are other cases where initial attempts to suppress a fire have been unsuccessful and a fire has re-flashed immediately upon removal of the suppressant. This is particularly true in cases where hand-held gaseous extinguishers are used to fire electrical fires. However, this case is unique because of the time involved. In this case, over one hour after the fire was initially declared out reports were received that the fire in one area had re-ignited. It is likely that the main cause of the re-flash was deep seated burning in the cable bundles and exposure to fresh air. The possibility of re-flash is not considered in a typical fire PRA. However, it can be argued that since the models used in fire PRAs are based on actual fire occurrences, it empirically includes the possibility of re-flash. This event points out that if one were to model fire suppression in great detail should include the possibility of re-flash in that model.

This event offers little insight into the impact of a fire on plant operations and operator actions because the plant was still under construction and was not in operation. However, it can be inferred from the available reports that had the plant been in operation, the impact on plant operations would have been severe. All three safety divisions were lost during the fire. Hence, it is likely that core cooling functions would have been severely challenged.

A10.6 References

A10-1 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A10-2 Soloviev, P.S. “Accidents and incidents in nuclear power plants”, Obninsk,1992.

A10-3 Lambright, J., S. Nowlen, V.F.Nicolette, and M.P.Bohn, *Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues*, SNL/USNRC, NUREG/CR-5088, January 1989.

A10-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A10-5 *Soviet-Designed Nuclear Power Plant Profiles*, USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 11 - Analysis of Kalinin, Unit 1 Fire on December 18, 1984

A11.1 Plant Characteristics

Kalinin is nominally a four unit nuclear power plant site located in Tver Volga, Russia.[A11!3,4] All four planned units are VVER-1000 type nuclear power plants. Units 1 and 2 have been in operation since the mid-1980's, Unit 3 is under construction, and construction has been suspended on Unit 4.[A11-4] At the time of the fire, Russia was a part of the former Soviet Union. Plant construction on Unit 1 began in 1977, and the first criticality was achieved in April 1984. First power operations began in May of 1984, but commercial operations did not commence until June of 1985. The fire described here occurred in December 1984, approximately seven months after initial power operations but before commercial operations had commenced. Construction on the sister unit, Kalinin 2, had been underway for approximately two years but had not been completed at the time of the fire.

Typical of Soviet-designed reactors, the unit has two turbine generators and two control rooms. A main control is responsible for reactor operations while the second “central control room” is responsible for the power generation side of the plant. Also note that the Kalinin design includes three safety trains.

A11.2 Chain of Events Summary

On December 18, 1984, at 18:28, while Kalinin Unit 1 was producing power, a service water pump was being restarted after a major repair. Sparks became visible on the cover of the pump and “unknown sounds” came from the direction of the pump (as reported by workers in the area who had apparently been working on the pump). Later it was determined that on startup, the service water pump started to turn in the wrong direction (likely due to a phase reversal on the power supply connections). This caused the electrical control system to fail. An additional breaker failure caused a breaker cubicle fire and a 6 kV cable fire in the turbine building.

A machinist and electrician working in the service water pump area tried to trip the pump using the emergency switch, but the pump would not trip. They called the control room and asked operators to trip the pump from there. The control room operators were not able to trip the pump either. After this the workers observed arcing in the motor and the cable connection to the motor started burning near the wall. Since the associated power feed breaker did not open, the electrician called the Central Control Room that controls the electrical distribution system and asked operators there to de-energize the safety power train. The 6 kV power train was tripped and the service water pump stopped. However, by this point a fire had started inside the breaker cubicle for the service water pump. The workers tripped the associated transformer, opened the cubicle door and applied CO_2 onto the fire. They were apparently successful at suppressing the fire in this cubicle.

However, at 18:28 the turbine building personnel noticed a fire burning in a cable tray at -4.0 m elevation under Turbine B. A fire had ignited on a 6 kV cable at several locations along the cable. The available reports state that it is suspected that the 6 kV cable had manufacturing defects and was damaged because of improper cable pulling practices. Thus, its insulation had weakened or was damaged and was susceptible to failure. From this one can surmise that the combination of the damaged insulation and the overload condition resulting from the pump and breaker problems combined to cause a self-ignited cable fire in the subject cable.

Plant personnel started the fire fighting process immediately and called for the off-site fire brigade. At 18:37 the fire brigade arrived on the scene and a full scale fire fighting effort started. By 20:12 (1 hour 46 minutes after the first alarm in the control room) the fire was considered under control and by 21:20 the fire was declared to be completely extinguished.

The automatic fire suppression systems functioned as designed although it was apparently ineffective. The fire fighting was done in severe smoke conditions using SCBAs. To vent the heavy smoke from the turbine building, several windows were broken. The hydrogen was drained from the generator and the 6 kV buses were de-energized.

A11.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A11-1] and [A11-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On December 18, 1984, the unit was operating at power.	
00:00	At 18:28:36 the control room received an alarm.	
--	Service water pump NTN-3 was being put back on line after a major repair. Sparks became visible on the cover of the pump and unknown sounds came from the direction of the pump.	Electrical fires are typical of the fire sources postulated in a fire PRA. The exact mechanism of initiation is not considered, but rather, fires are postulated based on statistical analysis of past fire experiences.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The machinist and electrician who were on the scene tried to trip the pump using the emergency switch, but the pump did not trip. They called the control room to trip the pump from there. The control room operators were not able to trip the pump either. After this they observed several arching in the motor and the cable connection to the motor started burning near the wall.	The breaker for the service water pump was later found to be in the test mode. This reduced the opportunity for mitigating the ignition processes before the fire could occur. Such details are not generally modeled in a typical fire PRA. The fire occurrence frequency is based on all recorded fire events and therefore, in theory includes human errors leading to fires.
--	The electrician called the Central Control Room asked them to isolate the safety power train. The 6kV power train tripped on protective breaker opening. It is not clear whether the operators tripped the breaker or it tripped on over-current.	
--	Fire was noticed inside the breaker cubicle for the service water pump. The technicians tripped the transformer and opened the breaker cubicle and applied CO_2 into the cubicle.	
00:00	At 18:28 fires were discovered in the cable trays at -4.0m elevation of the Turbine Building under turbine B. Fire had ignited at several places on a 6kV cable. It was later determined that the motor of Service Water Pump NTN-3 had rotated backwards. This had caused the electrical control system to fail, and lead to a demand for breaker trip. The breaker failed to open and this led to overcurrent condition in the 6kV cable. It was also suspected also that the 6kV cable had manufacturing defect and was damaged because of improper cable pulling practices.	In this incident, effectively there were three ignitions -- the service water pump, switchgear cubicle and 6kV cable. On the cable itself there were several ignition points. Thus, multiple simultaneous fire took place in this incident. Fire PRAs do not generally address multiple fires. It is assumed that all fires occur independent of each other and therefore their simultaneous occurrence is very unlikely.
00:02	The generator tripped offline.	
--	Plant personnel started the fire fighting process.	
--	The security personnel were notified.	
--	The automatic fire suppression systems in the turbine building functioned as designed.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:09	At 18:37 the fire brigade arrived at the scene.	
--	The fire fighting was done in severe smoke conditions using SCBAs. To remove smoke windows had to be broken.	Smoke hampering of fire fighting activities is often considered, but typically discounted, in fire PRAs. In this case, fire fighting may was hampered by the smoke.
--	The hydrogen was drained from the generator and 6kV bus bars were tripped.	This successful action potentially prevented a much more severe fire.
01:46	By 20:12 the fire was brought under control.	This is a relatively long fire in comparison to fires commonly postulated in fire PRAs. The possibility that a fire might burn for more than about 30 minutes is considered remote.
02:52	By 21:20 the fire was declared as completely extinguished	

Equipment Damaged

– 6 kV switchgear
– Service water pump motor
– Electrical cables below turbine B

Damaged Areas

– The switchgear and pump fires were localized to equipment of origin. The cable fire inside the Turbine Building affected a large number of cables.

Impact on Core Cooling

– Available sources do not specify the impact on core cooling functions.

Radiological Release

– No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

– There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

– The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

– There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A11.3 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events of the fire incident is compared to the elements of a typical PRA fire scenario. Entries are made only if specific information was provided by the available sources. No attempt was made to postulate a possible progression of the chain of events no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Kalinin 1, December 18, 1984**	**Fire PRA Insights**
Presence of combustible / flammable materials	The combustibles that were affected in this incident included the motor winding of service water pump NTN-3, the breaker cubicle serving the service water pump, the 6kV cables under Turbine B.	These are common combustibles that are considered in fire PRAs
Presence of an ignition source	The ignition source for was electrical overload aggravated by a breaker that failed to open.	Self-ignited cable fires are considered in fire PRAs but are judged to be unlikely events.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The following three fires occurred: - The service water pump motor threw some sparks (minor) - Switchgear cubicle serving the pump caught fire - 6kV power cable under Turbine B caught fire at several locations.	Simultaneous occurrence of several ignitions at different parts of the plant is not modeled by current fire PRA methodologies.
Fire growth within the combustible or component of original ignition	The service water pump stopped sparking as soon as the power was cut off from it. The switchgear fire was quickly suppressed by technicians at the scene and did not propagate. However, the cable associated with the pump caught fire did spread to other nearby cables.	The fire under the turbine was the only fire that saw significant propagation. Hence, while multiple fires did occur due to a common cause, only one really had any substantial impact on the plant.
Fire propagates to adjacent combustibles.	The cable fire in Turbine Building propagated to adjacent combustibles and grew to a considerable magnitude.	
A hot gas layer forms within the compartment of origin (if conditions may allow)		
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Large quantities of dense smoke were emanating from the cable fire in the Turbine Building.	There are no reports of any adverse fire effects in areas other than the turbine building.

Fire Scenario Element	**Incident - Kalinin 1, December 18, 1984**	**Fire PRA Insights**
Local automatic fire detectors (if present) sense the presence of the fire		
Alarm is sounded automatically in the control room, locally and / or other places	Operators did promptly activate the fire brigade upon initial reports of a fire.	
Automatic suppression system is activated (if present)	The automatic fire suppression systems activate as designed, but did not extinguish the cable fire.	In this case, a gaseous suppression system failed to either control or extinguish the fire. The design characteristics or the system are not, however, known so this failure cannot be clearly extrapolated to other cases.
Personnel are present in the area where fire occurs	Plant personnel were present in the service water pump and switchgear area and in the Turbine Building	Personnel did detect the fires and reported promptly to proper authorities (the main control room). In one case (the switchgear) these personnel apparently suppressed the fire as well.
Control room is contacted or fire alarm is sounded	Control room was contacted by the mechanical and electrical technicians who were at the service water pump area and were trying to startup a pump for the first time after a major repair. The contacted the control room to open the breaker for the pump but control room efforts failed. They later contacted the electrical control room and asked for the associated switchgear to be tripped, which was done successfully.	
Fire brigade is activated	The plant personnel and the plant fire brigade fought the fires.	The fire brigade was activated quite early in the incident and apparently responded within a short time period (several minutes). This is consistent with typical PRA assumptions regarding fire brigade response times.
Fire suppressant medium is properly applied	The fire brigade applied the fire suppressant properly.	There are no reports of collateral suppression damage.
Automatic fire suppression system is activated	Automatic fire suppression system is activated as designed.	While the system activated it was apparently ineffective.

Fire Scenario Element	**Incident - Kalinin 1, December 18, 1984**	**Fire PRA Insights**
Fire suppressant medium is properly applied to where the fire is.	The brigade had to work in dense smoke conditions. However, no fire brigade errors are noted.	The impact of heavy smoke on fire fighting effectiveness is not explicitly modeled in most fire PRAs.
Fire is affected by the suppression medium	With the help of the fire brigade the fire was brought under control in one hour and 46 minutes after the initial alarm in the control room and it was declared as completely out at 2 hours and 52 minutes after initial alarm.	Typical assumptions assume that fires will be very quickly suppressed once fire fighting begins. In this case the fire continued to burn despite active fire fighting efforts.
Fire growth is checked and no additional failures occur	The fire was brought under control in one hour and 46 minutes after the initial alarm in the control room	
Fire is fully extinguished and fire brigade declares it as out	Fire was declared as completely out at 2 hours and 52 minutes after initial alarm.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	There was apparently substantial fire damage, but the damage was confined to non-safety systems and equipment. Windows were broken intentionally to help in ventilating the Turbine Building to minimize the amount of smoke.	Actions outside the established procedures are not credited in a fire PRA. For example, in case of heavy smoke in a compartment, credit would not be given to the possibility of breaking windows to ease the density of the smoke.
Cable failure impacts equipment outside the fire location	The available sources do not provide information regarding this matter. There was apparently little damage to safety systems or components.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	no information	
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	no information	

Fire Scenario Element	**Incident - Kalinin 1, December 18, 1984**	**Fire PRA Insights**
Operators attempt to control the plant properly and bring the plant to a safe shutdown	no information	
Structural failures (if occurred) may jeopardize availability of equipment	None reported	
Water when sprayed over electrical equipment may fail the exposed equipment	no information	
The cooling effect of CO_2 may adversely impact equipment	n/a	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	None reported	

A11.5 Incident Analysis

This particular event was included in the current review largely because, from a classical fire protection engineering standpoint, the fire was rather severe. The fire burned for nearly two hours, produced copious amounts of smoke, required several fire fighters working in somewhat harsh conditions to suppress, and apparently caused some substantial physical damage to the plant. However, the operational impact of this fire was apparently modest, and plant operators appear to have responded appropriately to the fire incident. This again illustrates that not all large or prolonged fires will lead to significant nuclear safety challenges.

This observation is fully consistent with current PRA methods. Many fire areas are routinely screened from a fire PRA on the basis of minimal potential for operational impact. This commonly includes the screening of, in particular, turbine halls which are widely known to present severe fire hazards from a classical fire protection standpoint. This event provides confirmation of the general validity of this approach. In this case, there was apparently no safety significant equipment threatened by the fire, and a fire PRA would have likely concluded that even a prolonged fire would represent a very small risk contributor, provided of course that the fire remained confined to the turbine hall as it did in this case.

It is also interesting that in this incident there were, effectively, three fires at three different locations of the plant caused by the same root failure. The three locations are as follows: the service water pump itself, a switchgear cubicle, and a 6 kV cable. The common link was association with the same electrical circuit. Of the three fires, the most serious was the self-ignited cable fire in the turbine building. For the cable, there were actually several ignitions along the length of the cable, although all were in the turbine building. Thus, multiple, simultaneous fires took place in this incident. Fire PRAs do not address multiple fires. It is assumed that fires occur independent of each other and therefore simultaneous occurrence is very unlikely.

This case also involves a self-ignited cable fire. Such fires are commonly considered in fire PRAs, but are typically dismissed for newer plants and in cases where cables are certified as low flame spread per the IEEE 383 testing standard. This particular event confirms the potential for self-ignited cable fires in a very general context, but neither confirms nor refutes the assumptions regarding low flame spread cables.

A11.6 References

A11-1 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A11-2 Soloviev, P.S. “Accidents and incidents in nuclear power plants”, Obninsk,1992.

A11-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A11-4 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 12 - Analysis of Maanshan, Unit 1 Fire on July 1, 1985

A12.1 Plant Description

Maanshan is a two unit nuclear power station located near Herng Chuen, Taiwan. Both units are 890 MWe Westinghouse design, pressurized water reactors. Unit 1, where this fire incident occurred, started commercial operation in July 1984. The sister Unit 2 began commercial operation in May of 1985, just two months before the subject fire in Unit 1.

A12.2 Chain of Events Summary

While operating at power, a turbine blade failure occurred on July 1, 1985 at Unit 1 [ref. A12-1]. As a result of the imbalance, the turbine shaft came to a halt within a few seconds. The vibration caused by the loss of turbine balance, broke the generator seal allowing hydrogen to escape and seal oil to spill inside the turbine building. Both the hydrogen and the seal oil ignited starting fire inside the turbine building. The fires caused significant damage and the plant remained shutdown for repairs close to 11 months.

The heat detectors in the turbine building responded to the fire and the automatic carbon dioxide fire suppression system activated. The system was apparently ineffective. The local fire brigade was summoned and arrived about 1 hour after the turbine failure. The fire fighters experienced some difficulties and additional delays due to a failed fire protection system valve. Water was sprayed on the fire starting about 1 hour after turbine failure. The fire was apparently so intense that the fire fighters had to keep some distance. The fire was declared as completely extinguished about 10 hours after turbine failure.

The turbine failure also led to reactor trip. Although some electrical cables and motor control centers were affected, no safety related equipment were affected and there was apparently no adverse interference with reactor shutdown and core cooling capabilities.

A12.3 Incident Analysis

In this incident a relatively severe turbine building fire occurred because of turbine blade failure. However, despite a severe and prolonged fire causing extensive physical damage, the incident did not have an adverse effect on plant safety. The plant was shut down reportedly with little or no real challenge to nuclear safety. This incident confirms the conclusion that is often reached in fire PRAs; namely, that the turbine building can often be screened out as risk insignificant. This is a case where this conclusion would have been valid, although the actual risk significance of the turbine hall is plant specific depending on what equipment (including cables) is housed within or passes through that area.

The incident is included in this study because it does represent a major turbine building fire incident of a similar nature to others considered in this review (e.g., Narora and Vandellos). That is, a turbine blade failure leading to release of both hydrogen and oil and a resulting fire. As in other cases the fire was apparently severe and lasted for several hours. This incident does serve to illustrate that there are two quite distinct criteria for judging the severity of a fire incident. In the classical fire protection engineering sense, this fire was quite severe. However, from a nuclear safety standpoint, the fire had a very minimal impact.

A second aspect of this fire that is of interest is the apparent ineffectiveness of the carbon dioxide fire suppression system. While the system did actuate as designed, it was ineffective at either suppressing or controlling the fire. It is not, however, known how the system was designed. For example, CO2 systems are commonly designed as total room-flooding systems, but may also be used to protect locally against fires involving fixed sources. Given a space with the volume of a typical turbine hall, it would be quite unusual to provide a total flooding system. Hence, it is likely that the system was either provided as “point” protection, or was designed to protect specific zones within the larger turbine hall. Given these uncertainties it appears inappropriate to draw conclusions from this aspect of the incident.

A12.4 References

A12-1 W. Wheelis, , "User's Guide for a Personnel Computer Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SNL/USNRC, August 1986.

Appendix 13 - Analysis of Waterford, Unit 3 Fire on June 26, 1985

A13.1 Plant Description

Waterford 3 is a single unit pressurized water reactor (PWR) located near Taft, Louisiana. Unit 3 is the only nuclear power unit on the site (Units 1 and 2 being separate conventional units). The unit is rated at 1104 MWe and started commercial operation in September 1985. The fire being reviewed here occurred on June 26, 1985, after initial power operations had begun but prior to the commercial operation date [Ref. A13-2].

A13.2 Chain of Events Summary

On June 26,1985 the plant was operating at power, when a fire occurred in one of the main feedwater pumps. An electrician notified the control room that smoke was emanating from main feedwater pump A. An operator was dispatched to the scene and reported back to the control room that the pump was on fire. Control room operators tripped the cited pump, started reducing reactor power and declared an unusual event was underway.

Five minutes after the initial report of a fire, the control room was notified that the fire was actually in main feedwater B, rather than pump A as previously reported. As a result the control room operators immediately tripped the turbine, which in turn caused the reactor to trip. Since both main feedwater pumps were secured, the steam generator level dropped below the emergency feedwater system setpoint.

The fire brigade was activated upon confirmation of the fire. They used a local hose station and water streams to fight the fire and managed to extinguish it in about 10 minutes. The fire was limited to a small portion of the outer wrapping of insulation on the feedwater piping and was attributed to design and fabrication error.

A13.3 Incident Analysis

In most senses this fire was relatively small and, overall, the challenge to nuclear safety during the incident was relatively minor (a reactor trip with all safety systems available). The interesting aspect of this incident is that operator/personnel error led to an initial report identifying the wrong pump as the one on fire. As a result, the unaffected pump was first tripped, and eventually both main feedwater pumps were tripped. Although only non-safety related trains were involved in this incident, it provides an interesting insight into the possibility of indirect impact of fire on multiple train availability. That is, a fire for various reasons, may lead to unaffected trains being taken out of service. In this case the cause was operator error.

In this incident, the operator actions would be classified as an error of commission. That is, rather than failing to take a desirable action, the operator in this case took an action that was undesirable. Fire PRA methodologies are capable of identifying conditions where an operator action may exacerbate the situation (i.e., errors of commission). However, currently such scenarios are seldom considered in either general or fire PRAs. More likely is that a fire analysis of this scenario would have assumed a random failure probability for the unaffected pump, commonly a very low value. Human reliability methods currently applied are widely recognized as providing poor treatment of errors of commission.

A13.4 References

A13-1 W. Wheelis, "User's Guide for a Personnel Computer Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SNL/USNRC, August 1986.

A13-2 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix A14 - Analysis of Fort St. Vrain Fire on October 3, 1987

A14.1 Plant Characteristics

Fort St. Vrain is a single unit High Temperature Gas-cooled Reactor (HTGR). The power rating of the plant is 1,250 Mwe provided by one turbine generator. Plant construction began in 1968, commercial operation began in 1979, and the plant was permanently shutdown in 1989. [Ref. A14!3].

A HTGR reactor uses graphite as a moderator and helium gas for heat removal from the core. Fort St. Vrain had two main cooling (helium) loops. The helium, after passing through the core, flowed through the two steam generators (one per cooling loop). Motive power for the helium was provided by two steam driven circulators for each loop. The steam for the circulators comes from the discharge of the high pressure turbine of the turbine-generator. The steam is passed through the steam generators once more for superheating before it is taken to the intermediate and low pressure turbines.

The control room is located at the north end of the Turbine Building (see Figure A14-1). It is isolated from the open part of the Turbine Building by doors. The control room has four doors: 1) the west door on the south wall opens directly into the turbine area, 2) a double door, also on the south wall, is labeled in Reference [A14-1] as “non-opening”, 3) an east facing door next to the south wall that opens into a corridor type area that includes a door into the turbine area, and 4) a door on the east wall that opens into the locker room in Building 10.

A14.4 Incident Summary

On October 2nd, 1987 the plant was coming out of a long outage and was in the midst of its initial power ascension. As part of this process, the operators closed a hydraulic valve in the turbine building, when they noticed a drop in hydraulic oil pressure. An inquiry into the causes of this drop discovered that a filter bowl (canister) had failed and high pressure oil (about 3,000 psig) was spraying (close to 15 feet distance) onto hot exposed steel. The petroleum based hydraulic oil ignited starting the fire. The temperature of hot surfaces were above the auto-ignition point of the oil. The equipment operator who discovered the fire initially succeeded in extinguishing the fire using a portable dry-chemical extinguisher. However, since he did not close the valve feeding the failed filter, the oil continued to spray and re-flashed (re-ignited). By this time the size of the fire was relatively large (estimated as 8' x 3').

Plant fire brigade was called on immediately. An outside fire department was also asked to respond. A reactor operator was dispatched to the Reactor Building to close the two control valves for the hydraulic system to cut off the supply of oil to the failed filter. This operator managed to close one of the two valves immediately. The handle for the other valve was missing and therefore, some delay occurred in cutting off the oil from the fire. As soon as the oil was cut-off, the fire was extinguished and the operators managed to close off and isolate the failed filter and activate the available hydraulic system train.

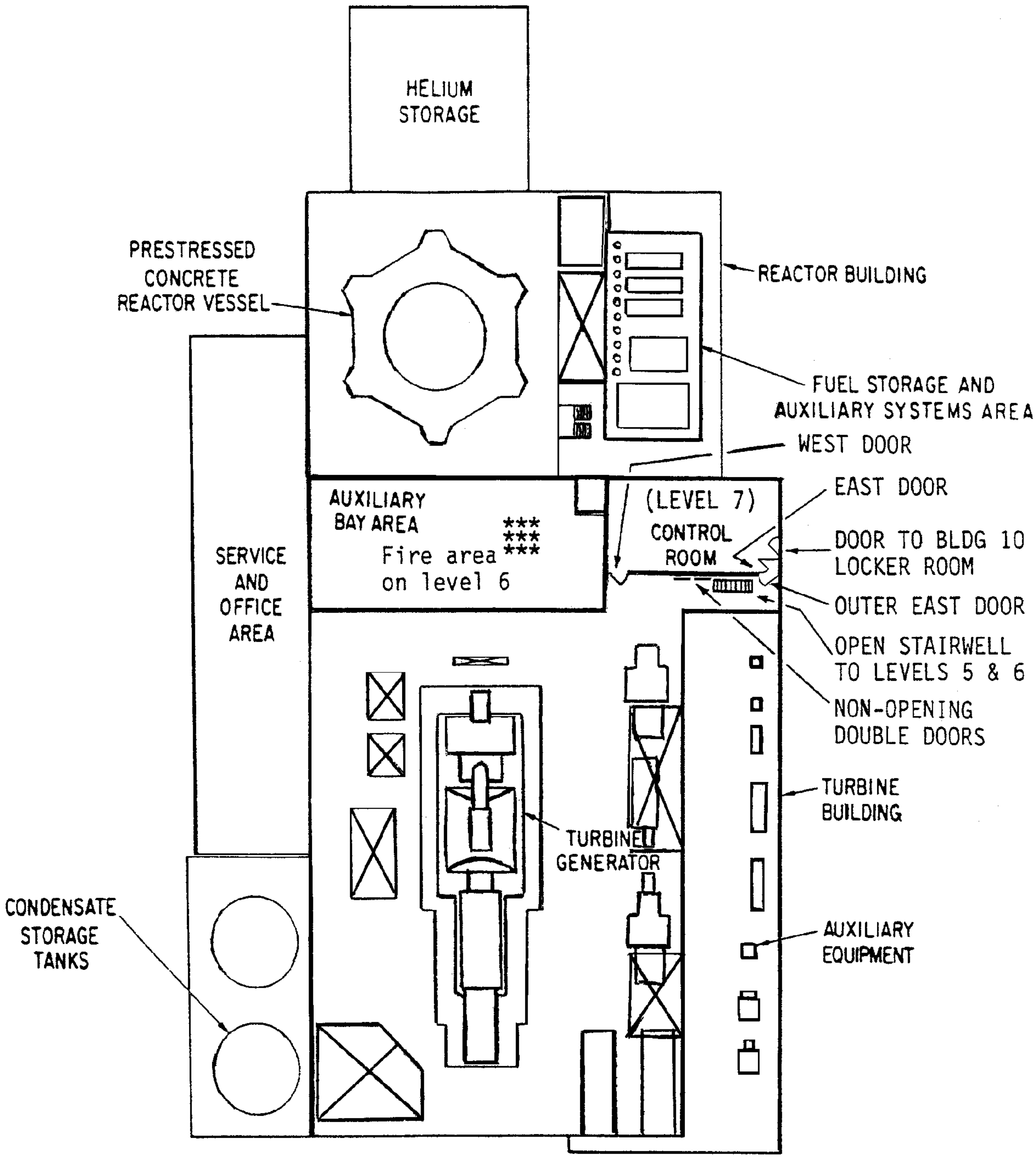

Figure A14-1: Plan view of the reactor building and turbine building including fire area on Level 6 and control room on level 7 (from Reference A14-1).

The damage caused by this fire was limited to the immediate area of the fire at the north end of the turbine building. Several cables were damaged that had some effect on the control room. Valves, instruments and structural elements were affected by the fire. However, there was minor impact on plant shutdown and reactor cooling capability.

The fire had some impact on control room habitability. Apparently large quantities of smoke were generated from burning oil and cables, that affected the initial fire fighting efforts. The cables damaged by the fire caused the control room ventilation system to shift to radiation emergency mode. Also, cable damage caused loss of electric power at the fire location rendering electric motor driven smoke ejectors useless. In this mode, the system shifts to suction from the turbine building. It therefore, drew some smoke from the turbine building into the control room. The operators, within two minutes of ventilation system shift, turned the ventilation system into the purge mode. However, smoke continued to enter the control room because positive pressure in the room could not be maintained due to frequent use of the door between the control room and the turbine building. The operators had to prop open the door separating the control room and Building 10 to allow fresh air to be drawn into the control room.

The control room was equipped with a piped-in Breathable Air System that provided fresh air via a common air supply header and individual masks for operators. Although the system was designed for 6 masks, only three were available during the incident and there were six operators in the control room. Scott Air Pacs were also available to the operators to make up for the shortage of masks.

A14.3 Detailed Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [14-1] and [14-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On October 2, 1987, the plant was coming out of a long outage and was in the process of power ascension.	

Prior to the incident	The audible alarm of the fire detectors located in the control room were turned off because of too many nuisance alarms.	In fire PRA such plant specific conditions are expected to be discovered during the plant walkdown. Typically an overall fire detection and suppression model is used to encompass all possible ways that detection and suppression is delayed or failed.
Prior to the incident	At 23:50, control room operators noticed that after activation of a major hydraulic valve hydraulic oil system pressure did not recover back to its normal 3,000 psi pressure.	In fire PRA, credit is seldom given to operators using indirect methods for discovering an adverse condition. This type of behavior is difficult to quantify.
Prior to the incident	At 23:51, a turbine equipment operator was dispatched to identify the causes for oil pressure drop.	
Prior to the incident	At 23:55, the turbine equipment operator reported that there was oil flowing into the catch basin under the turbine. This is located at level 5 of the turbine building. The oil was coming from a failed filter bowl of the hydraulic oil system at level 6. The oil was spraying out of the bowl for a distance of about 15 feet onto 20" diameter hot reheat piping and 2 associated reheat check valves..	
--	The equipment operator noticed a fire	
00:00	At 23:59, the equipment operator reported a fire at level 6 involving the sprayed oil. The ignition source was later found to be exposed hot steel parts of relief valves that could not be insulated. The auto ignition temperature of the oil was 620F. The hot surfaces of exposed reheat piping were between 680 and 690 F.	The fire source/cause is relatively common for a turbine hall fire, leaking lube oil, but PRA fire modeling rarely considers high pressure spray fires and would generally treat such fires as pool fires only.

--	The turbine equipment operator, who happened to be a member of plant fire brigade, discharged one bottle of dry chemical fire extinguisher at the fire, which extinguished the flames. He could not however reach an isolation valve to stop the flow of oil to the filter. The fire re-ignited. This time it was larger than the previous fire. The dimensions of the fire are estimated in one report as 8 feet by 3 feet. The equipment operator had to retreat from the area because of heavy smoke.	As mentioned above, in fire PRA under some methods an overall statistical probability model is used to account for all possible ways that fire detection and suppression may be delayed or failed. The possibility of failing to put a fire out in the initial stages of a fire fighting scenario is included in the overall suppression time. However, other methods might have given substantial credit to initial suppression efforts that may not be appropriate for this situation (a rapidly developing oil fire). Also note that the fire itself prevented the operator from shutting down the oil flow locally. As a result, oil continued to feed the fire. A typical fire PRA would not have credited this action because it required actions near the fire source.
00:01	At 00:00 (October 3rd) a reactor equipment operator was dispatched to level 1of the reactor building to manually close two control valves on the hydraulic oil supply to the entire system to stop the flow from the ruptured filter bowl. He managed to close one valve immediately and since the handle was not attached on the other valve, had to leave the area, find a wrench and then close that valve as well. He completed this task at 00:13.	A quality fire PRA, as part of the human actions analysis, would conduct a walkdown of the actions and potentially discover a missing valve handle. This incident demonstrates the importance of conducting such walkdowns. Consideration of the possible need to shut down the oil flow system from this remote location is, however, a subtle point that might easily be missed in a fire PRA.
00:02	At 00:01, the operators decided to start lowering the speed of recirculator D in anticipation of its shutdown because of hydraulic oil valve closure.	
00:04	At 00:03, outside fire department was contacted for assistance.	
--	Smoke leaked into the control room under the door opening into the turbine building.	
--	The equipment operator who had discovered the fire, went back to the fire area after donning fire brigade protective clothing and SCBA. He attacked the fire with a hose using a fog nozzle.	
00:05	Fire brigade arrived on the scene and attacked the fire using hoses from a different angle than the equipment operator who had discovered the fire.	
--	The smoke hampered the initial fire fighting efforts. Also, loss of electric power caused by the fire rendered the use of electric motor driven smoke ejectors useless.	

00:07	At 00:06, the "C" circulator tripped because of internal causes. Given the circulator "D" was coasting down, effectively the second reactor cooling loop was completely tripped.	
00:09	At 00:08, loop 1 circulators shut down because of loss of power to instruments caused by the fire.	It is interesting to note that a loss of instrument power is cited as the cause for loss of the loop 1 circulators. In a fire PRA, systems may be credited with continued operation even if the associated instrument circuits are lost.
00:09	Cable faults caused by the fire, shifted the control room ventilation system to minimum makeup mode from the Turbine Building. This allowed smoke from the Turbine Building to enter the control room.	In a quality fire PRA, the failure modes of a ventilation system should be studied. If such a study is undertaken, the possibility of ventilation system drawing smoke into the control room would be discovered. This is, however, a rather subtle aspect of the fire that might easily be missed in a PRA.
00:10	At 00:09, the operators initiated a manual scram because of indicated loss of primary and secondary cooling flow.	
00:11	At 00:10, the control room ventilation was manually shifted to purge mode to clear the light smoke entering the room. Air masks from a central Breathable Air System were distributed among the operators. However, an insufficient number of masks were available and operators had to share the available masks.	In fire PRA, in case of smoke in the control room it is conservatively assumed that the room is inhabitable. Therefore, lack of availability of sufficient number of working breathing masks would not be explicitly addressed, but the analysis may have assumed evacuation instead. Only a detailed fire risk analysis of the control room would identify such problem areas.
--	The door between the control room and building 10 was propped open to allow fresh air to enter the room and clear the smoke.	In a typical fire PRA no credit is given (conservatively) to the possibility of taking actions outside the normal procedures. As mentioned above, in the case of smoke in the control room., it is assumed that the operators will leave the room.
00:13	At 00:12, the operators placed the "B" (motor-driven) feed pump into operation.	The actions require to accomplish this recovery are not discussed.
00:14	At 00:13, the reactor equipment operator in the Reactor Building succeeded in closing the second hydraulic oil valve shutting off the source of oil to the fire.	
00:16	At 00:15, the fire was extinguished, but heavy smoke remained in the turbine building.	
00:26	At 00:25, Platteville Fire Department arrived on site	In this case, the fire was out before the off-site fire brigade arrived. The estimated response time is 23 minutes.
--	Smoke cleared from the control room.	

00:31	An ALERT was declared.	
00:41	At 00:40, certain phone lines to the plant were found to be lost because of fire damage to the cables.	In fire PRA, the availability of communication system is not explicitly modeled. Loss of the phone system would impact the possibility of contacting personnel who are not on-site. In a typical human action analysis in a fire PRA the possibility of calling in off-duty operators is not taken into account. Since most accident scenarios are modeled assuming an average number of operators in the plant, this omission is conservative.
01:31	At 01:30, the hydraulic oil isolation valve that had been engulfed in the fire was closed.	
01:36	At 01:35, the reactor equipment operator was dispatched to open one of the two hydraulic oil control valves from the Reactor Building.	
01:46	At 01:45, the Loop 2, Group 1 hydraulic header was returned to service. No leaks were discovered.	
01:59	At 01:58, the Technical Support Center was declared operational.	
03:51	At 03:50, the Forward Command Post was declared operational.	
06:03	At 06:02, it was verified that two independent safe shutdown paths were available and normal cooldown mode was being used.	
08:16	At 08:15 downgraded from ALERT.	

Equipment Damaged

- Electrical cables
- Instruments
- Valves
- Snubbers
- Fire detectors
- Offsite phone lines

Damaged Area

As shown in Figure A14-1, the fire occurred at the north part of the turbine building close to the control room. The fire itself was approximately 9 feet by 12 feet at its maximum. The area where the temperature was above 300^0F was estimated as 19 feet square at the base of the fire and covered and area of 53 feet by 35 at an elevation 17 feet above the base of the fire.

Impact on Core Cooling

Although normal cooling capability was affected and apparently lost for a short time during the fire, it was soon restored when the fire was extinguished. At no time during the fire was the core in any danger of overheating.

Radiological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A14.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in reaching a specific insight.

Fire Scenario Element	**Incident - Fort St. Vrain, October 3, 1987**	**Fire PRA Insights**
Presence of combustible / flammable materials	Petroleum based hydraulic oil of the hydraulic system was the main source of combustible material.	A common source for turbine buildings that would be considered in a PRA.
Presence of an ignition source	Hot exposed steel parts of relief valves that could not be insulated are deemed to be the ignition source. The temperature of the exposed steel was between 680 and 690F and auto-ignition temperature of the oil 620F.	These would be captured in a PRA
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The hydraulic oil, under close to 2800 psi pressure, was sprayed out of a failed filter bowl (canister). The oil spray arced 15' and came into contact with exposed hot steel and caught fire.	PRA fire modeling would typically consider a pool fire rather than a high pressure spray fire due to limitations of the commonly applied models.

Fire growth within the combustible or component of original ignition	The fire spread rapidly over the sprayed oil and created an 8'x3' fire. It propagated to nearby cables and started a fire in IEEE 383 qualified and non-qualified cables.	As with other turbine hall oil fires, the fire grew quickly. This should be captured in a PRA given the fuel source. IEEE 383 qualified cables were burning. This confirms the general assumption used in fire PRAs that qualified cables can sustain fire.
Fire propagates to adjacent combustibles.	Fire spread to adjacent cables was progressing towards Train B safety related cables. Cables were certainly damaged in this fire that had some impact on the control board in the control room.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	Although, given the large open areas of the Turbine Building perhaps only a relatively cool hot gas layer formed under the ceiling. Reference A14-4 indicates that hot gases were trapped between large structural beams of the Turbine Building and caused some deformation and damage to structural elements. However, per Appendix B of Reference A14-2 the high temperature region (300F) above the fire and below Floor 7 is approximately 53x35 feet.	Modeling of hot layer development in a very large open space is problematic for existing fire models.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke entered the control room because a cable failure caused by the fire put control room ventilation system into radiation release emergency mode. In this mode the control room HVAC draws air from the Turbine Building. This caused smoke to be drawn into the HVAC system and into the control room. Also, the west door was used extensively during the course of the fire. Frequent opening of that door caused loss of positive pressure in the control room and allowed the smoke enter the room through that door. Loss of electric power at the fire area rendered the use of electric motor driven smoke ejectors useless.	Turbine building fires are modeled in fire PRAs. In the case of Fort St. Vrain, a quality fire PRA would identify the potential for a turbine building fire affecting the control room. The west door would certainly be identified as the potential pathway for propagation of smoke into the control room. Although current methodologies are clearly capable of handling the scenario, given the level of detail employed in a typical fire PRA, it is doubtful that the analysts would identify the possibility of control room HVAC switching to radiation emergency mode and drawing from the turbine building. It is also not clear what the nature of the cable fault was leading to this switch in modes. This may be evidence of a cable failure induced spurious operation, but this cannot be established.

Local automatic fire detectors (if present) sense the presence of the fire	There were local fire detectors in the fire area that activate as designed. However, the operators would not have learned about the fire from the detectors because the main fire protection panels are located in a room separate from the control room with a closed door. Furthermore, the audible alarm in the control room was turned off because of nuisance alarms that had occurred prior to the fire. The fire was detected because of low pressure noticed by the operators in the hydraulic oil system.	If the operators were not alert to hydraulic oil pressure level, given that the audible fire detector alarm was silenced, it is possible that the fire would have remained unnoticed for an extended period of time. Plant specific conditions, such as those mentioned here (alarm in a separate room, annunciator turned off), would likely be identified during the plant walkdown and a degraded credit allowed for automatic detection.
Alarm is sounded automatically in the control room, locally and / or other places	See above	
Automatic suppression system is activated (if present)	There were no automatic suppression systems in the area.	
Personnel are present in the area where fire occurs	An equipment operator was dispatched to check the situation as soon as low hydraulic pressure was noticed.	
Control room is contacted or fire alarm is sounded	The equipment operator immediately contacted the control room about the oil spill and fire, and then returned to initiate an attack on the fire.	The operator in this case acted properly in reporting the fire. This, no doubt, helped to mitigate the extent of the fire and contributed to the final prompt suppression.
Fire brigade is activated	Fire brigade was activated practically immediately and they were on the scene within a few minutes. Local volunteer fire department was notified and they arrived at the plant withing a few minutes.	Fire brigade response is considered in PRA and this brigade responded as quickly or more quickly than is typically assumed.
Fire suppressant medium is properly applied	The equipment operator who discovered the fire managed to extinguish the fire initially by a dry-chemical portable extinguisher. However, since he was not able to close the valve to isolate the failed filter bowl, the fire flared up again and this time it was too strong to be handled by a portable extinguisher. The manual fire brigade was able to quickly extinguish the fire.	The actions of the fire operator on the scene undoubtably helped to control the fire and limit fire damage. However, in a fire PRA it is commonly assumed that once initiated fire fighting efforts will be successful.

Fire suppressant medium is properly applied to where the fire is.	Using fogging nozzles, the fire brigade attacked the fire from two sides and put out the fire as soon as a reactor operator closed the control valves to the two oil headers.	The was no report of collateral damage due to fire suppression activities.
Fire is affected by the suppression medium	Fire was affected by the water but was not brought under control until the oil supply was cut from the Reactor Building.	See note above regarding suppression effectiveness
Fire growth is checked and no additional failures occur	Fire growth was checked by the fire brigade attacking the fire from two sides.	
Fire is fully extinguished and fire brigade declares it as out	The fire was fully extinguished as soon as the supply of the oil from the two oil headers were cut off by manually closing two control valves in the Reactor Building.	The fire duration in this case is typical of the fires postulated in a PRA.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Hydraulic valves, cables, instrumentation and some structural related items sustained damage from the fire.	The damage would likely have been captured in a fire PRA, in particular, the damage to cables. Valves are commonly assumed invulnerable to direct fire damage.
Cable failure impacts equipment outside the fire location	Several cables failed from direct impact of the fire. Control room ventilation system shifted to radiation emergency mode because of this. One primary circulation loop train was apparently lost due to loss of associated instrumentation.	The ventilation mode switch may be evidence of a spurious operation, but this cannot be verified. The loss of a circulation train due to instrumentation failures would not typically be postulated, but a plant specific review of circuit design may have revealed this vulnerability.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	There are no indications of direct fire damage to equipment needed for safe plant shutdown. The operators had to trip the hydraulic oil system and close off the headers to stop release of oil into the fire. This in turn disabled several components needed for shutdown.	This is a case where safe shutdown equipment was rendered inoperable, in effect, through manual actions taken to fight the fire (shutting of the oil supply valves). This type of action could be easily missed in a fire PRA.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The first message that led to the discovery of the fire was loss of oil pressure. After that several failures occurred that did not cause much limitation for the operators to maintain safe reactor shutdown condition.	The operators appear to have performed well in this incident despite the fact that some smoke got into the control room, and there was some difficulty with the breathing air supply system (not enough masks).

Operators attempt to control the plant properly and bring the plant to a safe shutdown	See above	
Structural failures (if occurred) may jeopardize availability of equipment	Although some structural elements were affected by the fire, there were no failures of structures.	
Water when sprayed over electrical equipment may fail the exposed equipment	no information	
The cooling effect of CO_2 may adversely impact equipment	no CO2 systems were involved	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The audible fire detector alarm was turned off in the control room.	This condition would likely have been detected during PRA plant walkdowns.

A14.5 Incident Analysis

In this fire incident a relatively severe turbine building fire took place (approximate damage $2.5 millon per Reference A14-4) that impacted control room habitability. In many regards, the fire was quite typical of those considered in a typical fire PRA. The fuel source (oil), the reason for its exposure (a piping failure), and its ignition mode (hot surfaces) are quite typical of turbine hall fires. The fire propagated to adjacent cable tray containing IEEE 383 qualified and non-qualified cables. The fire severity and duration are also quite typical of the scenarios postulated in a fire PRA analysis.

One significant insight that may be gleaned from this incident is that under special circumstances, a turbine building fire may be important to plant safety via its effect on other parts of the plant. In this case it affected the habitability of the control room. This ultimately was not a serious challenge to the nuclear safety of the plant in this case, but illustrates the potential for such challenges to arise. Smoke entered the control room via two pathways. The fire failed cables that caused the ventilation system for the control room to shift to a mode where the system takes air from the turbine building. There was a door between the control room and the turbine building that was used frequently causing the ventilation system fail to establish a positive pressure in the control room. Using current fire PRA methods it is possible for both pathways to be discovered. Of course, it will require a detailed analysis of the ventilation system to discover the situations as it occurred at Fort St. Vrain.

It must be added that it is common in fire PRAs, in case of smoke in the control room, to conservatively assume that the room is un-inhabitable. In this incident, there were an insufficient number of breathing masks connected to a piped fresh air system to service the six operators present (3 masks). This initially caused the operators to share the available masks implying that they were working in an uncomfortable environment. At some point portable air packs were made available to alleviate this situation. In a fire PRA the lack of sufficient breathing masks would not be explicitly addressed. Only a detailed fire risk analysis of the control room would identify such problem areas.

Other events of note during this incident include the silencing of the audible fire detector alarm in the control room, and a missing valve handle causing a delay in shutting off a key valve. In a quality fire PRA, during the walkdown, the analyst is expected to look for such plant conditions. This incident demonstrates the importance of conducting detailed walkdowns.

In the case of the valve handle, it is quite likely that the analyst would miss this problem since it was associated with a secondary shutdown valve (the primary valves being local near the fire source) and because in terms of the manipulation of plant equipment and systems, the analysis will commonly focus on plant control and recovery actions rather than actions that might be needed to mitigate a fire. Hence, this particular item would be easily missed in a fire PRA. It is also interesting to note that shutdown of the oil system also led to loss of some additional plant equipment. Again, this would be an easily missed action, although the consequence would be anticipated given the action.

The telephone system was partially failed during this incident. Although, the impact on the outcome of this incident was minimal, it brings out an interesting point. In fire PRA, the availability of communication system is not explicitly modeled. Loss of phone system would impact the possibility of contacting personnel who are not on-site. In a typical human action analysis in a fire PRA the possibility of calling in off-duty operators is not taken into account. Since most accident scenarios are modeled assuming an average number of operators in the plant, this omission is conservative.

Finally, the fact that the ventilation system for the control room switched operating modes due to cable damage may be evidence of a spurious operation due to cable failure. This cannot, however, be verified based on the available information. Verification would require access to, and analysis of, the plant HVAC control circuit diagrams and cable routing details. Given that the plant has been shut down for over a decade, this is considered unlikely, and in any case, such an analysis is beyond the scope of this review. The likelihood and impact of spurious operations is a current area of debate for fire PRA.

A14.6 References

A14-1 Attachment to the letter addressed to Mr. Robert O. Williams, Jr., Vice President of Nuclear Operations, Public Service Company of Colorado, from L.J.Callan, Director of Division of Reactor Projects, U.S. Nuclear Regulatory Commission, October 30, 1987.

A14-2 "Preliminary Report on the Impact of the FSV October 2nd Fire", Fort St. Vrain Nuclear Generating Station, Public Service Company of Colorado, October 30, 1987.

A14-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A14-4 Schmalz, Gregory D. "Lessons Learned from the Fort St. Vrain Turbine Building Fire", Fire & Safety '94, Barcelona, Spain, December 5-7, 1994.

Appendix 15 - Analysis of Ignalina, Unit 2 Fire on September 5, 1988

A15.1 Plant Characteristics

Ignalina is a two unit nuclear power plant located near Visaginas, Lithuania, which at the time of the fire discussed here was a part of the former Soviet Union. The two units are both RBMK-1500 type reactors. The power rating of each unit is 3,950 MWt and about 1,250 MWe provided by two turbine generators one at 550 and the other at 700 MWE. Construction of both units began in 1974. Unit 1 began initial power operations in either October[A15-5] or December[A15-4] 1983. Unit 2, where this fire incident occurred, began initial startup in December 1986.[A15-5] The units started commercial operation in May 1985 and December 1987 respectively.[A15-4] A planned third unit on the site was canceled.[A15-4]

RBMK reactors use graphite as a moderator and boiling water for cooling the core. The generated steam is dried in the steam drum or steam separator before it is directed towards the turbine generators. Core cooling is composed of two parts, a Left Hand Side (LHS) and a Right Hand Side (RHS). These two sections of the core are not fully independent from one another. There is some interaction between them, and this includes the cooling functions as well. Each side of the core is serviced by separate core cooling loops, each with its own steam drum and main coolant pumps (four per side). The feedwater from the condenser is pumped into the steam drum, which serves as the source of water for the main coolant pumps as well.

The core for an RBMK reactor includes special reactor protection rods that travel inside dedicated cross shaped channels and are isolated from the rest of the systems entering the core. In the case of Ignalina Unit 2 there were 12 such rods. The channels are cooled by a separate water cooling system. Pumps CP-21 and CP-22, mentioned in the discussions below, belong to the cooling system for these channels.

Room 209, where the fire occurred, is a cable spreading room in Unit 2, located under the Main Control Room and computer room at elevation 5.9m (measured from the local grade). Ionization type smoke detectors and a water based fixed suppression system were provided for that room. At the time of the fire, fire resistant coating was not applied to the cables at Ignalina but such coatings have been applied since.

A15.2 Chain of Events Summary

On September 5, 1988, Ignalina Unit 2 was at 100% power when, at 00:52:39, the Main Control Room received a fire alarm from room 209. The exact cause of the fire was never conclusively determined. However, it is suspected that the fire started in one of the 220VAC cables in the lowest of a stack of cable trays. There were apparently no external fire sources identified. The lowest tray housed 31 cables including at least one 220 VDC cable. It is suspected that the fire started due to overheating caused by a short circuit in one of the cables. The postulated root cause for the short circuit is damage inflicted to the cable during plant construction and a slow deterioration of the cable after that. It is possible that the cable had deteriorated because of thermal cycling, thermal overload, undue mechanical tension or vibration. Inadequate circuit protection devices are also thought to have facilitated the overheating of the cables and thus the possibility of an ignition.

The automatic fire suppression system in room 209 activated within a short time of the alarm (either a sprinkler or deluge system). The fire brigade was called and plant personnel made an attempt to check the room but could not enter because of dense smoke. Within three minutes of notification, the fire brigade arrived at the plant with five fire engines and smoke removal apparatus.

Over the course of the fire incident several pumps related to core cooling and various plant instrumentation systems were lost affecting the core's LHS. Despite the losses, however, the operators managed to establish feedwater flow to the affected steam drum and facilitated the natural circulation of the coolant through the core. All systems associated with the core's RHS remained functional throughout the fire. Operators took some precautionary measures to ensure that the two sides of the reactor would not adversely interact given the losses to the LHS related systems.

Cable faults caused numerous electrical power system failures. Instrumentation and control cable faults caused supply breakers for normal and essential (non-safety) 6kV buses to open. Cable damage also prevented proper alignment of two of the six diesel generators to these buses. This led to the unavailability of the LHS reactor protection coolant pumps. Later, one of the diesel generators started and properly connected to one of these buses, and one of the reactor protection coolant pumps started. The power to the affected buses was restored within about 40 minutes from the first fire alarm and the operators managed to regain normal control of the reactor and its cooling functions at that time.

The fire also caused a partial loss of reactor core monitoring instrumentation systems. The indications for 4 out of the 12 reactor protection channels were lost. At about 10 minutes after the fire alarm, the operators de-energized control rod drive mechanisms to prevent any spurious movement of the rods.

The fire brigade attempted to enter room 209 to fight the fire directly but they were forced to retreat because of the dense smoke. At about 22 minutes into the incident, the smoke removal apparatus was activated. The fire brigade managed to enter room 209 about 16 minutes later, or 38 minutes after the fire alarm. They found the fire completely extinguished by the automatic fire suppression system. The fire had damaged 646 cables for a length of about 5 meters. Of these, 506 cables were associated with control and instrumentation circuits and 106 with power distribution systems. Cables in the upper-most cable trays were also found damaged by the fire.

Apparently the cable faults caused by the fire in room 209 led to failures in the Reserve Control Room as well. The Reserve Control Room is the back-up for the Main Control Room and it contains a control panel that can duplicate a large number of safety related controls and instrumentation available in the Main Control Room. For example, the level control signal for the LHS steam drum was restored from the Reserve Control Room about 40 minutes after the first fire alarm. Since by this time the feedwater flow had been established, but level control was apparently not functioning, the level was found to be above the measurable scale.

After the fire was extinguished, diesel generator #8 developed an oil leak and had to be tripped. Power to one of the buses was lost again which led to loss of one reactor protection cooling pump. These failures occurred from causes independent of the fire.

A15.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A15-1] through [A15-3]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, such events are included within the sequence of events based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On September 5, 1988, Unit 2 was at 100% power (i.e., the turbine generators were producing 550 MWE and 700 MWe). The fire detectors and fire suppression system for room 209 were in the automatic mode. The ventilation system of room 209 was operational Main coolant pump 12 was on stand-by.	
00:00	At 00:52:39 on September 5, 1988, the Main Control Room received a fire alarm from room 209. The exact cause of the fire could not precisely be determined during the accident investigation although a self-ignited cable fire is suspected.	Given the conclusions of the fire investigation, this incident demonstrates that self ignited cable fires can occur, even in a relatively low voltage circuit (220VAC in this case). The fire experience in US nuclear power plants contains only a few minor self-ignited fire events. In fire PRAs, such fires are commonly considered, but only for cables that are not qualified as low flame spread per standards implemented for the nuclear industry beginning in 1975 (IEEE-383). Given the differences that likely exist in cable characteristics and electrical circuit design features between US and Soviet-designed plants, the Ignalina experience may not be directly relevant to U.S. plants.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:00	At 00:52:49, a second fire alarm was received from room 209 in the Main Control Room. This alarm was also automatically transmitted to the plant fire brigade. At the same time, the automatic fire suppression system in room209 was activated automatically.	The fixed fire detection and suppression systems did activate as designed.
00:01	At 00:53:00, the fire brigade was called.	
--	A senior engineer and another member of the plant staff checked the situation from the corridor next to room 209, but could not enter the small entrance area to room 209 because of dense smoke.	
00:03	The fire brigade arrived at the plant with five fire engines and apparatus for removing smoke from a compartment. Upon arrival, they called for additional help and equipment.	As is typical of plants in the former Soviet Union, fire fighting is primarily provided by an associated fire brigade located near the plant but off-site.
00:03	At 00:55:55, the Control Room received oil level alarms for main coolant pump 14 (serving LHS) and the pump tripped automatically. This caused the power level to reduce to 2,830 MWt (60%). Cable faults in the circuits for oil level indicators and alarm are suspected to be the cause of the trip.	This is apparently a spurious trip signal caused by fire damage to instrumentation circuits. Some fire PRAs would not assume loss of a system given fire damage only to associated instrumentation circuits, although practice does vary from analyst to analyst.
00:04	At 00:56:25, main coolant pump 13 tripped because of cable faults related to the oil system and reduction in oil flow to the bearings. Loss of this second main coolant pumps led to automatic reactor trip. The automatic reactor trip led in turn to the startup of all six diesel generators associated with this unit.	This is the second system to be failed by the fire.
00:04	At 00:57:00, turbine generator #3 tripped on low steam drum level. Reactor coolant pressure was at 55kgf/cm^2 (780psi)	
00:04	At 00:57:15, turbine generator #4 tripped on high level in low pressure heater #4.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:06	At 00:58:31, main coolant pump 11 tripped because of cable faults. With loss of all main coolant pumps, natural convection became the motive force of coolant flow through left hand side of the core.	This is the third system failed by the fire.
00:06	At 00:59, level control of steam drum, feedwater control valves and main coolant pump valves, all associated with the LHS, were lost. Plant personnel established feedwater flow to the affected steam drum.	
00:06	At 00:59:14, cable faults caused numerous electrical power system failures. Instrumentation and control cable faults led to the opening of supply breakers of normal 6kV buses BA and BB and essential (non-safety) buses BV and BU. Cable damage also tripped Transformer 5 and prevented it from taking up the loads for these buses. Diesel generator #7, because of bus failures, did not connect to bus BU. Because of this, reactor protection system pump CP-21 failed to operate. Diesel generator #8 started and supplied power to BV to 2MW load. Since BV was powered, the reactor protection system cooling pump CP-22 began operation.	These are cases where instrumentation and control faults apparently led to spurious trip signals being sent to various supply power systems and breakers. See note above.
00:07	At 01:00, there was a partial loss of reactor neutron monitoring instrumentation. The indications for 4 out of the 12 reactor protection channels were lost.	
00:10	At 01:03:20, operators de-energized the control rod drive mechanisms to prevent any spurious signals from causing a control rod to move. Main coolant pump 24 (serving the RHS) was tripped by the operators to minimize the possibility of adverse interaction between the two sides of the reactor. Main coolant pump 22 was left in service.	De-energizing of the CRD system is an interesting precautionary measure taken by plant operators. Whether or not this was a procedure-based action is not clear. It does illustrate that operators were cognizant of the spurious actuation possibility and took actions to mitigate their potential impact.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:12	About 01:05, the fire brigade tried to enter room 209 to fight the fire but was unable because of the dense smoke.	This indicates a transit time from the plant entrance to the location of the fire of about 9 minutes (see 00:03). This is relatively fast in comparison to typically assumed response time from fire PRAs. Smoke hampering fire fighting efforts is commonly recognized as a potential issue but is also commonly considered unlikely based on fire brigade training.
00:18	At 01:11, the monitor for LHS feedwater flow was lost. The operators energized buses BA and BU from a working auxiliary transformer. This initiated the operation of one reactor protection system pump.	
00:22	At 01:15, smoke removal equipment was activated in Unit 2 corridors.	It is not clear if this was portable or fixed equipment. One must infer from the 10 minute time period from initial attempts to access the fire area to the time smoke removal was initiated that this involved the placement of portable smoke removal blowers.
00:27	At 01:20, an attempt was made to start main coolant pump 12, but it did not start.	
00:38	At 01:30, the fire brigade entered room 209. The brigade could not find a fire in the room. The water supply to the fire suppression system for the room was therefore stopped. It was concluded that the fire was extinguished by the automatic fire suppression system. 646 cables for a length of about 5 meters was found damaged by the fire. 506 cables were associated with control and instrumentation circuits and 106 were associated with power distribution systems. The ceiling of the room was found partially damaged.	In this case, the fire suppression system actuated and performed as designed. The time of detection and fire suppression system activation imply a very prompt system response, typical of what would be assumed in a fire PRA. It is interesting, however, that despite proper and successful operation of the fire suppression system, substantial damage was observed. It is commonly assumed that once a fire suppression system activates, further damage will be mitigated. In this case, the event clearly shows that fire damage continued to cause system losses well after the suppression system activated.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:40	The level control signal for LHS steam drum was restored from the Reserve[(1)] Control Room. The level was found to be above the measurable scale.	Note that this event indicates that a "partial abandonment" of the MCR was exercised. Operators were working from both the main and reserve control rooms to control the plant. From the information provided in the available sources, it can be inferred that the Main Control Room and Reserve Control Room were not completely independent and some of the failures caused by the fire in room 209 rendered some indicators and control functions on both control panels unavailable. For U.S. plants, potential interactions or dependencies between the control room and remote shutdown capability are explicitly addressed through the Appendix R analysis. It is common for current PRAs to rely on these deterministic assessments to assure remote shutdown independence, but confirmation of these assumptions was raised as a potential unaddressed risk issue in the Fire Risk Scoping Study (SNL) and was a common point of technical concern raised in the USNRC-sponsored IPEEE reviews.
00:45	At 01:38, in order to prevent spurious withdrawal of the rods, the drivers of the rods were mechanically blocked and the blocks were de-energized.	Recall that earlier in the event the CRD system had been electrically de-energized. Apparently operators did not fully trust this action and took additional measures to prevent rod withdrawl.
00:47	At 01:40, diesel generator #8 was manually tripped because of an oil leak from a flange. Power to bus BV was lost which led to pump CP-22 of the reactor protection system to trip.	This represents an independent event (failure) in that the loss of the diesel generator cannot be attributed to causes related to the fire. Diesel generator #8's oil system developed a leak and the operators had to shut it down. In this case, the impact of this event may not have been detrimental to the capability to provide core cooling. In fire PRAs, the possibility of occurrence of independent events is modeled explicitly through the use of internal events model.
--	Per Reference A15-2 "Shutdown key" on Reserve Control Room panel was lost.	

Notes: (1) The Reserve Control Room is a back-up of the Main Control Room. For Soviet-designed plants, the Reserve Control Room generally contains a control panel that can duplicate a large number of the safety related control and instrumentation functions in the Main Control Room.

<u>Equipment Damaged</u>

– Electrical cables (646 cables for a length of about 5 meters was found to be damaged by the fire. 506 cables were associated with control and instrumentation circuits and 106 were associated with power distribution systems.)

Damaged Areas

– Cable Spreading Room under the Main Control Room and Computer Room.

Impact on Core Cooling

– Safety related equipment were affected by this fire. Cooling capability for one half of the core was affected.

Radiological Release

– No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

– There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

– The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

– There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A15.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against a typical fire scenario which is expressed in terms of a list of elements. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Presence of combustible / flammable materials	Electrical cables were the main source of combustibles for this fire incident.	Cable fires are commonly considered in fire PRAs

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Presence of an ignition source	An electrical fault was apparently the source of ignition in this incident. The fire was concluded to have been ignited in a 220VAC cable servicing a valve motor. It was suspected that some of the cables were damaged during construction and they further deteriorated due to overheating, vibration or mechanical tension. Also, the inadequate response of circuit protection systems were suspected to be a contributor to the ignition of the cable.	The ignition was apparently exacerbated by physical damage to the cables and inadequate circuit protection. In fire PRA, fire initiation is handled as a statistical process and the exact mechanism of ignition is rarely considered.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Fire investigators concluded that this was a self-ignited cable fire. The exact cause of cable failure and ignition of the cables could not be conclusively determined.	Self-ignited cable fires are considered, in particular, for older plants that still contain significant quantities of cable that has not be certified as low-flame-spread per IEEE-383
Fire growth within the combustible or component of original ignition	From the information provided, it can be inferred that fire established itself quite rapidly.	It is commonly assumed in fire PRA that cable tray fires will develop slowly over the period of several minutes at the least. This fire appears to have grown more quickly than this, although differences in U.S. versus Soviet cable materials may have played a role so extrapolation to US plants may be inappropriate.
Fire propagates to adjacent combustibles.	From the timing of the events, it can be concluded that the fire propagated to other combustibles (trays above the ignition tray) nearby in a short time.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	Clearly, a hot gas layer did form in the fire room, but it is not clear if any damage was cause by the gas layer rather than direct fire involvement.	A common finding in fire PRAs (based on fire modeling) is that hot gas layers are not sufficiently hot so as to cause fire damage. Rather, fire damage is typically predicted to be limited to trays directly in the fire or fire plume. This incident appear to nominally support the validity of these findings.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	The fire remained in the compartment of origin and no damage outside the compartment was reported.	
Local automatic fire detectors (if present) sense the presence of the fire	The ionization type smoke detectors did actuation, apparently within a short time of fire initiation.	Fire detectors performed as designed

<u>**Fire Scenario Element**</u>	<u>**Incident - Ignalina 2, September 5, 1988**</u>	<u>**Fire PRA Insights**</u>
Alarm is sounded automatically in the Control Room, locally and / or other places	Alarms were sounded automatically in the Control Room and at the associated but fire brigade station. In fact two alarms were received at the initial stages of the fire, one from the smoke detectors and a second flow alarm on the fire suppression system.	
Automatic suppression system is activated (if present)	The fixed automatic water system of room 209 activated as designed.	The suppression system apparently actuated nearly simultaneous with the initial fire detection by smoke detectors. This is an indication of very prompt suppression system response.
Personnel are present in the area where fire occurs	Personnel could not enter the room because of dense smoke and low visibility.	Given these conditions a PRA would not typically credit any fire intervention actions by anyone other than the fire brigade. This event confirms the validity of this practice.
Control Room is contacted or fire alarm is sounded	The fire initiation time for this incident is measured from the moment that the Control Room received a fire alarm from room 209.	
Fire brigade is activated	Plant fire brigade was activated within a short time of the initial alarm in the Control Room. In addition to the Control Room, the fire alarm sounded in the fire station as well. Five fire engines arrived at the plant within 3 minutes of the alarm. Additional equipment and personnel were requested as well.	The fire brigade arrived on-scene very promptly. Typical PRAs would assume a somewhat longer brigade response time, particularly for brigades not physically located on-site.
Fire suppressant medium is properly applied	Water from the automatic fire suppression system sprayed on the fire. Fire fighters did not apply any suppressants but after clearing smoke, found the fire extinguished when they entered the room.	Fire suppression systems are typically designed to provide fire control rather than extinguishment. It is interesting to note that in this incident the fire suppression system worked as designed and apparently suppressed the fire completely. However, despite the successful operation, extensive damage was sustained. Even cables in the uppermost cable trays were damaged by the fire that apparently started in the lowest tray.

<u>**Fire Scenario Element**</u>	<u>**Incident - Ignalina 2, September 5, 1988**</u>	<u>**Fire PRA Insights**</u>
Automatic fire suppression system is activated	The automatic fire suppression system activated as designed.	See note above.
Fire suppressant medium is properly applied to where the fire is.	The fire brigade did not conduct any manual fire fighting.	
Fire is affected by the suppression medium	The fire was affected by the automatic suppression system. The fire was fully extinguished in less than 38 minutes after it was initiated.	
Fire growth is checked and no additional failures occur	The fire growth was checked by the automatic fire suppression system. However, a large number of cables (646 cables) were damage for a length of about 5 meters.	In fire PRA it is common to assume that if the fixed suppression system activates, any subsequent damage will be mitigated (prevented). In this case damage continued well after the suppression system activated.
Fire is fully extinguished and fire brigade declares it as out	The fire was extinguished by the automatic fire suppression system and declared as out about 38 minutes after the first fire detector alarmed in the Control Room. No manual fire fighting was necessary.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	A large number of cables were lost. No other equipment were affected directly by the fire or smoke. There was some structural damage to the ceiling.	See note above regarding damage timing versus suppression activation.
Cable failure impacts equipment outside the fire location	Cable failure certainly impacted equipment outside the fire area. The impact was mainly on the systems serving the LHS: part of the neutron monitoring instrumentation was lost, the main coolant pumps were lost, and feedwater flow control was lost.	The reported failures apparently include cases where control or instrument cable failures did lead to the generation of spurious trip signals for various electrical supply systems. (See note in previous table above.)

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Three of the four main coolant pumps for the left hand side of the core were tripped. As a consequence the reactor tripped. Feedwater flow control and steam drum level were lost. The power to several buses were lost. The reactor protection system cooling pumps were also affected. Overall a large number of equipment serving the left hand side of the core were affected. However, the core was not in any imminent danger of severe overheating.	This fire did present the operators with the loss of a number of important safety systems. However, the operators responded appropriately to recover the plant to a safe shutdown state.
Operators in the Control Room receive messages and respond to the information displayed on the control board or received verbally from the plant	The operators used the Main Control Room and the Reserve Control Room to monitor the condition of the reactor and core cooling systems. There was partial loss of neutronics related instrumentation. No specific information is provided regarding the adequacy of the information on the control board in the Main Control Room, reliance on Reserve Control Room readings and interaction with field operators.	This is one of the few fire incidents where an attempt was made to use the alternate shutdown panel. However, some interaction was experienced between the main panel and the alternate shutdown panels (i.e., the Reserve Control Room). In fire PRAs for US plants it is typically assumed that the analysis conducted as part of Appendix R compliance has resolved the potential interaction issues. Some attention is given to this issue in fire PRAs as part the response to the issues raised in Sandia Fire Risk Scoping Study. However, no probabilistic analysis of the potential interactions is conducted.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Operators were able to control the plant properly. The systems serving the right hand side remained available throughout the fire. The left hand side cooling was achieved by natural circulation and feedwater flow into the steam drum.	There were not significant operator errors noted.
Structural failures (if occurred) may jeopardize availability of equipment	The ceiling of the cable spreading room was found partially damaged.	
Water when sprayed over electrical equipment may fail the exposed equipment	No information	
The cooling effect of CO_2 may adversely impact equipment	Not applicable	

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	Main coolant pump 12 was on stand-by at the time of the event and could not be started.	

A15.5 Incident Analysis

The fire incident at Ignalina 2 can be considered as a classic case of relatively modest cable spreading room fire that ignited on its own, propagated to adjacent cables, was detected in a short time, and was extinguished by the automatic suppression system that functioned as designed. The fire remained confined to its compartment of origin, and damage was apparently limited to one stack of cable trays. The cables affected by the fire belonged only to a limited number of systems and components, and core cooling and reactor monitoring was never completely lost in this incident. Despite the available components and systems, the set of cable faults experienced in this incident made it difficult for proper control of the reactor core parameters and core cooling for the LHS. This is a scenario that is commonly postulated in fire PRAs.

One interesting aspect of this fire is that while the suppression system functioned as designed, and even extinguished the fire (the design basis for a typical automatic suppression system is to control the fire and not necessarily extinguish it completely), extensive damage was sustained. Furthermore, additional equipment losses were recorded well after the fire suppression system had actuated. This incident demonstrates that it may not be proper in a fire PRA to assume that activation of a fixed suppression system would stop any further damage from occurring. However, it must be added that a direct extrapolation of this incident for refuting the above mentioned assumption may be premature. The characteristics of the cables used at Ignalina would have influenced the propagation of the fire, apparently despite fire suppression system activation. It is not clear what correspondence (or lack thereof) there might be between cables used in the U.S. and those used in the Soviet designed plants.

This incident also demonstrates that self-ignited cable fires can occur. Furthermore, such fires can happen in relatively low voltage circuits (220VAC in this case). Fire PRAs treat fire ignition possibility through a statistical analysis of relevant fire incidents. For self-ignited cable fires, the fire experience in the nuclear power plants in the U.S. contains only a few minor incidents. For cases where the cables are certified as low-flame-spread (per IEEE 383) it is common to dismiss self-ignited cable fires as of extremely low probability. This incident neither supports nor refutes this aspect of fire PRAs given the differences that likely exist in cable characteristics and electrical circuit design features between US and USSR plants.

It is also interesting that in this event, operators acted from both the main and reserve control rooms. From the information provided in the available sources, it can be inferred that at the time of the fire the Main Control Room and Reserve Control Room at Ignalina were not completely independent. This is because some of the failures caused by the fire in room 209 rendered some indicators and control functions on both control panels unavailable. In fire PRAs for US plants, the Appendix R compliance analyses are commonly cited as ensuring the independence of the alternate shutdown capability. Verification of independence, rather than assuming independence, has been raised as a potential risk issue in both the SNL Fire Risk Scoping Study and in the USNRC-sponsored reviews of the IPEEE submittal. Again, given that the electrical design practices of the Soviet plants is likely substantially different from that of the US, the Ignalina experience may not be directly applicable to US plants.

A15.6 References

A15-1 Section IV, "Analysis of the Event: Partial Loss of the Control Room Unit 2 Due to Fire in Cable Room, 1988", in English

A15-2 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A15-3 Soloviev.P.S. "Accidents and incidents in nuclear power plants", Obninsk,1992.

A15-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A15-5 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 16 - Analysis of Oconee 1 Fire on January 3, 1989

A16.1 Plant Characteristics

Oconee is a three unit nuclear power plant located near Seneca, South Carolina. All three units are nearly identical 860 MWE Babcock and Wilcox design, pressurized water reactors. Unit 1 started commercial operation in July 1973. Each reactor has four reactor coolant pumps (RCPs). At Unit1, two of the pumps are powered by an Auxiliary Power System 6.9kV switchgear designated as 1TA and the other two by another Auxiliary Power System switchgear designated as 1TB. The following design/control features played a role in the fire incident being reviewed.

Per the technical specifications, reactor cooldown should be less than 50°F per 30 minutes. Main coolant loop pressure is maintained by controlling the sprays and heaters of the pressurizer. The normal pressurizer spray is fed from one of the cold legs of the main coolant loops. If control of the pressure via the pressurizer is not possible, the operators can use one of the following three methods:

- The Power Operated Relief Valve (PORV) of the pressurizer can be used to relieve main coolant into the Quench Tank.
- An auxiliary spray is available for the pressurizer using the high pressure injection system.
- By throttling open the Turbine Bypass Valve, steam from the steam generators can be dumped into the main condensers.

The plant, for normal operation, is controlled by the Integrated Control System (ICS). One of the features of the ICS is to automatically, upon loss of all reactor coolant pumps and availability of main feedwater function, swap the feedwater flow from the main feedwater nozzles to the auxiliary nozzles and to increase steam generator level to 50%. These actions facilitate establishing of natural convection cycle in the main coolant loop.

A16.2 Chain of Events Summary

On January 3, 1989, Unit 1 was being brought up to power after a trip that had occurred a few days earlier. It had reached 26% power at 19:16 when the 6.9kV Switchgear (1TA) failed explosively and caught fire. The precise cause of this incident could not be established in later investigations. As a result of the switchgear failure, the main turbine and two reactor coolant pumps tripped initiating a reactor transient.

The operators immediately started reactor power reduction. Average reactor temperature was 575EF at the beginning of the incident. Initially core cooling was maintained by the two operating reactor coolant pumps and main feedwater flow through the steam generators. Two high pressure injection pumps were started by the operators to compensate for contraction of the water in the main coolant loop as it was cooling down due to the power reduction. When the power dropped to 4%, the operators tripped the reactor.

Meanwhile, fire alarms were received in the control room. The fire brigade was activated to respond to the fire. Later, off-duty shift personnel were called in to assist in the fire fighting effort. Two initial attempts by the fire brigade to suppress the fire using carbon dioxide and dry chemical fire extinguishers failed to put the fire out. Control room operators de-energized the DC power bus in order to isolate the impacted 1TA switchgear from all electrical sources. It was then decided to apply water to the fire using a fog nozzle. To further protect the fire fighters, the other train of non-safety 6.9kV switchgear (i.e., 1TB), located near 1TA, was also de-energized. The water fog was used on the fire and at 20:15, about one hour after the switchgear failure, the fire was declared as completely extinguished.

Tripping of 1TB (to protect the fire fighters) caused the remaining reactor coolant pumps to trip. The Integrated Control System (ICS) is designed, under these conditions, to raise the water level in the steam generators to 50% and swap the feedwater nozzles from main to auxiliary. Due to fire damage to signal cables, the ICS failed and the operators had to execute these two actions manually. However, in doing so the operators forgot to close the main feedwater valve. This further accelerated the rapid cooldown process that was already underway. Furthermore, since the operators focused on in-core thermocouple readings to monitor reactor temperature, they did not properly monitor the rate of cooldown at different points of the main coolant loop.

Cold leg temperature dropped to about 426EF in about one hour. The shift engineer and shift supervisor determined that the temperature in parts of the reactor may have dropped faster than 100EF in one hour, which means that they may have entered the Thermal Shock Operation Region (overcooling).

Because operators had started the high pressure injection system, reactor pressure reached 2355 psig for a short time. Later, the pressure reached 2385, also for a short time. Operators then stopped the high pressure pumps to control the high pressure condition. These two pressure spikes, combined with the possibility of operating in thermal shock region, could have endangered the integrity of the main vessel if the conditions had persisted for an extended time.

At some point in the incident smoke did find its way into the main control room. The extent of the smoke and the path by which the smoke found its way into the control room are not described in the available sources. It is not clear if the smoke had any impact on operator performance, although one report cites this (rather in passing) as a contributing factor to the errors that led to the overcooling transient.

A16.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available source [Ref. A16-1]. If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Relative Time (hr:min)	**Event or Step Description**	**Fire PRA Implications**
Prior to the incident	Unit 1 had in the days before the fire tripped and was being brought back to power. The reactor had reached 26% power level at the time of the fire. Units 2 and 3 were operating at 100% power.	
00:00	At 19:16, 6.9kV auxiliaries were manually transferred from the startup transformer to the main transformer (1T). Differential alarms were received in the control room on two of the three phases on 1T.	
00:00	Switchgear 1TA failed explosively and caught fire. The causes of this event could not be established in later investigations. Two scenarios were suspected -- arcing at "plug-in" connections or a fire in the DC control circuits inside the switchgear that caused high voltage parts to arc and fail explosively. Main turbine and two reactor coolant pumps tripped as a result.	This incident involved and explosive fault in a switchgear panel. Typical fires modeled in a fire PRA involve an initial ignition that grows over time. In this case, the fault was energetic and ignited a substantial fire.
00:01	Fire alarms were received in the Control Room, which was followed by telephone calls reporting of a fire and an explosion at 6.9kV switchgear 1TA. The switchgear was de-energized.	Detection of the fire was very prompt as would be consistent with a typical PRA. Fire PRA will typically assume prompt detection given fixed detection systems.
--	The fire brigade was activated to respond to the fire.	There were no delays in declaring the fire and initiating a response.
--	Reactor ran back to 14% power.	
00:13	At 19:29, the DC control power was removed at 1DIA and 1DIB buses to completely isolate 1TA switchgear from power sources.	
--	Smoke entered the Control Room. The available information [Ref. A16-1] does not elaborate on how smoke entered the control room nor how dense it was. If the operators had to don breathing apparatus, this would likely have been mentioned in reports. Since it isn't mentioned, this is taken to indicate that the smoke density was low.	Smoke propagation is not explicitly addressed in fire PRAs. This incident demonstrates that a fire outside the Control Room can lead to smoke inside the Control Room. In Reference [A16-1], it is stated that the smoke may have had some impact on operators' performance. However, no details are provided.

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:17	At 19:33, carbon dioxide was applied to the burning switchgear. It did not put the fire out.	PRAs typically assume that once initiated, fire fighting efforts will be successful. The two failed fire suppression attempts demonstrate that the availability and application of a fire suppressant does not necessarily lead to fire extinguishment. Rather, the effectiveness of the fire suppression system or method is important. Fire fighting is a decision-making process involving the selection and application of fire suppressants, and this decision making process is not explicitly modeled in current PRAs
00:25	At 19:41, dry chemical extinguisher was applied. This also failed to extinguish the fire.	
00:29	At 19:45, the shift supervisor declared an Unusual Event.	
00:39	At 19:55, operators started reactor power reduction. Average reactor temperature 575F.	
00:40	At 19:56, two high pressure injection pumps were started by the operators to compensate for the shrinkage of the water in the main coolant loop as it was cooling down because of power reduction.	
00:41	At 19:57, Technical Support Center and Operational Support Center were activated.	
--	Shift supervisor asked for off-duty shift personnel to be called in to assist in the fire fighting effort.	
00:42	At 19:58, a suction valve on the High Pressure Injection system from the Borated Water Storage Tank opened automatically and a reactor coolant loop injection valve throttled open.	
00:43	At 19:59, decision was made by fire brigade leaders and shift supervisors to use water to fight the fire.	Here again fire fighting is seen as a progressive exercise in decision making. See note above.

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:44	At 20:00, reactor power had decreased to 4% of full power and the reactor was tripped manually. The two remaining reactor coolant pumps were also tripped manually in preparation to de-energize 1TB switchgear. At 20:00, the operators de-energized 1TB switchgear to allow for the fire fighters use water on the fire.	With the de-energizing of 1TB, effectively two opposite trains of a system, albeit a non-safety system, were temporarily out of service. This demonstrates that it is not necessary for the fire itself to cause all system trains to fail. In the course of fire fighting, equipment may be de-energized possibly leading to the unavailability of redundant trains. Current fire PRA methodologies include provisions for analyzing the actions that should be taken by fire brigade. In that analysis, such special condition as that discussed here may be discovered and modeled properly.
00:44	The Integrated Control System (ICS) that controls the normal plant operation was affected by the fire because of signal cable failure. Upon loss of reactor coolant pumps and main feedwater available, the ICS is designed to raise steam generator levels to 50% and swap feedwater nozzles from main feedwater to auxiliary feedwater to facilitate natural circulation in the main coolant loop. It failed to implement these two actions.	Failure of the ICS was a direct result of fire damage to the associated signal cables. This would have likely been predicted in a fire PRA.
00:48	At 20:04, reactor pressure reached 2,355 psig, the set point for Reactor Protective System. The Turbine Bypass Valve was throttled to 10% open by the operators.	
00:49	At 20:05, the operators manually increased steam generator levels to 50% and swapped feedwater from main feedwater nozzles to the auxiliary nozzles. However, the main feedwater block valves were left open (in error), which further enhanced the rapid cooldown process. Turbine bypass valves closed automatically.	An error of omission occurred at this point in the chain of events. In fire PRA such errors are modeled as an integral part of the event tree and fault tree models developed for the internal events analysis. The human error probability assigned to these events is generally includes consideration of the conditions that fire imposes on the operators. However, it is common to assume that actions in the main control room are not impacted by fires in other plant areas. The fire in this case created the need for a manual operator response, but it is not clear whether or not the fire directly increased the likelihood that failures might then result.
--	The high pressure injection system caused the main coolant loop pressure to reach 2395 psig.	

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:50	At 20:06, apparently due to internal system control features the high pressure injection valve first opened fully, then closed completely. Operators stopped the high pressure pump 1A because of the increasing pressure and placed the pump in the automatic mode.	
00:54	At 20:10, plant personnel determined that the requirements for “Thermal Shock Operating Region” has been met. A control room operator tried to establish high pressure injection auxiliary pressurizer spray to depressurize the reactor, but his efforts were not successful. Later, a containment entry was made and the isolation valve for this spray path was found closed.	Failure of the auxiliary spray capability was caused by an independent failure (i.e., not related to the fire). This failure had an impact on the chain of events, and demonstrates the importance of such events. In fire PRA, independent failures are modeled explicitly using the event trees and fault tree of the internal events model.
00:54	The high pressure injection pump 1A was started.	
--	A second rapid pressure increase of the main coolant loop took place. The pressure reached approximately 2300 psig.	
00:59	At 20:15, water fog was used and the fire was declared as completely extinguished.	This fire was of relatively long duration in comparison to typically modeled PRA fire scenarios. In this case, there was a substantial delay in the application of effective suppression methods.
00:59	Cold leg temperature reached 426F. Given a drop of more than 100EF per hour from the average temperature of 575EF in the main coolant loop augmented by two pressure spikes, there was a threat of thermal shock.	Thermal shock is generally considered in internal events PRAs. However, it is often eliminated from the sequence models because multiple random equipment failures reduce the likelihood of such an event. Fire PRAs commonly rely on these same internal events models. Fire can act as a common threat to several items whose simultaneous random failure probability may be very low. Elimination of low-frequency sequences in the internal events analysis may have implications for the fire analysis.
01:47	At 21:03, 1TB switchgear was re-energized	
02:03	At 21:19, the Technical Support Center was established.	
02:04	Cold leg temperature reached 398F	

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
02:34	At 21:50, members of the Technical Support Center determined that Thermal Shock Operating Region (TSOR) was not reached. However, recommended, after reactor coolant pump restart, to maintain the reactor in a three hour soak period to allow vessel and other reactor parts to reach a steady state condition.	

Equipment Damaged

- 6.9kV switchgear.
- Electrical cables (including ICS cables)

Damaged Areas

- The damage was limited to a switchgear and electrical cables nearby.

Impact on Core Cooling

- Core cooling was maintained at all times during the incident. The reactor was subjected to rapid cooldown and may have entered thermal shock operating region.

Rediological Release

- No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A16.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire incident is compared against the elements that make up a typical fire PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Oconee 1, January 3, 1989**	**Fire PRA Insights**
Presence of combustible / flammable materials	Switchgear cabinet contents and electrical cables around the switchgear were the available combustibles.	
Presence of an ignition source	Electrical equipment were the source of ignition.	
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The exact cause of ignition could not be determined. Arcing at the connectors or a DC circuit related component fire may have led to the energetic failure of the switchgear.	In this case, the initial fault was energetic in nature and the fire, in effect, bypassed the typical fire initiation and growth stages assumed in a PRA. It would appear that the entire switchgear panel was engulfed in fire almost instantaneously.
Fire growth within the combustible or component of original ignition	1TA switchgear failed explosively and its internal components caught fire.	
Fire propagates to adjacent combustibles	Cables near the switchgear caught fire.	This is a case where a fire starting inside an electrical panel did propagate out of the panel. Some PRA methods discount this possibility, and this was a topic of debate with regard to application of the EPRI *Fire PRA Implementation Guide* to the IPEEE analyses (see report body for further discussion).
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information provided	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	From Reference [A16-1] it can be inferred that some smoke found its way into the control room.	This event demonstrates that smoke can propagate to other locations. In fire PRA smoke propagation is generally not modeled in detail.
Local automatic fire detectors (if present) sense the presence of the fire	The fire detectors activated within a short time of switchgear failure.	
Alarm is sounded automatically in the control room, locally and / or other places	Fire alarm did sound in the control room.	
Automatic suppression system is activated (if present)	No information provided. It is inferred that the switchgear area was not protected by a fixed automatic suppression system.	

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Personnel are present in the area where fire occurs	No information is provided although personnel did report an explosion in the switchgear room to the MCR.	
Control room is contacted or fire alarm is sounded	The control room was contacted by telephone, about the fire in a short time after switchgear failure.	
Fire brigade is activated	Fire brigade was activated immediately upon receiving news about the fire.	
Fire suppressant medium is properly applied	Two attempts to suppress the fire were made with portable CO_2 and dry chemical extinguishers, but it was not successful. The fire re-flashed in both cases. The power to 1TA was completely de-energized (including the DC power). The power to the adjacent switchgear 1TB was also de-energized by the operators to allow for the use of water with fogging nozzles.	The failure of initial fire suppression efforts is not typically considered in a fire PRA. A PRA would have assumed a very high probability of suppression and no further damage based on the initial fire brigade response time.
Automatic fire suppression system is activated	It is inferred that there was no fixed fire suppression system.	
Fire suppressant medium is properly applied to where the fire is.	No collateral damage due to fire suppression was reported.	
Fire is affected by the suppression medium	The fire was finally extinguished by the use of water in about one hour.	
Fire growth is checked and no additional failures occur	No information is provided regarding fire growth and extent of fire damage. It is inferred that the fire remained limited to the switchgear of origin and cables adjacent to the switchgear itself.	
Fire is fully extinguished and fire brigade declares it as out	Using water, the fire was completely extinguished in about one hour.	This fire was relatively long (about one hour) compared to fires typically modeled in a fire PRA (10-30 minutes).
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Switchgear 1TA was lost, as it was the source of the fire. Fire damaged cables near the switchgear.	The impact of fire damage would likely have been predicted in a fire PRA.

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Cable failure impacts equipment outside the fire location	Switchgear failure and de-energization led to the unavailability of several components needed for normal reactor cooling and power operation. Cable failure led to failures of certain functions of ICS.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Loss of 1TA switchgear led to tripping of two reactor coolant pumps. The reactor power level started decreasing. At a certain point ICS had to adjust steam generator level to 50% and swap feedwater nozzles from main to auxiliary. It failed to do so because of cable damage.	
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The instrumentation was not affected in this incident. In-core thermocouple readings were the focus of the operators. Adequate attention was not given to cold leg temperature. Because of this the operators did not realize that rapid cooldown is underway and there is a potential for the reactor entering the thermal shock operating region.	It is not clear how much the operators were influenced by the fire and its effects (i.e., failures and smoke in the control room). In fire PRA, operator errors are modeled explicitly. Methodologies exist that attempt to model the influence of complex set of events on human error probability. However, it is interesting to note that this incident, since it occurred in non safety related switchgear with no safety related cables and equipment affected, would be considered as an insignificant risk contributor and would be screened out in the initial stages of the analysis.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Operators took the steam generator levels to 50% and swapped the feedwater nozzles, but forgot to close a main feedwater valve. This omission added to the overcooling scenario. The operators started high pressure injection system to makeup the water in the main coolant loop that had shrunk. HPI activation led to pressure spikes (twice) over the course of the incident.	Operator errors are modeled in fire PRAs. The available report attributes the error, at least in part, to the presence of smoke in the control room, although the actual role of the smoke remains unclear. Most PRAs assume that in-control room actions are not impacted by fires outside the control room.
Structural failures (if occurred) may jeopardize availability of equipment	No structural damage was reported.	

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Water when sprayed over electrical equipment may fail the exposed equipment	Switchgear 1TB was de-energized to allow for the use of water on the burning switchgear.	PRAs would not typically consider that nearby equipment will be de-energized to facilitate fire fighting.
The cooling effect of CO_2 may adversely impact equipment	Reference [16-1] does not indicate occurrence of such a phenomenon.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	Several independent failures occurred in the course of this fire. An isolation valve inside the containment had been left closed that prevented the use of auxiliary pressurizer spray. A push button was stuck on the control board that caused a device to cycle several times. The yoke bearing of a feedwater valve experienced a mechanical failure. The feedwater control valves experienced calibration drifts.	In this incident several independent failure occurred. In fire PRA, an important element of calculating the core damage frequency for a fire scenario is the proper accounting of independent failures that may occur in tandem with the fire. This incident demonstrates that such failures can occur and may influence the chain of events.

A16.5 Incident Analysis

The most important insight from this incident is that a fire in non-safety-related area led to a potential challenge to reactor safety. The fire occurred in a non-safety switchgear that is not co-located with any safety related cables or equipment. In a fire PRA this fire scenario would generally be considered as risk insignificant, and would likely have been screened out from detailed analysis because of the lack of any threats to safe shutdown equipment.

The significance of this incident also lies in the actions that the operators took in the control room in that they caused an overcooling transient that had the potential to cause a thermal shock. It is not clear whether or not the mistake made by the operators (i.e., failure to close the main feedwater valve) was influenced by the fire itself. However, by failing the ICS, the fire did put the operators in a position where they had to take additional manual control actions, and it was while they were taking these actions that the mistake occurred. Reference [16-1] also states that some smoke did enter the control room and implies that this was, at least in part, the reason that mistakes were made. The smoke ingress aspect of the incident is not well described in the available information; hence, it can not be determined whether or not there was any actual discernible impact on control room habitability.

In fire PRA, operator errors are modeled explicitly. Methodologies exist that attempt to model the influence of complex set of events on human error probability. In fire PRAs it is widely assumed that fires outside the control room will not impact operator actions that take place within the control room. In this case there may have been such an influence, although the evidence for this is inconclusive. The chain of events experienced during this fire incident (i.e., a fire in a non-safety area of the plant leading to a complex chain of events with operator interactions and mistakes) would not typically be identified as a risk significant scenario in a typical fire PRA.

In this incident the most significant operational impact was the overcooling transient coupled with high reactor pressures. The possibility of thermal shock of the main vessel has been addressed in some internal event PRAs. Fire PRAs commonly use the same event sequences as those used in the internal events analysis. However, often in the internal events analysis, the analysts make simplifying assumptions based on the likelihood of a given chain of events. In fire conditions, the likelihood of a given chain of events may be significantly greater than that calculated in internal events analysis. However, if the chain of events is eliminated during the internal events process, the fire analysis may not recognize that chain of events as a potential risk scenario. The fire versus internal events difference lies in the fact that fires can simultaneously impact several items including, in particular, cables. In the internal events analysis, the same equipment would be failed as a result of random factors that are not correlated. Sequences involving multiple random failures quickly become probabilistically insignificant. In this incident, the fire damage caused two of the four reactor coolant pumps to trip, failed parts of the Integrated Control System (ICS), and affected the control room operators to an undetermined extent.

This incident also demonstrates that even with rapid detection, fire fighting can be a prolonged process and that the application of a fire suppressant does not necessarily lead immediately to either fire control or fire extinguishment. In this case two initial suppression attempts were ineffective, and the fire ultimately burned for over an hour. In many current fire PRAs fire duration is based primarily on the manual fire brigade response time. This approach may not be a proper representation of the potential chain of events that may occur. Earlier PRA methods had commonly utilized generic fire duration probability curves based on historical experience. These curves would inherently capture this type of behavior, but are not amenable to plant-specific adjustments. This issue is discussed further in the body of this report.

It is also interesting to note that the neighboring switchgear (1TB) was purposely de-energized in order to facilitate fire fighting and protect fire fighters from electrical hazards. With the fire-induced loss of 1TA and de-energizing of 1TB, two opposite trains, albeit non-safety trains, of a system were taken out of service. This demonstrates that equipment may be lost from causes other than direct fire damage in a fire incident. That is, actions taken to support fire fighting may also lead to the intentional isolation of redundant trains and this may have unanticipated consequences. A parallel example of such a condition lies in the so called self-induced station blackout (SISBO) that has been incorporated in the procedures of a few power plants. The SISBO procedure instructs the operators to intentionally isolate as-yet unfailed equipment. This is done to isolate the adverse effects of a cable fire. Current fire PRA methodologies include provisions for analyzing the actions that should be taken by the fire brigade and are nominally capable of dealing with these kinds of actions. However, other than SISBO type scenarios, actions such as manual isolation of an unaffected train are rarely identified or considered. This is discussed further in the body of the report.

A final aspect of this incident that is of interest is the explosive nature of the initial electrical fault. It has been observed that certain electrical faults will be manifested as an energetic release of electrical/thermal energy. In this case, a 6.9kV switchgear faulted with an explosive release of energy substantial enough to have been heard in other areas of the plant. This is not the typical fire modeled in a fire PRA. Typical fire PRAs will assume a fire that ignites, grows within the initial fuel package, and then exposes and potentially spreads to adjacent combustibles. In this case, the initial fire initiation and growth behavior was essentially by-passed, and a rather substantial fire was apparently ignited as a result of the fault. There are no clear indications as to how extensive the initial fire actually was. However, the fire did clearly propagate and caused damage to cables outside of the originally involved panel. This has been an area of methodological debate, in particular, associated with the IPEEE process. See the body of the report for further discussion.

A16.6 References

A16-1 Licensee Event Report # 26989002, "Fire in 1TA Swtichgear Due to Unknown Cause", Oconee Nuclear Station, Unit 1, Event Date 01/03/89.

Appendix 17 - Analysis of H. B. Robinson, Unit 2 Fire on January 7, 1989

A17.1 Plant Description

H. B. Robinson, Unit 2 is a 665 MWE Westinghouse design, pressurized water reactor located near Hartsville, Southern Carolina. Unit 2 is the only nuclear unit on the site. The plant started commercial operation in March 1971.

A17.2 Chain of Events Summary

At the time of this incident the plant was in a refueling outage. At 22:30, on January 6, 1989, as part of an air test of the main generator, a maintenance crew erroneously connected the instrument air header to the main generator hydrogen manifold using a rubber hose. This allowed the bulk hydrogen supply, which is at 120 psig, to be directly connected to the 95 psig station compressed air system. The configuration was such that hydrogen flow to the generator was blocked, but flow into the Station Air System was not. Hence, hydrogen spread into the plant's general purpose compressed air system.

At the time this hose connection was established the Station Air compressor was out of service and the Station Air System was connected to the Instrument Air System. The Station Air System was in greater demand because air-driven tools were being used throughout the plant. This caused the majority of the hydrogen to migrate into the Station Air System.

Approximately one hour after the connection had been made, it was noticed that generator pressure had not increased. At approximately the same time a small fire was discovered in an air junction box inside the turbine building, on the turbine deck. The fire was extinguished quickly and no damage was noticed. Approximately three hours after the connection was made, a contract worker reported that flames were coming out of his air operated grinder. Upon this discovery, all work that could cause a spark was stopped and the use of the air system was prohibited.

Samples of the air were taken at several locations. The hydrogen concentration was discovered to range from 50% to 150% of lower explosive limit. The hydrogen had migrated into the entire system at practically all plant locations, including the auxiliary building and the containment. No further fires apparently occurred, and the system was eventually purged of hydrogen.

A17.3 Incident Analysis

This incident is of interest to the current review because it illustrates a somewhat unique point, namely, that unexpected fire sources can arise during a refueling outage. In this case, at least two minor fires occurred, and there was clearly an inherent potential for more, and perhaps more serious, fires. Only a few shutdown fire PRAs have been conducted. The typical methodology follows the same process as that used in an at-power fire PRA. It is unlikely that a typical fire PRA of any type would have identified an error of this type as a possible contributor to fire risk. In this event flammable gas was introduced into a system and areas of the plant that are normally void of such gases. Also, it created a condition where several, potentially severe fires could have occurred at the same time at different locations of the plant. The possibility of multiple fires is not addressed in fire PRAs.

A17-4 References

A17-1 Licensee Event Report # 26189001, "Hydrogen Introduced Into the Instrument Air System", H. B. Steam Electric Plant, Unit 2, Event Date 01/07/89.

Appendix A18 - Analysis of Calvert Cliffs, Unit 2 Fire on March 1, 1989

A18.1 Plant Description

Calvert Cliffs is a two unit nuclear power station located near Lusby, Maryland. Both units are 850 MWe Combustion Engineering PWRs. Unit 2 started commercial operation in April 1977.

A18.2 Chain of Events Summary

On March 1, 1989, Unit 2 was operating at 100% power. At 16:45 a fire was discovered in a control panel in the Main Control Room. An operator was in the process of verifying a repair on the over-speed trip mechanism of the Auxiliary Feedwater Pump trip/throttle valve actuator. As part of this procedure, the operator put the hand switch for the valve in the "shut" position. The shut position indicating light flickered and a buzzing noise was heard on the control panel. The operator repeated the action with the same result. The operators opened the panel cover and discovered a fire at the hand switch. Using a hand-held Halon extinguisher, the operators put out the fire in 1-2 minutes. In the meantime, a 10amp fuse in the associated circuit blew. Since the fire was extinguished quickly, the control room supervisor did not call out the fire brigade.

When the fire was discovered, a turbine building operator was called to reset the throttle valve. In the attempt to reset the valve, that operator discovered that a solenoid associated with the valve was smoking. There were no visible flames. The solenoid stopped smoking apparently when the 10amp fuse blew. The fire in the main control room panel caused some damage to wires nearby. No other damage was noted from this incident. This incident did not cause a significant safety hazard and its impact was limited to an isolated part of a safety related system. The lack of damage can be at least in part attributed to the immediate response of the operator whose actions had led to the fire being initiated.

A18.3 Incident Analysis

This incident caused very limited damage and had no real impact on plant safety. Hence, the fire was not severe from either a classical or nuclear safety perspective. It is included in this review because this is one of only a very few incidents in the U.S. lending insight into multiple fire ignitions in a single incident. In this case there was a small fire in the main control room, and an incipient fire (the smoking solenoid) in the auxiliary feedwater pump room. Once again, the common link in the fire is a common electrical circuit. In fire PRAs, the possibility of simultaneous fires in two different compartments is not generally addressed. See further discussion in the body of this report.

A18.4 References

18-1 Licensee Event Report # 31889004, "Auxiliary Feedwater Pump Trip Circuitry Fire in Control Room Due to Maintenance Error", Calvert Cliffs, Unit 2, Event Date 03/01/89.

Appendix 19 - Analysis of Shearon Harris Fire on October 9, 1989

A19.1 Plant Description

Shearon Harris is a 900 MWE, Westinghouse design PWR located in New Hill, North Carolina. The plant started commercial operation in May, 1987.

A19.2 Chain of Events Summary

On October 9, 1989, the plant was operating at full power. At 23:05, a turbine generator and main power transformer differential relay tripped and started a chain of events that led to fires at three locations involving one main transformer and the main generator. As a result of the relay trip, the main generator output breaker also tripped. This in turn caused a turbine trip and a reactor trip. The auxiliary feedwater system actuated as designed. However, the turbine driven pump failed to operate properly. Motor driven auxiliary feedwater pumps were used. The operators closed the main steam isolation valves to limit the cool-down rate.

The initial cause of the event was multiple ground faults in a bus duct near the "B" main power transformer. Reference [A19-1] states that the cause of the ground faults is thought to be aluminum debris carried into the duct by the forced air ventilation system used for cooling the bus duct. The debris is suspected to have entered the ventilation system as a result of two damper failures, one that occurred on February 27, 1988 and a second during the summer of 1989. The ground fault caused arcing over a fifty foot length of the bus. The arcing reduced the dielectric strength of the air. The air, per the design of the system, entered the bushing box of the transformer. This caused ground faults in the bushing box, which led to a crack in the low voltage bushings. The bushing crack, in turn, led to a spill of oil and ignition of a fire at the transformer (the first fire).

The faults in the main transformer bushing box and the "A" bus duct, caused the voltage of the generator neutral to become elevated. A current transformer was mounted around the neutral conductor, and was isolated from the neutral conductor by insulating tape. The insulation resistance of the insulating tape was apparently insufficient to withstand the elevated neutral voltage, and an electrical breakdown occurred causing the neutral conductor to short to ground. The arcing caused by this short burned holes in generator related piping, which in turn allowed generator hydrogen to escape and catch fire (the second fire). The oil in the main generator housing above the hydrogen fire was subsequently ignited (the third fire).

At 23:09, the Control Room was notified of a fire at the "B" main power transformer, and an oil fire on the second level of the turbine deck underneath the main generator. The site fire brigade was activated immediately. The fire fighters also noted a hydrogen fire on the second level of the turbine deck underneath the main generator. The deluge system at the main transformer activated as designed.

Off-site fire departments were also contacted shortly after the initiation of the incident to assist in the fire fighting efforts. Later, the prompt notification of outside fire departments was credited as having limited the damage caused by the fires.

As noted above, the auxiliary feedwater system actuated automatically in response to the incident. However, the turbine driven auxiliary feedwater pump tripped shortly after it started. The cause of the trip was later determined to be a spurious over-speed trip signal from the tachometer. No link between the failure of the auxiliary feedwater pump and the fire has been established, and this appears to have been an independent (random) failure event.

At 23:35, an alert was declared and the Technical Support Center (TSC) was activated. By 00:13 October 10 (a little over 1 hour after initiation of the event), the oil fire at the generator housing was extinguished. Also, the fire at the main power transformer was believed to be under control by the deluge system. The hydrogen fire underneath the generator was also considered under control.

By 01:45, a small residual oil fire at the main transformer was extinguished using portable dry chemical extinguisher. By this time, all three fires were considered extinguished. By 02:45 (2 hours and 40 minutes after incident initiation) walk-downs were completed to verify that all three fires were extinguished. Fire watches were posted at the fire locations and the main generator was purged with carbon dioxide.

A19.3 Incident Analysis

The fires in this incident were of relatively long duration, about 1 hour 45 minutes total, and were relatively severe from a classical fire protection perspective. However, from a nuclear safety perspective, the overall impact of the fires was relatively modest. The plant did trip automatically, and an auxiliary feedwater pump did fail, apparently a random failure. However, the operators responded appropriately to the situation and properly controlled the plant shutdown including proper control of the cool-down rate. This incident again demonstrates that not all fires that are severe from a classical fire protection standpoint are severe from the nuclear safety perspective. As noted elsewhere in this report, this is fully consistent with the findings of current fire PRA studies.

The incident is of interest to the current review primarily because it is one of the few incidents in the U.S. that involves multiple fires occurring concurrently. The incident demonstrates that multiple fires may occur simultaneously at different areas of a plant. As seen in other such incidents, one of the common links was a common electrical system. However, the secondary hydrogen fire was apparently the result of damage caused by the failure of the current sensor on the generator neutral cable so there are multiple contributing factors, rather than simply a common electrical system that becomes overloaded. Concurrent multiple fires are not addressed in current fire PRAs. As discussed in detail in the body of this report, current fire PRA methods could, at least in theory, predict the potential impact of multiple fires if the locations and characteristics of the individual concurrent fires could be established. However, there is currently no basis for identifying the frequency or characteristics of multiple fire incidents.

A19.4 References

A19-1 Licensee Event Report # 40089017, “Electrical Fault on Main Generator output bus Causing Plant Trip and Fire Damage in Turbine Building”, Shearon Harris Nuclear Power Plant, Event Date 10/09/89.

Appendix 20 - Analysis of Vandellos, Unit 1 Fire on October 19, 1989

A20.1 Plant Characteristics

Vandellos Nuclear Power Plant Unit 1, which is currently decommissioned, was a gas cooled, natural uranium fueled, graphite moderated reactor located 140 km South of Barcelona, Spain. It shared the site with Vandellos, Unit 2, a pressurized water reactor. Vandellos, Unit 1 started commercial operation in May 1972 and has not been operated since the October 19, 1989 fire incident described in this appendix. The rated thermal power of Unit 1 was 1750 MWt. It used a concrete pressure vessel and CO_2 as the primary coolant. Each unit had two turbine generators, rated at 250 MWe each. There were four steam driver turbo-blowers for primary circuit coolant (i.e., CO2) recirculation. After shutdown, one blower could provide sufficient cooling.

A20.2 Chain of Events Summary

At 21:39 on October 19, 1989, while the plant was operating at partial power level (about 80%), the high pressure section of turbine No. 2 ejected 36 blades. The turbine blade failure was later attributed to stress corrosion phenomenon. The blade ejection altered the balance of the turbine leading to high vibration and excessive friction around the turbine shaft. This in turn caused the shaft to come to a full stop within a few seconds. Vibration also caused the seals around the generator to fail allowing hydrogen gas to escape. According to available reports, the escaped hydrogen is thought to have ignited on the hot surfaces of the shaft. Available reports also state that a hydrogen deflagration did occur, but apparently caused no significant damage.

The ejected blades also cut through turbine lube oil lines. All oil pipes feeding the bearings of the high pressure side of the turbine and one pipe for the bearing located between the two low pressure turbines were broken spilling the lube oil. Hot surfaces caused by the excessive shaft friction are thought to have served as the ignition sources for the oil as well. The oil supply system, upon loss of oil pressure in the bearings, started all four oil pumps and transferred, in 55 seconds, close to 4,500 liters (more than 1,100 gallons) of oil to the broken pipes. A total of about 12,000 liters (more than 3,000 gallons) of oil spilled into the turbine building from the severed pipes during the course of this incident.

The control room became aware of the incident almost immediately because of the loud noise caused by blade failure, the reported hydrogen deflagration and observations made through a window from the control room that overlooked the turbine hall. At 21:40, a minute after blade ejection, the external fire brigade was called. At 21:54, 14 minutes after being notified, the off-site fire brigade arrived. It took them until 04:00 on October 20 (more than 6 hours from ignition) to extinguish the fire using hose streams.

Of the four coolant loops of the reactor, two (numbers 3 and 4) failed because of fire-induced cable failures. In addition to the turbo-blowers, the fire caused the shutdown heat exchanger (a defense in depth feature) to fail as well. Core cooling capability remained available through steam generators No. 1 and 2, their associated feedwater pumps and turbo-blowers. However, the control of feedwater flow proved to be difficult. The control air supply was lost because hot gases under the ceiling of the turbine building damaged the copper piping of the air system (this was presumably due to failure of solder joints in the piping). Operators, using SCBAs and hand held lighting, entered darkened and smoke filled valve rooms to manually adjust the flow control valves.

The turbine lube oil, as it was burning, cascaded down to the lower floors of the turbine building and created a pool of burning oil underneath the turbine. A part of the oil flowed down along a wall and behind a large (2m diameter) pipe from the circulating water system. A rubber expansion joint was located on the pipe near the location where burning oil was flowing down along the wall. The joint was directly exposed to the flames and softened. It eventually ruptured at the point that was closest to the wall. The rupture allowed seawater to spill into the basement of the turbine building. The joint itself, because of water flow, did not burn.

Water from the broken pipe joint collected in the basement of the turbine building. A sufficient amount of water escaped to cause a large pool to form. The building sump pumps did not activate because the cables feeding the pumps were damaged by the fire. The water also entered the reactor building's lowest elevation through an open door and through piping and cable penetrations. The water in the reactor building and turbine building basements eventually reached a depth of 81cm (about 32 inches).

The sprinkler system in the turbine building activated as designed. However, it did not control the fire because there were no sprinkler heads near where the fire occurred. It is interesting to note that, despite the proper operation of the sprinkler system protecting the hydraulic oil tank, the fire overwhelmed the sprinkler system and the tank was completely destroyed.

Smoke entered other areas of the plant and activated the suppression systems in areas where there were no actual fires burning. Smoke also entered the control room. Self contained breathing apparatus (SCBA) were issued to control room operators. However, the SCBAs were not used (apparently the smoke level never reached a point where operators felt the SCBA was needed). Portable fans were brought in to clear the smoke and provide fresh air into the control room.

The fire ultimately damaged 90% of Turbine Generator No. 2 and 10% of Turbine Generator No. 1 as well as numerous cables and the one pipe joint.

A20.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A20-1] through [A20-4]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	Stress corrosion eroded the strength of turbine blades. The blades were not inspected specifically for this phenomenon.	
Prior to the incident	The door between basement of Turbine and Reactor Buildings was left open. This was apparently in violation of administrative control requirements.	Often a small probability is assigned to the likelihood of a door being open that is administratively required to be kept closed. This event points to the importance of inspecting the plant in a detailed walkdown, as part of fire PRA, where the existing conditions are observed and recorded carefully. However, the possiblity of the door being left open might still be judged small if the door happened to be closed at the time of the walkdown.
Prior to the incident	The plant was operating at 400 MWE output. Turbine Generator Number 1 at 190 MWe and Number 2 at 210 MWe.	
00:00	At 21:39 on October 19, 1989, Turbine No. 2 ejected 36 blades from wheel number 8 because of stress corrosion phenomenon. This led to high vibration of the turbine (located on elevation +16.0m), and friction around the shaft, which caused the shaft to come to full stop within a few seconds of blade failure. The friction energy caused the shaft to reach red hot temperature range. A vibration alarm (>180micron) and Turbine Generator No. 2 trip annunciation was received in the control room. The control room had a window overseeing the turbine generators. A flash was seen in the control room and the shift operator manually tripped the reactor. Fire was observed in the high pressure turbine housing and in the generator vent at the excitor side. Fire alarms (audible and luminous) were received in the control (the exact time of the alarm is not known)	In a typical fire PRA, ignition of oil fire in turbine building is assumed to occur from an arbitrary cause. The specific causes are generally not addressed explicitly. However, it is commonly assumed that oil is released, ignited and a large fire ensues.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The vibration (actually a jump) caused the generator's terminals and the seals to fail and allowed 5m^3 of hydrogen to escape. The escaped hydrogen ignited on the hot surfaces of the shaft and deflagrated. An eyewitness described hydrogen burning as a fire ball leaving the bottom of the generator, traveling horizontally towards the bottom of the turbine. The eyewitness noted that the fireball took a spiraling (scrolling) movement as it went from the generator towards the turbine. The deflagration was very short and it only charred (not burnt) the areas where it touched. The instrumentation within the area were tested after the fire and were found in working condition. However, the deflagration did damage a movable ceiling at elevation +16.0 meters.	Two types of fires occurred - a deflagration of hydrogen gas and a large oil fire. In a typical fire PRA, only one type of fire is postulated. Since, extensive damage is often postulated for turbine building fire scenarios, lack of consideration of simultaneous occurrence of a deflagration and a fire is of minimal consequence. In this particular case the hydrogen fire apparently caused no significant damage.
--	The ejected blades cut through turbine oil lines. All oil pipes feeding the bearings on the high pressure side of the turbine and one pipe for the bearing located between the two low pressure sections were broken. Hot surfaces caused by shaft stoppage served as the ignition sources for the oil as well. The oil supply system, upon loss of oil pressure in the bearings, started all four oil pumps that sent the oil from the storage tank to the broken pipes. Per the design feature of the oil system, it was impossible for the control room to manually stop the oil pumps when they started on low oil pressure. This eventually led to 11,000 liters (about 3,000 gallons) of oil being pumped out through the open pipes.	The oil fire was ultimately the fire of most significance. In a typical fire PRA the specific details of oil fire is generally not considered. This event points out that the analysts cannot assume that the quantity of oil involved in the fire is limited to the oil within the turbine. Under special conditions, the entire contents of the oil storage tank may have to be postulated at a location away from the oil storage tank itself.
--	A cascade of burning oil poured to the lower elevations of the turbine building. Oil also poured on cable trays, causing part of the flow to be diverted horizontally. In all cases the oil was burning as it was flowing about. Eventually the bulk of the oil dropped down to the lowest elevation floor, formed a burning pool and flowed towards the floor drain. The pool fire damaged all of the equipment in its pathway to the drain.	In this case the fuel (oil) was quite mobile and spread readily. In a typical fire PRA, fires are assumed to occur in a particular location. Hence, this aspect of the fire may not have been captured in a typical fire PRA. Severe oil fires occurring in various areas of the turbine building would likely have been postulated as noted above, but each scenario would likely have considered a relatively confined fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:01	Within 55 seconds of blade failure, close to 4,500 liters (more than 1,100 gallons) of oil were spilled from the broken pipes that fueled the fire (see note 1). (See 00:06 below - eventually 12,000 liters (more than 3,000 gallons) of oil was ejected from the broken pipes.)	Even by the standards of a typical fire PRA turbine hall fire scenario, this is a very large quantity of burning oil. Some fire PRAs do consider catastrophic loss of the turbine hall. However, other fire scenarios would typically involved more limited fires.
00:01	At 21:40, the external fire department was called by radiotelephone to respond to the fire and the plant management and reserve personnel were notified (per procedures). The plant maintained a fire brigade of plant personnel who were trained and certified in fire fighting techniques. A 5-member team was on site for every shift. If the fire brigade had to be activated, the reserve personnel would be called in to look after the plant while the brigade is focused on the fire.	
--	The oil fire propagated to other combustibles -- some of the cables in the lower elevation of the turbine hall and the hydraulic oil in its storage tank. The insulating material of cables were PVC.	
--	A part of the oil went down against a wall, behind a 2 meter diameter pipe from the circulating water system. A rubber (reinforced by a metallic mesh) expansion joint was located at this same location. The expansion joint was 2m in diameter (as was the pipe), 40cm long and 1.5cm thick. The joint became directly exposed to the flames and softened. It eventually broke from water pressure at the part that was closest to the wall opening a vertical gash in the joint of about 2 meters long (this is about 1/3 of the circumference of the joint). The area of the break is estimated to be about 2,000 cm^2 (310 in^2) The opening allowed seawater to spill into the basement of the turbine building. Burning oil collected on top of the pool created by the spilled water. The expansion joint, because of water flow, did not burn. The normal flow rate through the circulating water pipe is $12m^3/s$ (about 190,000 gpm) at about 18°C temperature.	This event, failure of the expansion joint, would not typically be captured in a fire PRA. The location of the joint with respect to the oil pipes and the turbines led to the possibility of direct flame impact. In a typical PRA, the chain of events leading to a breach in the integrity of a water carrying system is not considered. As mentioned above, in a typical turbine building fire analysis, it is postulated that the fire is large and damages all those items that are susceptible to fire. However, large water-filled pipes and associated equipment are not generally considered vulnerable to fire damage because of the large heat capacity of the water inside the pipe. This event directly contradicts this common assumption, at least in the case of flexible rubber expansion joints. Failure of the pipe joint did lead to significant flooding of two buildings. PRAs would not typically consider a large flood concurrent with a fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The sprinkler system in the turbine building activated as designed. However, it could not control the fire because there were no sprinkler heads near where the fire had started. The sprinkler system inside the turbine building only covered the oil storage tanks (lubricating and hydraulic oils) and big motors. The rest of the Turbine Building had fire detectors only. At the hydraulic oil tank, the fire suppression system was an open head (deluge type) system. This system was activated by heat detectors with one alarm level. The detector did activate, the fire water pump did start and valves to feed the sprinklers did open. At the lubricating oil tank, the sprinklers heads were also of open (deluge) type. The system activated on heat, optical and smoke detectors that were arranged in two alarm levels. At the first alarm level, the fire water pump was started and a permissive signal was given for opening the isolation valve of the concerned area from the control room. At the second alarm level, pump operation would be confirmed and the valve would open automatically, thus allowing fire water to spray from the open heads.	The fixed fire suppression systems did actuate as designed but covered only select areas of the building. They were apparently ineffective at either controlling or extinguishing the fires. In conducting a fire PRA, as part of the detailed analysis, the characteristics of the fire protection system for each fire area is studied. Such systems are commonly credited with suppressing fires quickly and effectively (on the order of 95% reliability or higher). This incident illustrates the need to consider both the system design and the fire threats that it may face in assessing system effectiveness. Note that if only manual fire brigade actions are postulated, the likelihood of a large fire in the turbine hall would be postulated to be significant.
--	As noted above, water from the ruptured expansion joint and the fire suppression systems collected in the basement of the turbine building. Although, there is no eyewitness confirmation, it is inferred in the available reports that the burning oil floated on top of this water spreading the fire further.	Occurrence of major flooding as a result of fire is not postulated in a typical fire PRA. Although, theoretically speaking, current methodologies can accommodate the proper identification of such events, in a typical fire PRA the progression of the event scenarios is not carried through to such level of detail to allow for the identification of additional external event phenomena.
--	The sump pumps in the turbine building did not activate because the cables feeding the pumps were damaged by the fire.	Cables for a system such as sump pumps would not typically be identified in a fire PRA. Hence, the potential for loss of these pumps would not typically be captured by a fire PRA analysis.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The water also entered the reactor building lowest elevation because of an open non-water tight door. There were also cable and pipe penetrations in the wall separating the two buildings that would have allowed the water through. The flood depth reached 81cm at elevation +3.50m of the turbine and reactor buildings.	See note on fire and flooding above.
--	Smoke entered the control room through the ventilation system. The control room is located at +28.20m elevation of the electrical/control building, next to the Turbine Building The control room was about 50m from the fire itself. SCBAs were provided for the operators, but they did not use them.	Propagation of smoke and its impact on plant personnel is typically addressed using conservative and simplified models. The possibility of smoke egress into the control room is often not considered, unless there are clear indications that this could be possible. If a fire PRA were to be conducted of Vandellos 1 prior to the incident, given that the control room ventilation communicates with the turbine building, the analysts would likely have postulated the possibility of smoke inside the control room. Actually, it would have conservatively been assumed that the control room would become inhabitable.
00:06	In a few minutes, the three oil transfer pumps, transferred all the oil in the storage tank into the severed oil piping. A total of about 12,000 liters (3,000 gallons) of oil spilled into the turbine building from the severed pipes and caught fire (note 1).	
--	The cables for non safety 5.5kV switchgear DG2A that provided power to condenser, feedwater and vacuum pump loads was lost.	
00:07	At 21:46 Turbo-Blower No. 4 (provides primary coolant flow) failed because of cable failure. The cables to safety related 5.5 kV switchgear DS4A, that powers Turbo-Blower No.4 was lost. A 10m length of cable tray, located in the lowest level of the turbine building, was damaged from direct exposure to fire. It is suspected that cable fire contributed heavily to smoke generation during the fire.	The cable trays were doused with burning oil. In a typical PRA cables are assumed to be exposed to external fires. In this case a PRA would have likely postulated a pool fire on the floor below the cables. The observed damage would likely have been covered in fire PRAs as part of a postulated large fire. However, this incident points out that the typical fire propagation calculation methods may not be valid for such a scenario.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	At 21:49 Turbo-Blower No. 3 and the feedwater pumps for heat exchangers no. 3 and 4 failed because of cable failure. The cables to safety related 5.5 kV switchgear DS3A, that powers Turbo-Blower No. 3 was lost. As for DS4A, 10m length of cable tray was damaged at the lowest level of the turbine building.	
00:10	Electric cables of the power supply for the shutdown heat exchanger was lost.	
--	Power to the safety and normal lighting was lost. Battery powered emergency lighting remained functional.	Loss of lighting is not typically explicitly postulated in a fire PRA. This incident points out that for human action analysis and human error probabilities, severe performance shaping factors may have to be postulated.
--	Per Reference [A20-3], none of the cable failures led to spurious actuations or instrumentation drift on the control board.	It is not known whether or not the potential for spurious actuations did, in fact, exist. In particular, since the damaged cables were all in the Turbine Building, it is not clear what portions of the impacted instrument and control circuits were threatened. Hence the implications of this “negative” finding regarding spurious operations are not clear.
00:15	At 21:54, outside fire brigade arrived. Up to 30 fire fighters came to the site to help in putting out the fire. Outside fire fighters were not familiar with the plant and feared radiological exposure. To alleviate these problems, a member from the available plant personnel was assigned to each fire fighting team.	In typical fire PRAs, the impact of external fire brigade on the progression of the fire is combined with the plant brigade in an overall manual fire fighting model. In this incident, the external fire brigade did not have any adverse effects on the fire. However, the training and familiarity of external fire brigades with plant layout and special conditions may need to be taken into account when it is assumed that a large turbine building fire will eventually be brought under control.
--	Fire fighters used hose streams to attack the fire. They attacked the fire from elevation +9.00m and +16.00m. The fire fighters had to work in total darkness using hand-held flashlights. There were no additional failures attributed to the fire fighting activities.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	Smoke was pumped into other areas of the plant by the ventilation system. In the reactor building this activated the suppression system at certain locations. The air intake of the reactor building ventilation was in the turbo-generator area of the Turbine Building, above elevation +16.0m. Also, the doors between the turbine and reactor buildings at elevation +3.50m and +9.00m were not tightly closed.	The spread of smoke to areas remote from the fire points out that some special attention is warranted in the human error probability evaluation. Plant conditions may be degraded by movement of smoke, and therefore, human error probabilities taken directly from the corresponding internal events PRA may not be applicable. It is also interesting that this incident involved spurious actuation of a fire suppression systems in areas remote from the fire. In the U.S. reliance on smoke detectors for fire suppression actuation is no longer common (due largely to adverse spurious actuation experience). No damage due to suppression activation was reported.
--	Hot gases accumulated under the floors and the ceilings. Some equipment damage occurred near +9.00m ceiling at areas not reached by the flames. No damage were noted at elevations below the ceiling level. Copper pipes of the control air system melted under the ceiling and caused failure of automatic control of feedwater control valves.	The loss of the control air system piping integrity would not be captured in a typical fire PRA. Fire PRAs typically focus on cables, and may not consider the loss of other equipment. Some special attention to solder-joint air control supply piping in fire PRAs may be warranted if, for example, the operation or failure of air-operated valves is risk important.
--	Although the main part of the fire was only 10 meters from the lubricating oil tank at elevation 9.00m, the combined effect of sprinkler system and fire brigade hose streams managed to protect the tank from catching fire.	
--	The hydraulic oil tank was entirely destroyed by the fire, despite the presence of and successful operation of the sprinkler systems. This tank was located at elevation +3.50m, under the high pressure side of the turbine. It was doused by the burning oil raining down from the elevations above this point. The access to the area became impossible for the fire fighters during the first hour. Therefore, the tank did not benefit from the fire fighting activities.	This incident points out that a fixed suppression system may be overwhelmed by the fire. An important basic assumption underlying fire PRA methodology is that all fire protection systems are properly designed and will be effective against postulated fire threats. This incident points out that, at least in such areas as the Turbine Building where large concentration of combustible materials exist, this underlying assumption may not be valid in all cases.
--	From live broadcasts of the fire on TV and radio, many plant personnel heard about the event and came to the plant to help.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:30	The ventilation system for the control room was stopped to prevent further smoke ingress. Portable fans were brought to the control room to clear the smoke and bring in fresh air from non-smokey areas of the plant. Operators remained in the control room at all times from the beginning of the fire and did not have to wear breathing apparatus. No equipment failures occurred because of the smoke in the control room.	Smoke in the MCR was apparently not severe given that operators never felt the need to don their SCBAs. In a fire PRA conservative assumptions are made if smoke is assumed to enter the control room. This would typically lead to MCR abandonment. However, it is also rare for a fire PRA to postulate that smoke from fires outside the control room would actually enter the control room.
--	Operators did not need to take any actions within the areas impacted directly by the fire. However, the operators had to take actions at other parts of the plant that were either without a functioning lighting and/or engulfed in smoke. Also, the public address system was not functioning as a result of the fire.	Fire PRAs will typically make conservative assumptions with regard to operator actions. Actions that require entry into a smoke-filled room would not typically be credited. By the same token, most fire PRAs do not explicitly consider potential smoke spread, and would commonly assume that areas not directly involved in the fire could be safely entered for manual actions. Hence, it is likely that a fire PRA would have given credit to many of the cited manual actions that were taken.
01:54	Beyond 23:33 no additional electrical faults appeared.	It can be concluded that the effective fire duration was about 2 hours. This brings up an interesting issue about the duration of a fire. From PRA standpoint, when the fire stops to propagate such that no additional failures of safety related equipment would occur, the severity of the fire, given the typical compartmentilization of the plant, becomes of secondary importance to the risk model. Attention to such detail, of course, is non-conservative and may not be warranted for most fire scenarios of a PRA.

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:00	In the first two hours of the incident, the feedwater and condenser pumps were used in an on/off mode of operation (i.e., the pumps were run at full flow or stopped). Operators were able to regain controlled auxiliary feedwater flow to main heat exchangers No. 1and 2 by manually adjusting the flow control valves at the valve location at elevation +9.00 of the reactor building which was filled with smoke. The operator had to use an SCBA to be able to approach the valve. Although there were no specific written procedures for the actions taken by the operators at those valves, the operators' experience (over 15 years) in plant operation and periodic training were considered as key contributors to the success of valve manipulation operations. The operators knew the proper position of the valves to stabilize water levels in the turbo-blower's condensers and in the heat exchanger. During the periodic training (administered for one week once per six weeks), manual adjustments to the automatic control of the system was always covered.	See note above about operator actions and smoke spread. In a typical fire PRA, no credit is given to operator actions beyond established procedures. Clearly, this event demonstrates that the assumptions regarding non-proceduralized actions as used in fire PRAs are conservative.
03:51	At 01:30, the fire was declared under control. The damage was later estimated to be 90% of Turbine Generator No. 2. The other turbine generator did not sustain any damage.	
04:21	At 02:00, the intense spraying on the fire stopped.	
06:21	At 04:00, fire was declared as completely extinguished	

Note 1 - There is some inconsistency between two sources regarding the total quantity of oil spilled and spill rate. A second source reports that 6000 liters spilled in the first 6 minutes and a total of 15,000 liters burned during the fire.

<u>Equipment Damaged</u>

- Turbine Generator No. 2
- Turbine auxiliary equipment
- Electrical cables, that led to failure of:
  - Turbo-Blowers No. 3 and 4
  - Feedwater pumps to heat exchangers No. 3 and 4
  - Turbine building sump pumps
  - Control air to valves
  - Shutdown heat exchanger
  - Area lighting in many parts of the plant
  - The public address system
  - Condenser control valves

Damaged Areas

– About 90% of Turbine Generator 2 was damaged. Smoke propagated into the control building and the control room. Flooding occurred at the lowest elevation of the Turbine Building and Reactor Building.

Impact on Core Cooling

Core cooling was maintained at all times. At no time during the fire, did core cooling functions stop. Fuel cladding, the primary envelope and the containment were not adversely affected by the fire. Core cooling capability remained available through steam generators No. 1 and 2 and associated feedwater pumps and turbo-blowers. Two turbo-blowers remained fully functional (i.e., blower speed control remained available). Only one blower is needed to provide sufficient core cooling. However, the control of feedwater flow proved to be difficult. Control air supply was lost. In the first two hours, the feedwater flow control was achieved using the system in an on/off mode of operation (i.e., full flow or stopped). This caused the pressure and temperature of CO_2 in the primary circuit to oscillate around a large range. The range, although outside the normal operating values, remained within the authorized limits. The flow control valves for the steam generators were locally (manually) adjusted after the second hour. A previous computer simulation of the event found that if the remaining two turbo-blowers had been lost and complete shutdown of the feedwater pumps had occurred, core damage was estimated to ensue at about 70 hours after the initiation of these additional failures. The long time period is mainly due to the thermal inertia provided by the gas-graphite reactor design. Given this time period, some substantial recovery actions could have likely been accomplished to prevent core damage (as demonstrated by other events covered by this review).

Rediological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A20.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared to the elements that make up a typical fire PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Vandellos 1, Oct. 19, 1989**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubricating oil and hydrogen were the primary combustibles in this event. Cable insulation was a partial contributor to the combustible load. Hydraulic oil also caught fire.	
Presence of an ignition source	A turbine blade ejection event was the root cause of the fire, but ignition was attributed to hot surfaces created by the severe vibration of the shaft that led to shaft stoppage from friction.	
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Blade ejection led to double ended break of several oil pipes and generator seal failure. Oil and hydrogen ignited on hot shaft surface.	In a typical PRA, only those sources of ignition that are present at all times are considered. The possibility of an accident creating an ignition source is not generally modeled. However, since the frequency of fire initiation is based on a statistical analysis of the fire events, the impact of unusual conditions leading to fire ignition is covered by those frequencies to the extent experienced by the fire events. Given this understanding, a current fire PRA would consider oil/hydrogen fires as a result of turbine failure.
Fire growth within the combustible or component of original ignition	Hydrogen deflagrated through its vapor cloud and dissipated rapidly. Oil started burning and flowing downwards. It created a burning pool of fire under the turbine and along various cable trays.	The mobile nature of the oil would not be explicitly modeled in a typical fire PRA. For example, the oil cascading onto cable trays directly would not typically be captured. Rather the fires wold likely be postulated to be an oil pool on the floor. Several such fire locations would be postulated individually.
Fire propagates to adjacent combustibles	The fire propagated to cables inside cable trays where the oil had fallen. Cascading oil also caused the hydraulic oil storage tank to catch fire.	See note above regarding the mobility of the initial fuel. Fire PRAs typically considered fire source that remain where they initiate.
A hot gas layer forms within the compartment of origin (if conditions may allow)	Hot gas layer formed under the ceilings and caused damage at elevation +9.00m.	

Fire Scenario Element	**Incident - Vandellos 1, Oct. 19, 1989**	**Fire PRA Insights**
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke propagated to other parts of the plant and caused initiation of automatic suppression system. Smoke entered the control room. Mitigative steps were taken to minimize the impact of smoke on the operators. The operators did not have to leave the control room.	This event verifies that suppression systems outside the fire area may become activated from smoke ingress into other parts of the plant depending on the system design (in this case actuation by smoke detectors). Such scenarios are typically considered in fire PRAs conducted for U.S. plants as part of a deterministic survey of various fire related issues.
Local automatic fire detectors (if present) sense the presence of the fire	Automatic fire detectors sounded an alarm inside the control room in a very short time after fire ignition.	
Alarm is sounded automatically in the control room, locally and / or other places	The control room became aware of the fire almost immediately because of the noise caused by blade ejection and by visual observation through a window overlooking the turbine hall.	
Automatic suppression system is activated (if present)	Sprinkler and deluge systems inside the Turbine Building were activated as designed. However, there were no coverage in some of the areas where fire occurred and therefore, it could not control the fire.	
Personnel are present in the area where fire occurs	Personnel were present in the turbine building when the event started. There were eyewitness accounts of how hydrogen gas deflagrated and how oil cascaded down to a lower floor.	
Control room is contacted or fire alarm is sounded	Control room personnel became aware of the fire almost immediately because of the window between the control room and the turbine building and the loud noise caused by blade ejection.	
Fire brigade is activated	Outside fire brigade was called within one minute of fire ignition. A 30 person team responded and applied water hose streams to the fire.	
Fire suppressant medium is properly applied	Hose stream was used to fight the fire. The sprinkler system had only partial coverage of the building	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
Automatic fire suppression system is activated	Automatic sprinkler and deluge systems were activated but, because of lack of coverage in the area of fire proved to be ineffective in controlling the fire. In the case of the hydraulic oil system, since the fire fighters did not train their hose streams on them, despite the sprinkler system, the tank was destroyed by the fire.	This event demonstrates the importance of special conditions influencing the effectiveness of fire suppression system. One of the objectives of walkdowns conducted as part of fire PRA is to identify special conditions under which the suppression system may fail to be effective. In a fire PRA it is assumed that the fire protection system is properly designed to handle all possible fire scenarios of the area. The possibility of the suppression system being overwhelmed is not considered.
Fire suppressant medium is properly applied to where the fire is	There is no evidence in the available sources that the fire fighting efforts led to additional damage or complications, including areas where spurious actuations were observed.	
Fire is affected by the suppression medium	It took about 4 hours for the fire brigade to control the fire, and another two hours to extinguish the fire	This is a rather long fire in comparison to fire typically postulated in a fire PRA.
Fire growth is checked and no additional failures occur	At about 2 hours after the start of the fire no additional failures were observed.	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire	The burning oil cascaded down to the lower elevations of the turbine building. It caused the failure of cables in cable trays underneath the turbine and it caused the failure of a rubber expansion joint on a 2m diameter circulating water pipe. The rubber failed from softening under high temperature conditions and led to water spilling into the basement of the turbine building. Heat damage breached the control air piping and led to loss of control air pressure. Smoke from fire initiated automatic suppression systems outside the immediate fire area. Smoke propagated to other parts of the plant including the control room through the ventilation system that interacted with the turbine building. Some minor structural damage was later noticed that was attributed to hydrogen explosion.	In fire PRA the possibility of secondary effects, such as flooding caused by expansion joint failure, is not typically considered. Large water-filled pipes are commonly assumed to be invulnerable to fire damage. This event demonstrates that in fire PRA the analysts should focus attention on the specific chain of events that may ensue given a fire's propagation. The loss of the control air piping also would not typically be considered in a fire PRA. Smoke propagation is modeled in fire PRAs using simplified assumptions. At Vandellos, if a fire PRA was conducted prior to this incident, the possibility of smoke entering the control room and other buildings would have been predicted from the information obtained during plant walkdown.
Cable failure impacts equipment outside the fire location	Cable failures caused the failure of No. 3 and 4 heat exchangers (led to turbo-blower failure) and failure of control air system that led to the failure of remote control capability of the flow control valves to No. 1 and 2 heat exchangers. Cable failure caused the failure of the sump pumps and therefore the water from the suppression system and circulating water system water flooded the basement of the turbine building. Per Reference [20-3], no spurious activation of equipment was observed.	The control and power cables of such non-safety related components as drain pumps are not traced in a fire PRA. Although, in this case flooding had minimal effect on the core cooling functions and recovery actions, this incident points out that lack of knowledge about non-safety related components has the potential for indirectly affecting the analysis.

Fire Scenario Element	**Incident - Vandellos 1, Oct. 19, 1989**	**Fire PRA Insights**
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Operators initiated a reactor shutdown almost immediately after the fire. Some defense in depth equipment were lost to the fire. Core cooling was achieved through the use of two remaining turbo-blowers and feedwater flow to the steam generators.	More than one safety train was affected by the fire. See further notes above.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	Operators apparently responded properly to the incident. Some smoke did enter the control room. However, the control boards were not adversely affected by this fire. The operators remained inside the control room at all times. They had SCBA units available to them, but did not use them.	In a fire PRA, if the control room is postulated to be filled with smoke, no credit would be given to further operator actions from the control room. In this incident, the operators remained in the room and continued to take proper actions to maintain core cooling despite some smoke ingress. By the same token, it is rarely assumed that smoke from fires outside the control room would actually enter the control room, let alone in quantities sufficient to cause abandonment. Most abandonment scenarios derive from fires that start in the control room itself. Hence, a fire PRA would likely not have postulated abandonment for this particular fire scenario.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators manually adjusted the flow control valves of the functioning heat exchanger, by donning SCBA and walking through darkened and smoke filled compartments.	The operators took actions under environmental conditions that in a typical fire PRA would not be given any credit for. In particular, actions in smoke-filled rooms would not typically be credited. By the same token, smoke spread is rarely considered explicitly, and a typical fire PRA would assume that areas not involved in the actual fire would be accessible. Hence, it is likely that a fire PRA would have credited many of the actions taken by operators.
Structural failures (if occurred) may jeopardize availability of equipment	Hydrogen deflagration had some impact on the movable ceiling at elevation +9:00m.	
Water when sprayed over electrical equipment may fail the exposed equipment	No evidence of water damage to electrical equipment is provided.	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
The cooling effect of CO_2 may adversely impact equipment	Only water was used or was activated for fire fighting.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The only pre-existing condition was the fact that the door between the turbine and reactor buildings that was left open. The door was not water tight and there were piping and cable penetration that would have allowed water through into the reactor building regardless of the position of the door. Hence, this had minimal impact on the development of the incident.	Fire PRAs would have assigned a very low probability to this door being left open based on the existence of administrative controls requiring that the door be kept closed.

A20.5 Incident Analysis

The Vandellos, Unit 1 fire incident is considered a major fire from the classical fire protection perspective. The fire also presented a modest challenge to nuclear safety. The fire caused extensive damage, failed several key safe shutdown related components, created an adverse environment for the operators in the control room and in other areas of the plant, and ultimately led to the permanent shutdown of the plant.

The root cause of the fire is failure of a turbine wheel and blade ejection caused by stress corrosion of the blades. The configuration of turbine oil pipe routing with respect to the turbine blade trajectories influenced the severity of the incident in that the ejected blades severed the oil piping at several points. Also, the design of the lube oil pumps, which auto-started on loss of oil pressure, contributed to the very large quantity of oil released into the turbine building in a very short time period. Operators were unable to stop these pumps from the main control room, and presumably, manual local shutdown was not possible due to the fire and/or short time period involved with the oil discharge (the total inventory was apparently discharged within about six minutes). In a typical PRA, fire initiation is modeled using statistical analysis of actual incidents. The actual configuration of the systems that may or may not influence the occurrence rate or initial severity of a fire is not explicitly taken into consideration.

Two ignitions took place in this fire incident – an oil fire and a hydrogen deflagration. Since the hydrogen fire did not cause much damage, outside of superficial charring of cables and equipment, it did not have any serious contribution to the overall incident. In a typical fire PRA, the possibility of multiple, simultaneous of concurrent fires is not modeled. A hydrogen deflagration event, and the associated pressure effects, are also not typically considered. However, it must also be noted for areas such as a turbine building where large quantities of flammable materials are present, in fire PRAs it is often conservatively assumed that the fire would affect the entire building. This would inherently encompass this scenario.

In a typical fire PRA, fire-induced damage is limited to failure to function or spurious actuation of active components. Other types of potential failure are not typically considered in fire PRAs. For example, in this incident, the rupture of an expansion joint of a water-filled pipe from direct exposure to flaming oil led to the flooding of the basement of the reactor and turbine buildings. In this case flooding of the basements had little impact on the progression of the events and core cooling function. However, a typical fire PRA would consider the likelihood of failure of a water-filled component (e.g., expansion joint) to be invulnerable to fire damage; hence, the potential problems associated with flooding concurrent with a fire would not be captured in a typical PRA (with the possible exception of flooding due to fire water discharge). A second example is the heat-induced loss of the control air piping and loss of control air pressure. A typical PRA would not currently consider this potential. This could be an important aspect of some scenarios, if for example, air operated valves are involved in the scenario (either their failure on loss of air or reliance on their operation for plant shutdown). In this case, it is presumed here that the piping was probably of a soldered copper type, and the heat caused failure of the solder joints. Other types of piping would not likely be vulnerable to similar fire damage. A third example is the loss of plant lighting systems. The fire apparently caused loss of lighting in several areas of the plant. This is cited as a specific complicating factor in the fire fighting response and in operator actions taken locally. A typical fire PRA would not trace lighting cables nor consider the potential impact of their loss. In this case, emergency lighting was available. Fire fighting efforts in the turbine hall were apparently impacted significantly, but a number of local operator actions were successfully taken, including in some darkened areas.

In a typical fire PRA, the control and power cables for sump or drain pumps are usually not traced because these pumps have no direct reactor safety function. This incident points out that even those non-safety grade systems that require control and power circuits may become unavailable from the fire itself, and that their loss may complicate a fire incident. This could have implications for events involving the release of significant quantities of fire fighting water, or situations where a water-filled pipe may be vulnerable to failure (e.g., direct flame impingement on an expansion joint as in this case). The loss of sump pumps may lead to flooding problems that would not be captured in a typical fire PRA.

The need to consider the effectiveness of a fixed fire suppression system is mentioned in most fire PRA methodology documents. However, specific guidance on how to accomplish an effectiveness assessment is lacking, hence, effectiveness assessments are often not incorporated into actual analyses. Certainly, the phenomena that would lead to degradation of the effectiveness of a suppression system are difficult to identify, analyze and quantify in terms of suppression reliability. Typical PRAs will assume that if the suppression system actuates, then the fire will be controlled and/or suppressed and that any subsequent damage would be prevented. While exceptions exist, this is commonly given a high reliability - on the order of 95% success rates or higher. In this incident, the suppression systems did not cover those areas where the fire occurred (i.e., the general turbine building sprinklers) and/or were inadequate to deal with the fire that occurred (i.e., in the case of the deluge system for the hydraulic oil tank). Fire-induced damage continued well after actuation of the suppression systems. This possibility is not covered in typical fire PRA methodologies and applications. This incident also reiterates that a fire duration on the order of several hours is possible.

Smoke entered several important areas of the plant, including the control room. Operators managed to function properly and maintain core cooling functions with available equipment. While SCBA equipment was available in the control room, it was never used indicating that only a modest amount of smoke must have made its way to the control room. Control room ventilation was shut down to prevent further smoke ingress and portable fans were brought in to provide ventilation. Other actions were successfully undertaken that required operators in SCBA to enter smoke-filled compartments in order to manipulate certain valves manually. The situation with regard to current PRA practice is somewhat dichotomous. On one hand, a typical fire PRA would assume that the presence of smoke in an area would prevent operator actions in that area. This incident illustrates that this fire PRA assumption may be conservative since operators did take actions successfully in smoke-filled areas using SCBA equipment. On the other hand, fire PRAs rarely give explicit consideration to the potential for smoke spread to areas not directly impacted by the fire. In particular, operator actions in areas that are not actually involved in the fire are widely credited without explicit consideration of potential smoke spread paths. Performance shaping factors are often applied in these cases, although not universally, to reflect an increased likelihood of failure for actions taking place outside the main control room. Hence, current PRA practice contains elements with the potential to introduce both conservative and optimistic assumptions. Overall, the "trick" would appear to be to achieve a proper balance between the two.

Smoke also caused the activation of fire protection systems in other parts of the plant where fire had no direct impact. The suppression system actuations in these areas had no known impact on plant equipment. However, this points out that the spurious activation of fire suppression systems due to smoke migration, an issue included in the scope of Generic Issue 57, is possible. Spurious suppressant discharge has a potential to cause secondary equipment damage, may divert suppressants from areas where they are actually needed to fight the fire and may also create hindrances or distraction for the operators. In this case the systems were apparently actuated on smoke detection alone. This is now a rarely encountered configuration for plants in the U.S., largely due to adverse spurious operation experiences of the 1980's.

A20.6 References

A20-1 E. Pla, "Fire at Vandellos 1: Causes, Consequences and Problems Identified"

A20-2 "Fires in Turbine Halls and Nuclear Power Plant Safety", ASSET/IRS Activity, International Atomic Energy Agency, Vienna, Austria, December 11-13, 1991.

A20-3 Personal communication between Mr. E. Pla of International Atomic Energy Agency and Dr. M. Kazarians, 1999.

A20-4 "Fires in Turbine Halls and Nuclear Power Plant Safety - ASSET/IRS Activity", International Atomic Energy Agency, Vienna, December 11-13, 1991.

Appendix 21 - Analysis of Chornobyl, Unit 2 Fire on October 11, 1991

A21.1 Plant Characteristics

The Chornobyl plant site is located near Pripyat Ukraine. At the time of the fire incident addressed in this Appendix, Ukraine was a part of the former Soviet Union. The plant site originally had four units. Unit 4 was destroyed in an April 1986 reactor accident.[A21-7] The three remaining units were brought back online after the Unit 4 accident, and after implementation of several improvements including upgraded fire protection systems and cable protection. This appendix discusses a fire that occurred in Unit 2 about five years after the Unit 4 accident.

All four units are RBMK-1000 type reactors. This type of reactor has a vertical channel, boiling water, graphite moderated, light water cooled core with two turbine-generators per unit. Turbine-Generators No.3 and No.4 serve the Unit 2 reactor. The thermal power rating of Unit 2 is 3,200 MWt and each turbine-generator is rated at about 500 MWE power. Unit 2 started commercial operation in 1979 and was apparently was shut down permanently following the fire described here.[A21-7] The only currently operating unit is Unit 3.

Each reactor unit is cooled by two independent loops; each cooling half of the reactor and providing steam to a separate turbine-generator. Each loop includes four coolant pumps and one separator drum for drying the steam before it enters the turbine. The condensate from the turbine condensers flows back via five main feedwater pumps (for use during power operation) or three emergency feedwater pumps (for use during an emergency) to the separator. The main circulating pumps of the main coolant loop take suction from the separators.

A21.2 Chain of Events Summary

On October 11, 1991, Unit 2 was in the process of start-up after a two-month shutdown when a steam leak was discovered on Turbine-Generator No. 4. The reactor was at about 50% power (1,570MWt) and Turbine-Generator No. 3 output was at 425 MWE. The operators tripped Turbine-Generator No. 4 and attempted to take the generator off the gird by closing the valves to the turbine which caused the automatic opening of the 330kV air-operated breaker between the generator and the grid. However, before the field operators could open the isolator that de-energizes the air breaker, a short circuit in the control cable for the 330kV air breaker caused the breaker to close spuriously and re-connect the grid to generator No. 4.

It was later determined that the short was caused by mechanical damage to a section of cable insulation about 120 mm long in an underground duct. Cable pulling practices during construction in 1977 were thought to be the cause of insulation failure. Cable tests were carried out periodically during operation, but the defect was not discovered in any of those tests. The short occurred between the conductor that carried the control signal for breaker control and the conductor that carried the indication signal that the breaker is closed. Both conductors were located inside the same cable.

The closure of the breaker, in effect, turned the generator into a motor. However, the breaker closure was such that the generator started to turn in an asynchronous mode. Its speed reached 3,000 rpm in about 30 seconds. Due to the asynchronous operation, the alternator rotor overheated causing damage to the alternator rotor windings. Displacement of the rotor windings produced out of balance forces during the acceleration of the rotor and damage to the bearings and seals. This led to the release of hydrogen from the generator cooling system and release of oil from the turbine lube system. Both materials ignited on hot surfaces and started a large fire in the Turbine Building near Turbine-Generator No. 4.

Upon the initiation of the fire, operators tripped the reactor manually and started cool-down procedures. The shift supervisor ordered rapid cool-down of the reactor (30°C/hr) using the steam dump valve discharging into the steam suppression tank. The makeup for the Steam Drum Separator was provided by a main feedwater pump.

The fire brigade was called almost immediately. They arrived at the plant within 5 minutes. A total of 63 people including both plant personnel and off-site fire fighters were ultimately engaged in fighting the fire.

There was one error of omission made by the operators in response to the fire. The circuit breakers for Turbine-Generator No.3 were left closed even after the reactor had been tripped. Therefore, after the reactor trip this generator also received power from the grid and rotated, in this case in synchronous mode, like a motor. The generator remained in this condition for close to 20 minutes but did not suffer any observable damage. Ultimately this error had no impact on the progression of the event.

The steel roof supports located above Turbine-Generator No. 4 deformed from high temperature and collapsed. This is attributed to the build-up of hot gases under the ceiling, the lack of smoke discharge capability and insufficient cooling of the steel structure. The fire brigade's hose streams did not have enough pressure to reach the ceiling. This led to the collapse of the roof over Turbine-Generator No. 4 within about 20 minutes. The generator was completely destroyed by the collapse of the roof. Main feedwater and emergency feedwater pumps and their electrical boards were also affected. As a result, three out of five main feedwater pumps and one out of three emergency feedwater pumps were damaged. Thus, multiple safety trains were rendered unavailable in this incident.

The failure of the roof structural elements and the impact of fire on these elements caused release of radioactive aerosols into the atmosphere from contamination that was deposited during the April 1986 accident at Unit 4. The total radioactive material released from this event was about $1.4x10^{-13}$ Ci, which is less than daily admissible level. No other radiological release or undue contamination occurred as a result of the fire.

Initially, the makeup water was provided by a main feedwater pump. A flow control valve failed to adjust the flow and caused a high level condition in the steam drum. This in turn caused the main feedwater pump to trip. Later, the steam dump valve failed partially open because of a mechanical failure causing depressurization of the reactor coolant loop. All high pressure feedwater capability was eventually lost. Some of the pumps and their associated control valves were damaged by the debris from falling roof elements and the rest were de-energized to allow for fire fighting activities in the vicinity of their associated electrical panels.

At about 1 hour into the incident, the water level in the Steam Dump Separator dropped to the emergency set point. However, none of the main and emergency feedwater pumps were available to provide water to the separator. Although the operators were successful in starting one main feedwater pump, the electrical supply to all main and emergency feedwater pumps were removed, at about 1.5 hours, to allow the fire fighters continue their efforts in the vicinity of the associated electrical equipment. At about 2 hours, the operators started the seal water supply system to the main circulating pumps to provide makeup to the reactor. This can be regarded as a change in the core cooling and coolant makeup strategy.

About 3 hours after the incident started, the water level in both Steam Drum Separators dropped below the measurable range. Due to the decrease in reactor pressure and low temperature of the feedwater, the water had contracted and the level in Steam Drum Separator had dropped. The reactor pressure eventually decreased to the level where the low pressure feedwater injection from the clean condensate storage tank could be activated. Water level was regained when the low pressure pump was started. Thus, the operators lost control over the coolant flow rate through the core. For a time they relied on the seal water to provide the core cooling, but had no clear idea of the rate of coolant entering the reactor. The water level in the Steam Drum Separator was restored only after a feedwater pump was re-activated.

About 3.5 hours after the fire started, it was declared under control. At about 6 hours, the fire was completely extinguished. Reference A21-7 cites that Unit 2 was shutdown (permanently) in October of 1991. While not stated explicitly, one can infer that the unit was permanently shutdown due to the extensive damage realized during the fire.

A21.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A21-1] through [A21-5]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	The unit was in the process of start-up after a two-month shutdown. The reactor was at about 1,570MWt, with Turbine-Generator No. 3 at 425 MWe. Turbine-Generator No. 4 had to be tripped because of a steam leak and it was coasting down. Its rotational speed was 50 rpm when the incident started. Two main feedwater pumps and 6 main circulating pumps were operating.	
Prior to the incident	At 19:46, on October 11, 1991, the operator switched off the Turbine-Generator No. 4 from the grid. This was achieved by closing the valves to the turbine and automatic opening of the 330kV air-operated breakers 1, 2 and 3 between the generator and the grid. The operator in the Central Control Room (the control room that controls plant connection to the grid) instructed a field operator to open the isolator TP-4GT to de-energize the air breaker. He had to walk 150m to verify the position of the breaker before he could de-energize the breaker.	
00:00	At 20:10, Turbine-Generator No. 4 had coasted down in the range of 50 to 200rpm, before the field operator could reach his destination and open the isolator, a short circuit in the control cable for the 330kV air breaker caused the breaker 2 to close spuriously and re-connect the grid to generator No. 4. The short was caused by a mechanical damage to about 120 mm of cable insulation thought to have been caused during the cable pulling operation through an underground duct during construction in 1977. Cable tests were carried out periodically and the defect was not discovered. Because of poor or damaged insulation, a short occurred between the wire that carries control signal for breaker control and the wire that carries the signal that the breaker is closed. Both wires were located inside the same cable. The operator in the Central Control Room noticed that the 330kV breaker was switched on.	This event demonstrates that spurious actuation of a device can occur from a short between two wires inside a cable. This type of event is often postulated in fire PRAs as a consequence of fire damage to control cables. This case is somewhat unique because the failure led to the fire rather than resulting from the fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The operators in the Unit Control Room and Central Control Room felt vibration of the building and noticed severe vibration of Turbine-Generator No.4. Almost at the same time, both operators discovered the fire in Turbine-Generator No. 4. The closure of the breaker, in effect, turned the generator into a motor (sometimes referred to as "motorizing" of the generator). It started turning in an asynchronous motor regime. Its speed reached 3,000 rpm in about 30 seconds. The alternator rotor overheated and resulting in damage to the alternator rotor windings. Displacement of rotor windings produced out of balance forces during the acceleration of the rotor. Severe vibration took place that led to rotor displacement. The forces of this event led to damage in rotor components, bearings (numbrs 10 to 14) and generator seals. Hydrogen and oil were released that caught fire.	
00:00:40	At 20:10:40, the oil fire affected generator bus bar and caused a 120,000 amp short circuit of all 3-phases. The generator protection system activated and opened the generator circuit breaker 2. However, because of the short in the control cable, breaker 2 closed again in 0.25 sec. The breaker cycled once more at a period of about 0.2 second. At this point the air pressure became insufficient to allow further action of the air-operated breaker. The grid circuit breaker, located 200km away, opened by actions of the grid protection system, which disconnected the generator from the grid. The duration of these actions was estimated as about 1.18 second.	
00:01	At 20:10:52, the reactor was tripped manually. According to the procedures, the operators immediately initiated emergency oil removal process from the turbine and purging of the generator hydrogen with nitrogen.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The generator circuit breakers on Turbine-Generator No.3 were left closed. This generator also received power from the grid and rotated, in this case synchronous, motor mode. Although, the generator remained in this condition for close to 20 minutes, it did not suffer any observable damages.	This is an error of omission in that an erroneous configuration of plant equipment went unnoticed for a long time. One possible cause for this may be operators' pre-occupation with dealing with the fire damage, reactor shutdown and core cooling. Although this element of the event was not important to plant safety, it demonstrates that it is possible for operators to fail to monitor a condition that could potentially cause adverse consequences because other events are in progress. The possibility of occurrence of overlapping scenarios is not explicitly addressed in typical fire PRAs.
00:01	Loss of vacuum occurred on both main condensers.	
00:01	Manual fire fighting activities using portable and fixed equipment were initiated and fire suppression systems activated as designed. Turbine oil sprinkler and area sprinkler systems were activated manually.	None of the references indicate the effectiveness of the suppression systems. Since it took a long time and the efforts of a large number of fire fighters to put the fire out, it is inferred that the fire overwhelmed the suppression systems and manual actions were necessary.
00:01	The fire brigade was called in.	
00:03	At 20:13, the control room shift supervisor ordered rapid cooldown of the reactor (30ºC/hr) using steam dump valves discharging into the steam suppression tank.	
00:04	Two main feedwater pumps were operating. At 20:14, operators tripped one of the two pumps.	
00:06	At 20:16, the fire brigade arrived on the scene of the fire. A total of 63 people from the fire brigades and plant personnel were ultimately assigned to fight the fire.	
00:08	At 20:18, the operators tripped the turbine-generator oil pumps and started manually draining the oil in the lubricating oil tanks which are located outside the turbine building. An oil spill occurred as a result of this activity, but not in the vicinity of the fire.	Plant personnel were perhaps lucky that the oil spill did not contribute to the fire. This part of the event demonstrates that it is possible for personnel actions to influence the spread and severity of the fire. In fire PRA, actions taken by plant personnel that may aggravate the severity of the fire is not addressed.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	At 20:20, high level in the Steam Drum Separator tripped the operating main feedwater pump. The high level was caused by a failure in the main feedwater discharge valve to modulate properly.	This is a case where an event (failure) has occurred independent of the fire. In fire PRA, such independent failures or events are routinely included in the core damage frequency evaluation of fire scenarios using event trees and fault trees.
00:13	Fire brigade begins the fire fighting activities.	The response time of the fire brigade is quite typical of the times assumed in fire PRAs. Given that the brigade is largely an off-site unit, this is, in fact, a relatively prompt response.
--	The fire brigade aims water streams towards the ceiling. However, it later becomes evident that because a large number of equipment (including two sprinkler systems) drew water from the fire water system, its pressure had dropped and the hose streams did not reach the ceiling. Because of dense smoke in the turbine building, the fire fighters could not tell whether their water streams were reaching the ceiling.	Specific causes for the failure of manual fire fighting is generally not modeled in a fire PRA. This specific scenario (i.e., insufficient pressure in the system because of water over use) is typically not addressed in a fire PRA. Simplistic, perhaps conservative, models are used that is intended to cover a wide range of failure scenarios.
00:20	At 20:30, the steel roof supports located above Turbine-Generator No. 4 deformed from high temperature and collapsed. This is attributed to lack of smoke discharge capability and insufficient cooling of the steel structure. Attempts to cool the ceiling and structural elements failed because of lack sufficient pressure in the fire hoses for the water to reach the full height of the building. It must be noted that roof collapse occurred despite the upgrades in 1986, when combustible components of the roof were replaced with fire resistant elements, and the fixed fire fighting systems were improved.	This event demonstrates that a severe turbine building fire may cause catastrophic structural damage, even with proper fire protection measures. The relatively short time from fire initiation to collapse of the roof (20 minutes) is somewhat unexpected. In this case, the fire grew very quickly and must have been quite severe. However, in fire PRA it is relatively common to consider catastrophic loss of the turbine building without explicit consideration of the timing of that loss. Hence, most modern full-scope fire PRAs would nominally capture this potential.
00:20	Debris from the ceiling fell over Turbine-Generator No. 4. The generator was completely destroyed from the collapse of the roof. Main feedwater and emergency feedwater pumps and their electrical boards were affected. As a result 3 out of 5 main feedwater pumps and one out of three emergency feedwater pumps were damaged.	Multiple safety trains were rendered unavailable in this event. Such failures are the focus of all fire PRAs.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The roof materials caught fire and released radioactive materials from contamination deposited during the April 1986 accident. From this part of the event, one can infer that a portion of the roof structure was combustible (Reference [A21-3]) and that excessive heat caused them to ignite. This may have contributed to the structural collapse.	
00:28	At 20:38, the Steam Dump Valve failed partially open because of a mechanical failure. This caused the level in the Steam Dump Separator to drop.	This is another case of an independent failure that occurred during the course of the fire. (See note above).
00:30	At 20:40, because of debris falling from roof and impact of fire, control of main feedwater pumps 2, 3 and 4 and their associated control valves were lost. Hot metal debris and electrically active wires prevented operators from reaching control cabinets to restore a feedwater pump.	
00:50	The level in the Steam Dump Separator reached emergency set point. However, none of the main and emergency feedwater pumps were available to provide water to the separator.	
01:05	At 21:15, operators were successful in starting one main feedwater pump (No.1).	
01:10	At 21:20, the operating main feedwater pump had to be stopped based on high water level in Steam Drum Separator.	
01:30	At 21:40, the electrical supply to all main and emergency feedwater pumps were removed to allow fire fighters to continue their efforts in the vicinity of pump motors and control cabinets. This left the reactor cooling system without make-up water.	This incident demonstrates that direct fire damage may not be necessary for a set of equipment to become unavailable. One cause for equipment unavailability is intentional tripping of the equipment as part of fire fighting activities. This type of scenario is not generally considered in a fire PRA.
--	Operators initiated reactor coolant system pressure decrease by opening steam relief valves into the pressure suppression tank.	
02:00	At 22:10 the operators, initiated reactor cooling through an auxiliary system that is normally used to supply main circulating pump seals cooling.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:51	At 23:03, water level in both Steam Drum Separators dropped below the measurable range. Because of decrease in reactor pressure and low temperature of the feedwater, the water had shrunk and the level in Steam Drum Separator had dropped. The reactor pressure decreased to the level where the low pressure feedwater injection from the clean condensate storage tank could be activated. The operators, per Reference A21-6, had no previous experience with this type of operation.	Similar to a few other fire events, operators in this case have gone beyond the well established written and practiced procedures. In fire PRA, no credit is given to such actions and it is conservatively assumed that operators would not deviate far from set procedures.
03:03	At 23:15, the water level in the right Steam Drum Separator increased to above the measurable level.	
--	The operators maintained the makeup and core cooling using the seal water system and regained control of the Steam Drum Separator level by 23:45.	
03:31	At 23:41, the fire is declared under control.	
03:35	At 23:45, water level in the left Steam Drum Separator increased to above the measurable range.	
03:48	At 23:58, the level in both steam drums reached normal range.	
06:10	At 02:20 on October 12, the fire was completely extinguished.	

Equipment Damaged

- Generator
- Five main feedwater pumps
- Three emergency feedwater pumps

Damaged Areas

- The turbine building sustained severe damage. The roof above the Turbine-Generator No. 4 collapsed. No effects outside the turbine building were noted.
- The plant apparently was permanently shutdown following the fire.[A21-7]

Impact on Core Cooling

- Some safety related equipment was affected by this fire. However, core cooling functions remained available at all times.

Radiological Release

- The disruption of roof structural elements and impact of fire on these elements caused release of radioactive aerosols into the atmosphere from contamination that was deposited during the April 1986 accident at Unit 4 (Reference [21-3]). The total radioactive material release from this event was about 1.4×10^{-3} Ci, which is less than daily admissible level. No other radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire. The fire fighters and plant personnel involved in fire fighting activities received radiation exposure that ranged from 0.02 to 0.17 rem, which did not exceed the two-week dose.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- Available sources do not indicate any radiological releases beyond the re-lofting of previously deposited contaminants as noted above. There was no significant, contamination or any other adverse environmental impact.

A21.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubricating oil and generator hydrogen were the combustible materials that contributed to this fire.	
Presence of an ignition source	Hot surfaces of the turbine-generator and steam pipes or the heat generated by asynchronous operation of the generator may have served as ignition sources.	

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The fire ignited because of oil and hydrogen release from Turbine-Generator No. 4. The release occurred because the generator was inadvertently connected to the grid and rotated up to 3,000 rpm as an asynchronous motor. The generator breaker had closed because of a short between two wires from the breaker control circuit and breaker closure status signal. The short occurred because of mechanical damage to the cables inside a duct.	
Fire growth within the combustible or component of original ignition	The fire became large, apparently in a short time. Per Reference A21-6, the hydrogen flame was 6 to 8 meters high.	Turbine building are widely recognized in fire PRAs as presenting unique fire hazards. This incident confirms these assumptions and the potential for a very rapidly growing and severe fire to occur.
Fire propagates to adjacent combustibles.	The fire apparently caused parts of the roof to ignite although reports imply that ignition occurred only after the roof had collapsed. It is not clear whether or not any other aspects of fire spread were significant.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	The hot gas layer under the ceiling caused the roof to collapse over the turbines. Combustible elements of the ceiling and the roof may have caught fire contributing to the early collapse.	This is well beyond the typical hot layer effects characteristic of fires postulated by a PRA in most plant areas. However, for turbine buildings many PRAs will postulated total loss of the turbine building without specific consideration of the mechanisms of loss beyond postulating a severe fire.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	From the available information it is inferred that the fire remained confined to the turbine building close to Turbine-Generator No. 4	
Local automatic fire detectors (if present) sense the presence of the fire	No information is provided regarding the presence of any fire detectors in the area.	

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Alarm is sounded automatically in the control room, locally and / or other places	No information is provided regarding alarms. However, the control room became aware of the fire in a very short time. The operators felt the vibration caused by generator rotor rotating as an asynchronous motor.	
Automatic suppression system is activated (if present)	From the available information it can be inferred that there were manually activated sprinkler systems at the turbine oil and the general area that were activated by plant personnel upon discovering the fire. However, no further information is given regarding the effectiveness of the systems. It can be inferred that they were overwhelmed, since it required a large number of people and a long time to put the fire out. Also, their combined activation with manual fire fighting activities caused the pressure in the fire water system to drop and starve the fire fighter from the capability to properly spray the ceiling to prevent its collapse.	The possibility of a suppression system being ineffective or being overwhelmed by the fire is not explicitly modeled in a fire PRA. PRAs commonly assume that if the system actuates it will be effective.
Personnel are present in the area where fire occurs	Personnel discovered the fire and were present in the turbine building at the time of the fire.	
Control room is contacted or fire alarm is sounded	Control room became aware of the fire in a very short time after ignition The vibration caused by generator No. 4 was felt in the control room.. The exact mechanism of informing the control room of the presence of a fire is not provided in the available sources.	
Fire brigade is activated	The fire brigade was called immediately upon discovery of the fire. They arrived at the plant in five minutes and began suppression efforts in about 13 minutes.	The fire brigade response is typical of the response times assumed in a fire PRA for an on-site fire brigade. Given that the brigade was made up of off-site personnel, the response time can be cited as quite fast compared to typical PRA assumptions.

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Fire suppressant medium is properly applied	Although not specifically mentioned in the available sources, in addition to the sprinkler systems that were activated manually, it is apparent that water and hose streams were used to fight the fire. Because there was excessive demand on the fire water system the hose streams did not have enough pressure to spray water on the structural elements of the ceiling.	
Automatic fire suppression system is activated	See the discussions above.	
Fire suppressant medium is properly applied to where the fire is.	There is no evidence that the hose streams were misapplied. The power to all main and emergency feedwater pumps had to be turned off to allow the fire fighting to continue around the pumps and control cabinets.	
Fire is affected by the suppression medium	The fire was brought under control in about 3.5 hours.	
Fire growth is checked and no additional failures occur	No additional failures caused by the fire were reported beyond the first half hour of the event.	In this case, the structural collapse of the roof apparently did the most serious damage. After this, there were few additional damage reports noted. (See related notes above).
Fire is fully extinguished and fire brigade declares it as out	The fire was declared as completely out about 6 hours after the event started.	This is a relatively long fire in comparison to fires considered in a typical PRA. However, as noted elsewhere, catastrophic loss of the turbine building is often postulated.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	The roof above generator No. 4 collapsed because of the failure of structural elements. The roof debris caused the failure of 3 out of 5 main feedwater pumps and one out of 3 emergency feedwater pumps. All feedwater capability was eventually lost because the power to the system had to be turned off to allow for fire fighting in the vicinity of the electrical cabinets.	

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Cable failure impacts equipment outside the fire location	No information is provided regarding this issue. However, the entire sequence of events started with a short in a cable caused by mechanical damage.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	The plant was scrammed immediately after the fire was discovered. Core cooling was established opening a Steam Dump Valve and makeup of water by one main feedwater pump. The feedwater capability was lost completely during this event, in part due to intentional shutdown of associated power busses. The operators had to use condensate seal water system for the main circulating pumps to add water to the core. To be able to accomplish this, reactor coolant system pressure had to be reduced by opening steam relief valves. The operators had no previous experience in providing makeup water in this manner. The control of the water level in the Steam Drum Separators was lost during the course of the event and was later regained when the seal water system was initiated.	Operator recovery actions were a key element of this incident. The operators took at least two different approaches for maintaining core cooling (use of feedwater and use of the seal water system). They also decided to implement the rapid cooldown (i.e., 30ºC/hr) procedure. This last decision had implications in terms of loss of water level in the steam drums. Overall, the operators were successful in maintaining core cooling. At one point, for a duration of about 45 minutes, the water level in the Steam Drums was below its measurable level, thus the exact status of core cooling capability was not known to the operators. The operators relied on pump seal flow to provide coolant to the core. In PRA, small probability of success is typically assigned to the possibility of changing course in recovery strategy. Also, in fire PRA, core damage is assumed to occur if the water drops below a measurable level.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	No information is provided regarding this issue. Since the fire was in the Turbine Building, the affected cables likely had little impact on safety related instrumentation.	
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators attempted several methods for rapid cooldown of the plant. Despite many difficulties in controlling the water from the feedwater systems and the water level in the Steam Drums, the operators managed to maintain core cooling at all times with the help of one main feedwater pump and seal water system for the main coolant loop recirculating pumps.	

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Structural failures (if occurred) may jeopardize availability of equipment	Structural failure occurred in this event and the debris caused the failure of main and emergency feedwater pumps.	
Water when sprayed over electrical equipment may fail the exposed equipment	The electrical equipment were de-energized to allow for the spray of water in the vicinity of the electrical equipment.	This is an aspect of the fire incident that would not be captured in a typical fire PRA. The possibility that redundant equipment might be taken out of service to facilitate fire fighting is not considered. This may be an artifact of Soviet fire fighting procedures that call for de-energizing equipment before fighting fires so the applicability to US plants is uncertain..
The cooling effect of CO_2 may adversely impact equipment	No information.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	At least two independent failures did occur during the event. The feed valve of operating main feedwater pump failed to modulate flow properly and the Steam Dump Valve stuck half open.	This demonstrates that independent failures can adversely impact the progression of a fire incident. In PRAs, independent events are an integral part of the event tree/fault tree models. In general the occurrence of more than one such failure in a single incident would be judged highly unlikely.

A21.5 Incident Analysis

The fire in the Chornobyl Unit 2 turbine building was clearly a severe fire from a classical fire protection standpoint because significant damage was inflicted on the turbine building structure, one generator, and several safety related pumps and equipment. Damage from the fire apparently led to a permanent shutdown of Unit 2.[inferred based on A21-7] The incident is also judged to have led to a significant nuclear safety challenge because the strategies employed by the operators for core cooling, were not according to an established procedure and perhaps could have led to adverse conditions for the core.

Operator recovery actions were a key element of this incident. The operators took at least two different approaches to maintaining core cooling (use of feedwater and use of seal water system) and decided to implement the rapid cool-down (i.e., 30EC/hr) procedure. This decision had adverse implications in that it led to a drop in water level in the steam drums and a depletion of the coolant inventory. Overall the operators successfully maintained core cooling. This was initially accomplished using the main feedwater pumps. After that option was lost (due to manual isolation of the operating pumps to facilitate fire fighting efforts) operators used reactor coolant pump seal flow. Thus, two different strategies were employed in maintaining coolant flow. At one point, for a duration of about 45 minutes, the water level in the Steam Drums was below its measurable level, thus the exact status of core cooling capability was not known to the operators. In PRA, a small probability of success is typically assigned to the possibility that operators will change course in their recovery strategy in the midst of an unfolding accident. Also, core damage would conservatively be assumed to occur if the water level drops below the measurable level.

At least two independent failures occurred that adversely impacted operator recovery efforts; failure of the feedwater flow control valve and failure of the steam dump valve in a partial open condition. The occurrence of independent failure events is an integral part of fire PRAs since such failure are included in the plant fault trees and event trees. However, the occurrence of two such failures during a single incident would generally be considered highly unlikely. This incident does illustrate that even unlikely events can occasionally occur, again, a concept consistent with the core basis of PRA which inherently deals with unlikely events.

The root cause of this incident was a short circuit between two wires inside a cable that resulted in spurious operation (closing) of a breaker circuit. The incident therefore demonstrates that spurious actuation of a device can occur from a short between two wires inside a cable. This case is somewhat unique in that the fire was a result of the short rather than a short resulting from fire damage to cables. Spurious equipment actuation is often postulated in fire PRAs as a consequence of fire damage to control cables. Current methods of analysis for this are, however, subject to considerable debate. See the body of this report for further discussion.

Another interesting factor in this incident is the fact that an erroneous alignment of plant equipment went unnoticed for a long time due to an operator error. Following the reactor trip, operators failed to isolate the second turbine generator from the grid. As a result Turbine Generator No.3 rotated in synchronous motor mode for close to 20 minutes. Ultimately this had little significance in this particular event. However, it must be noted that it was a spurious connection of generator 4 to the grid that led to the fire. Had this second generator also operated in an asynchronous mode, a second fire may have ensued.

The actual cause for the operators failing to notice the condition of this generator has not been established in any of the available documents. The most plausible apparent explanation is that the operators were pre-occupied with assessing and responding to the fire, implementing a reactor shutdown and maintaining core cooling (certainly these would appropriately be their top priorities). Although this element of the incident was ultimately not important to plant safety, it does demonstrate that fires can lead to adverse impacts on operator responses, even if those actions take place from the main control room. In this case operators failed to monitor a condition that could potentially cause adverse consequences beyond the original chain of events. In fire PRA methodology, it is commonly assumed that fires occurring outside the control room will not impact the reliability of operator actions that take place within the main control room. Also, the possibility of occurrence of overlapping scenarios or operator demands resulting from the fire is not explicitly addressed. In a fundamental sense, current methods do allow for the possibility of addressing such events in a fire PRA, this is simply not typical practice.

The available information sources indicate that the manually activated sprinkler systems activated as designed. Although, no information is provided about the effectiveness of those systems, it is noted that the pressure of the fire water system had dropped because of excessive demand on the system. Since the fire did cause extensive damage, and because it took a long time and the efforts of a large number of fire fighters to put the fire out, it may be inferred that the fire overwhelmed the suppression systems. The possibility of suppression system failing to control the fire because of the intensity of the fire is not generally modeled in a fire PRA. It is commonly assumed that if the systems actuate, they will control the fire. It is also commonly assumed that the activation of a fire suppression system will prevent any further damage from occurring. In this case, damage clearly continued to occur well after the suppression systems actuated. Again, the turbine building presents unique fire hazards as compared to other plant areas.

Roof collapse in the turbine building occurred despite upgrades made in 1986. The upgrades included replacement of combustible components of the roof with fire resistant elements, and the fixed fire fighting systems were improved. It would appear, however, that at least some combustible elements were left in place as the reports do cite that, at least after collapse and perhaps before the collapse, some elements of the roof did burn. (One might suspect, for example, that the roofs exterior sheathing was combustible.) The major structural supports were apparently steel, and the fire was sufficiently severe so as to cause failure of these steel structures. This incident demonstrates that a severe turbine building fire may cause catastrophic structural damage, even with fire protection measures in place. However, the specifics of the upgrades are needed to fully understand the reasons for the failure of the protective measures. It is also interesting to note that in this case the failure occurred in a rather short time, about 20 minutes. This is a further indication of that the fire was quite intense and grew rapidly following ignition.

Another human action that was noted in this event was that the electrical supply to all main and emergency feedwater pumps was intentionally removed to allow for the fire fighters continue their efforts in the vicinity of the associated electrical equipment. This incident demonstrates that direct fire damage may not be necessary for a set of equipment to be taken offline during a fire. Fire fighters are commonly reluctant to apply water to electrical fires due to personal safety concerns. In this case, the systems were taken off-line to alleviate such concerns and to facilitate fire fighting activities. Various incidents in the U.S. also demonstrate a reluctance on the part of fire fighters to apply water to energized electrical equipment (beginning with the Browns Ferry fire in 1975 and continuing through current events). This may have particular relevance in scenarios where redundant equipment is separated only by spatial separation within a single room. If the room fills with smoke, fire fighters may seek isolation of the redundant train power sources before applying water to the fire. This could delay fire fighting efforts and/or result in the isolation of the redundant train. This would not be considered in a typical fire PRA given current methods of analysis.

A21.6 <u>References</u>

A21-1 “Fires in Turbine Halls and Nuclear Power Plant Safety; ASSET/IRS Activity” Working Material, Report of a Consultants Meeting Organized by the International Atomic Energy Agency, Vienna, 11-13, December 1991.

A21-2 “Report of the ASSET Mission to the Chornobyl Nuclear Power Plant, Ukraine, 22-26 June 1992 - Review of the Root Causes of a Safety Significant Incident that occurred 11 October 1991 at Unit 2 - Loss of the Emergency Feedwater Supply due to a Fire in the Turbine Hall", IAEA-NENS/ASSET/92/A/03.

A21-3 Vasil’chenko, V.N., A.Ya. Kramerov, D.A. Mikhailov, and A.P. Nikolaeva, Analysis of the Accident in the Second Power-Generating Unit of the Chornobyl Nuclear Power Plant Caused by Inadequate Makeup of the Reactor Cooling Loop”, Translated from Atomnaya Energiya, Vol 78, No.4, pp. 249-255, April, 1995, Plenum Press Corporation, 1995.

A21-4 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A21-5 Soloviev.P.S. “Accidents and incidents in nuclear power plants”, Obninsk,1992.

A21-6 Shteinberg, Nicolai, J. Joosten and S. Routchkine, “Fire at Chornobyl 2", Fire & Safety ‘94, Barcelona, Spain, December 5-7, 1994.

A21-7 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 22 - Analysis of Salem, Unit 2 Fire on November 9, 1991

A22.1 Plant Description

Salem is a two unit nuclear power plant site located near Salem, New Jersey. Unit 1 is a boiling water reactor and Unit 2, which is completely separate from Unit 1, is a pressurized water reactor. Unit 2 is rated at 3411 MWt and 1106 MWE. Unit 2, where the fire being reviewed occurred, started commercial operation in October 1981.

A22.2 Chain of Events Summary

On November 9, 1991, Unit 2 was operating at full power when a reactor trip occurred (References [A22-1] and [A22-2]). As a result of the trip, the main generator breaker opened. The Auto Stop Oil System was in test mode and as a result the turbine valves cycled open while the generator was disconnected from the grid (i.e., the turbine “re-started” without an appropriate generator load on the system). An over-speed condition took place, but the over-speed protection system failed to function properly and allowed the turbine’s rotational speed to exceed 2500 rpm compared to the normal operating speed of 1800 rpm. The forces associated with this level of over-speed caused the blades to break apart and fragments were ejected from the turbine casing. Hydrogen gas escaped and caught fire because of seal failure caused by excessive vibration. The lube oil pipes were also severed causing release of the oil that also caught fire.

The following automatic fire suppression systems actuated promptly as designed.

- Deluge system protecting inboard generator bearing housing
- Deluge system protecting low pressure bearing housing
- Low pressure carbon dioxide system protecting the main generator excitor
- Wet pipe sprinkler system below the main generator pedestal

Per Reference A22-3, the entire sequence of events leading to turbine failure lasted 74 seconds. Fires had occurred by then and some of the automatic suppression systems had activated within that time frame. The automatic suppression systems managed to extinguish some of the fires.

The fire brigade happened to be outside the protected area at the time of fire. Withe the assistance of plant security, the brigade re-entered the plant proper promptly and managed to be on the scene within 5 minutes of fire ignition in full gear. With the help of plant fire brigade personnel, the fire was contained rapidly and was extinguished within 15 minutes. The damage caused by the fire in this incident was small compared to the damage done by the ejected blades. The turbine and exciter end of the main generator were found to be impacted by the fire.

Since the main turbine generator of Salem 2 is not enclosed, the hydrogen and smoke from the fire escaped directly into the atmosphere. The fire brigade did not need to be concerned with pocketing of hydrogen under ceiling structural elements.

A22.3 Incident Analysis

This incident is considered important because despite the potential for a very severe fire, only very limited fire damage was observed. In this case, catastrophic failure of a turbine occurred leading to a fire. In this sense, the event is similar to other turbine hall fires including some incidents covered by this same review (i.e., Narora, Maanshan and Vandellos). However, this event is somewhat unique in that the fire suppression system was adequate to control the ensuing fire, and coupled with brigade response, the fire was put out very quickly. There was some localized fire damage, and the costs for replacement of the failed turbine were extensive, but there was no impact on the safety related elements of the plant. The fire had no specific impact on the control room functionality nor the operators. This event illustrates the importance of rapid response to fires.

In this incident a main turbine-generator related system failure led to turbine disintegration. Fire was a consequence of that failure. In PRA, categories of external events are defined that include internal fires and turbine blade failures as two separate categories. In this incident both categories took place This incident demonstrates that when analyzing turbine failure (especially turbine blade ejection) in a general PRA, special attention should be given to the possibility of fire occurrence in the turbine building.

Finally, it is interesting to note that two independent events contributed directly to the initiation of the fires. First, the Auto Stop Oil System was in test mode and this created a condition where the turbine was, in effect, re-started without an appropriate load and this in turn led directly to the potential for an over-speed condition to occur. Second, the over-speed protection system failed to function allowing the over-speed condition to progress unchecked. PRAs rarely model the actual process of fire initiation, instead relying on statistical estimates of fire initiation based on past experience. Nominally, concurrent random failures tend to be considered low likelihood events. Nonetheless, current PRA practice would have captured the potential for such fires.

A22.4 References

A22-1 "Fires in Turbine Halls and Nuclear Power Plant Safety - ASSET/IRS Activity", International Atomic Energy Agency, Vienna, December 11-13, 1991.

A22-2 Licensee Event Report # 31191017, "Reactor/Turbine Trip on Low Auto Stop Oil Pressure Followed by Turbine/Gen. Failure", Salem Generating Station - Unit 2, Event Date 11/09/91.

A22-3 Braddick, Rita E., "The Role of Fire Protection - Salem Generating Station Turbine Failure", Fire & Safety '94, Barcelona, Spain, December 5-7, 1994.

Appendix 23 - Analysis of Narora, Unit 1 Fire on March 31, 1993

A23.1 Plant Characteristics

Narora Atomic Power Station (NAPS) is a twin unit pressurized heavy water reactor (PHWR) located in Utal Pradesh, India. Each unit is rated at 220 Mwe. Unit 1 started power operation in July 1989 and was declared as commercial in 1991. Unit 2 started power production in 1992. There are two turbine-generators, one per unit, housed in the same turbine building. The two units share the same control room, but separate control panels.

A23.4 Chain of Events Summary

On March 31, 1993, Unit 1 (NAPS-1) was operating at 185 MWe. Unit 2 (NAPS 2) was in cold shutdown but containment was pressurized. At 03:32, a turbine blade failure took place on the Unit 1 turbine-generator set that led to severe vibrations, rupture of oil lines and the release of hydrogen. These fuels ignited causing an explosion and fire in the Turbine Building. The reactor was tripped manually. A plant emergency was announced within a few moments of the accident and was not lifted until 22:45 of the same day, about 19 hours after the initiation of the accident.

Cool-down of the primary reactor cooling loop was initiated by manually opening small Atmospheric Steam Discharge Valves (ASDVs). The operators, observing the gravity of the situation, later opened the large ASDV valves to start a “crash” cool-down. In less than ten minutes all primary coolant recirculation pumps tripped and all safety related power sources were lost. This effectively placed the plant in a station blackout condition for Unit 1, and this condition persisted for 17 hours.

The oil-initiated fire propagated along cable trays inside the turbine building toward the Control Equipment Room. Apparently, the lack of proper fire barrier penetration seals allowed the fire to propagate to other areas as well. A large number of cable trays were damaged.

Within about 10 minutes, the operators manually started two diesel-driven fire water pumps. These pumps provided fire water and were later used to pump water into the steam generators. They operated for about 3.5 hours, when they both tripped simultaneously. Based on the information available, no clear cause for the pump trips can be established. There appears to be no direct link to any observed fire damage; hence, the trips were likely caused by an independent (random) common cause failure. One of the pumps was restored about 1.75 hours later (after the pumps tripped), although no details on how the pump was recovered are available.

A large quantity of smoke entered the Main Control Room from the Control Equipment Room and air supply diffusers. The operators for both units were forced to leave the Main Control Room at about 10 minutes after the blade failure and could not re-enter it for close to 13 hours. An attempt was made to take control of the plant from the emergency control room. Unit 2 efforts were apparently successful, but there was no power available to the Unit 1 side and therefore the Unit 1 control panel of the emergency control room had no functioning indications.

Thus, the operators had no indications of the condition of the reactor and were, in effect, “flying blind”.

Fire fighting started about 20 minutes after blade failure in the area below the generator using water from fire hydrants and a fire tanker. Within about 1.5 hours the major part of the fire was extinguished. The rest of the fire was put out within another 7.5 hours, or about 9 hours after blade failure.

Members of Advisory Committee for Accident Management reached the site in about 30 minutes. and took charge of the situation. The guard house at the entrance of the turbine building was used as the command center for guiding the operations. The plant design had included an emergency back-up connection between the fire water system and the steam generators. A group of plant personnel were sent to the boiler room to check on the status of the valves to the fire water back-up circuit. The valves were opened manually to their 50% point. This established fire water flow into the steam generators that served as a heat sink for decay heat removal by maintaining natural-circulation cooling of the core.

Borated heavy water was added to the core to ensure sub-criticality. The Gravity Addition of Boron (GRAB) system was used for this purpose per established emergency operating procedures. GRAB was specifically designed to remain functional during a station blackout condition. Later, fire water hoses were also connected to the End-Shield Cooling System.

Some portion of the neutral bus ducts of the main generator and the vertical portion of the phase bus ducts below the generator melted because of the oil fire in the area. The turbine generator support structure and portions of the slab around the turbine generator set also suffered damage from intense heat. A number of glass window panes in the turbine building shattered.

At about 4.5 hours into the incident, the operators entered the primary containment of Unit 1 where they could read the primary loop instrumentation readouts directly. This lifted the “flying-blind” condition and restored the operators’ ability to monitor reactor conditions.

A third diesel generator that serves both units was started and loaded about 5.5 hours into the incident. This allowed essential equipment to be energized. However, the shutdown cooling pump was not energized until about 17 hours into the accident. This point in the chain of events was used by Narora management to define the end of the station blackout condition.

A23.3 <u>Incident Progression and Implication for Fire PRA</u>

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A23-1] and [A23-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	**Event or Step Description**	**Fire PRA Implications**
Prior to the incident	Unit 1 (NAPS-1) was operating at 185MWe full power level. Unit 2 (NAPS 2) was in cold shutdown but pressurized.	
Prior to the incident	One of three diesel engine driven fire water pumps was under maintenance and was inoperable.	
00:00	On March 31, 1993, at 03:31:40 a turbine trip signal was initiated, caused by fatigue failure of two turbine blades on the 5th stage of flow path 2 of the low pressure turbine. The initial failures resulted in breakage of 14 additional blades. The control room registered several alarms at the same time on the control panel for turbine and related auxiliaries. The specific parameters that initiated the turbine trip could not be identified.	In a typical fire PRA, ignition of a large fire in the turbine building is assumed to occur from an arbitrary cause. The specific causes are generally not addressed explicitly. However, it is assumed that oil is released, ignited and a large fire ensues.
--	Turbine blade failure led to turbine-generator imbalance, that led to the failure of bearing # 4 and later failure of bearings #5 and 6. Turbine imbalance led to frictional forces in the shaft.	
--	The vibration of turbine-generator caused the hydrogen seals of the generator to be "thrown out." A large quantity of hydrogen gas escaped from the generator and caught fire. A hydrogen explosion and fire took place. The hydrogen escaped into the bus ducts past the terminal and seal-off bushings. A hydrogen explosion caused damage to the bus ducts and excitation panels. The vibration also caused the oil pipes connected to the turbine to snap and spill the oil, which ignited and started a large fire in the turbine building.	Two types of fires had occurred -- an explosion of hydrogen gas and a large oil fire. In a typical fire PRA, only one type of fire is postulated. Since, extensive damage is often postulated for turbine building fire scenarios, lack of consideration of simultaneous occurrence of an explosion and a fire is of minimal consequence.

Time (hr:min)	**Event or Step Description**	**Fire PRA Implications**
--	The control room personnel and other staff inside and outside the turbine building heard the sound of an explosion. The control room personnel felt vibration in the floor and a gush of hot and dusty air. A “huge” fire was observed at elevations +111.0m and +104.0m of the turbine building near the generator. The crane operator of turbine building crane was inside the crane cabin parked near the Unit 2 turbine and noticed a fire near the Unit 1 turbine-generator set with a bluish flame.	
--	The turbine trip initiated the opening of the unit transformer breaker, main generator breaker and field breaker and closure of start-up transformer breaker, as designed.	
00:00:38	A reactor trip was immediately, manually initiated upon turbine failure.	
00:00:40	Turbine-generator shaft stopped under friction caused by turbine imbalance (normal turbine coast down is 45 minutes).	
--	The control room received several reactor trip signals.	
--	The motor-generator set tripped.	
--	Cooldown of Primary Heat Transport (i.e., primary reactor cooling loop, the PHT) was initiated by manually opening small Atmospheric Steam Discharge Valves (ASDVs).	
--	The fire spread to control and power cables. Because of lack of separation between redundant trains, cable damage caused a station blackout (see Note 1). Control power supply cable trays on the mezzanine floor (+106.0m elevation) were severely damaged.	Multiple safety trains were affected by this fire. Impact on multiple trains in a fire incident is relatively rare. Current PRA methodologies would properly identify the possibility of occurrence of station blackout from a turbine building fire.
--	The diesel generators (2 for Unit 1) started automatically, but tripped because of loss of control power supply.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:05:45	Operators, upon observing the gravity of the situation, initiated a "crash" cool down of the primary coolant loop (the PHT) by opening the large Atmospheric Steam Discharge Valves. The Secondary Shutdown System (SSS) was initiated automatically because of crash cooldown.	Operators took the proper actions throughout the course of the event. Current PRA methodologies would properly identify the operator actions that had to take place. However, PRA methodologies put considerable emphasis on written, available emergency procedures. Little or no credit is given to actions outside written procedures.
00:06:47	All PHT pumps tripped. A complete loss of class IV supply was experienced.	
--	Control room staff noticed that PHT pressure is at 50kg/cm2(g) (about 700 psi) and that the fueling machine pump is running.	
00:07:04	Isolation of primary containment was noted.	
00:07:40	Complete loss of power supply systems (station blackout) on Unit 1 side of the plant was experienced. All Class I and II power supplies were lost.	
00:07:59	The breaker for motor-generator set MG-3 (of the control circuits) tripped leding to a complete loss of control power supply.	
00:08	Senior plant management were informed of the fire. Using the Unit 2 public address system, plant emergency was announced.	
--	Fire propagated along the cable trays towards the Control Equipment Room next to the Turbine Building. Lack of complete fire barriers allowed the propagation of the fire to other areas. A large number of cable trays, Emergency Transfer Relay (EMTR) panels and Line, Transformer and Generator (LTG) panels were damaged.	
--	Large quantity of smoke entered the Main Control Room from the Control Equipment Room and air supply diffusers. The operators for both units 1 an 2 had to leave the Main Control Room.	This is one of the few fire events where operators had to evacuate the Main Control Room. In fire PRAs, upon presence of smoke or other adverse conditions in the control room, it is assumed that the operators will not be able to function properly and will have to leave the control room.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	Two diesel engine driven fire water pumps were started by the operating crew.	Recall that the third pump was out of service for maintenance. A PRA will not typically consider specific unavailability times for fire protection equipment as a part of the fire suppression assessment. Rather, suppression system reliability is based on generic overall system reliability estimates.
--	An attempt was made to take control of the plant from the emergency control room. However, there was no power supply to the Unit 1 side of the emergency control room and therefore Unit 1 control panels had no functioning indications.	This is one of the few fire incidents where the operators had to go to the emergency (reserve) control room. However, this event demonstrates that common causes can lead to failures for both control rooms. Because of complete loss of vital buses, the emergency control room was rendered useless. In PRA studies for U.S. plants independence of the remote shutdown station is commonly assumed by virtue of the deterministic Appendix R compliance analyses. However, confirmation of remote shutdown independence has commonly been cited as a point of potential technical concern during the IPEEE review process.
--	The operators had no indications of the conditions of the reactor and therefore were in "flying blind" operating mode.	This is perhaps the only fire incident where the operators have faced "flying blind" conditions. In a PRA it is generally assumed that core damage will ensue given a total loss of instrumentation.
00:20	Fire fighting started in the area below the generator using water from fire hydrants and a fire tanker.	By the time that fire fighting efforts had begun, severe damage had already been experienced. This is actually quite consistent with assumptions commonly made in fire PRA, that is, there is a competition between fire growth and damage and fire suppression. In this case, the fire was simply too severe and too fast growing for fire fighters to intervene before critical damage had been done.
00:30	Members of Advisory Committee for Accident Management reached the site and took charge of the situation. The guard house at the entrance of the Turbine Building was designated as the control center for guiding the operations.	
00:30	A quick radiation survey of the outside areas of the reactor building was conducted and no signs of abnormal radiation levels were noted.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	A group of staff members was sent to a boiler room to check the status of, and open, valves on a fire water back-up connection to the main coolant system. The valves were opened manually to the 50% point. This established fire water flow into the steam generators that served as a heat sink for decay heat removal by maintaining natural convective circulation cooling of the core.	The manual connection of the fire water system to the steam generators and use of diesel engine driven fire water pumps were the main method for providing core cooling in this incident. In a fire PRA, credit to the use of such core cooling method would be given only if a written procedure is available and the operators are trained in the implementation of the procedure. In this case, the connection did apparently pre-exist as a part of the plant design so one must presume that procedures for its use were available.
--	Borated heavy water was added to the core to ensure sub-criticality. Gravity Addition of Boron System (GRAB) was used for this purpose per established emergency operating procedure. GRAB is designed to be used during a station blackout condition.	
--	Some portion of the neutral bus ducts of the main generator and the vertical portion of the phase bus ducts below the generator melted because of the oil fire in the area.	
--	The turbine-generator support structure and a portion of the slab around the turbine-generator set suffered damage from intense heat. A number of glass window panes in the turbine building shattered.	
--	Fire brigades from nearby stations were summoned for additional help.	
--	More than 50 staff members from different sections of plant organization came to the site to help the Advisory Committee. Remaining staff members were asked to be on stand-by at a nearby community center.	
01:30	Major fires on the ground and mezzanine floors of the turbine building were extinguished.	This is interpreted as the time of fire being brought under control.
02:00	A radiation survey of the inside of the secondary containment was conducted and no signs of abnormal radiation levels were noted.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
03:50	The two operating diesel driven fire water pumps tripped. The cause for this failure is not known.	It seems that the cause for the failure of the diesel engine driven fire pump were linked (a common cause failure) and it was not related to the fire itself. In a fire PRA, the independent failure of equipment is postulated and the probability of occurrence of such events is included in core damage frequency calculations.
04:00	A radiation survey of the Reactor Building (primary containment) showed normal radiation levels.	
04:25	First entry into the Reactor Building (primary containment) was made by operating staff	
04:25	PHT pressure noted at the master gauge at Elevatoin +103.0m inside secondary containment.	
04:35	Fire water hose is connected to the End-Shield System.	
05:30	Inside the primary containment, fire water was connected to the suction side of the End-Shield Cooling System Pumps to provide cooling of the end-shields. Although the End-Shield Cooling System Pumps could not be used, the pressure in the fire water system was sufficient to push through past the pumps and provide cooling to the End-Shields (see Note 2)	Entry into containment is not typically credited in a fire PRA.
05:35	About 1:45 after they tripped, one of the two diesel driven fire water pumps was restarted. Cooling to end-shields provided in addition to putting fire water into the steam generators.	The steam generators remained without make-up water for about 1 hour 45 minutes. This demonstrates that the steam generators had sufficient capacity to allow for a lack of water make-up for an extended time. None of the incident reports indicate the capacity of the steam generator. The time to core damage after all make-up (primary and secondary) capability is lost is an important measure that is used in a PRA to establish the likelihoods of success or failure of operator recovery actions.
05:35	Diesel Generator #3 that serves both units was started using electrical power from Unit 2.	
06:00	Start up of Diesel Generator #3 allowed for Class Bus Q to be energized. From this point on, essential systems were started one after another.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
07:00	Non-active high pressure process water pump (feedwater pump # 2) started.	
09:00	The fire was completely extinguished	There is a long time difference between the fire being brought under control and complete extinguishing of the fire. This is not modeled in a typical fire PRA and is not generally considered as an important contributor to the chain of events. In this case, the most critical damage occurred within the first 20 minutes of the fire.
13:10	Operators went back to the Main Control Room.	
17:00	One of the shutdown cooling pumps was started after 17 hours. This is considered by the plant operators to represent termination of the station blackout condition.	
17:05	Shutdown cooling pump # 2 was started.	
19:15	Plant emergency was lifted at 22:45.	
32:00	One End-Shield Cooling System Pump is activated to operate on its own power (see Note 2).	

Note 1: The original design basis accidents of the plant did not include station blackout. Hence, this event is considered as "Beyond Design Basis Accident".
Note 2: The use of fire water pressure to pass through the End-shield Cooling Pumps is inferred from the information provided in Reference [A23-1]. There may be some conflict in the exact timing of these actions given that other reports state that the first fire pump was not recovered until five minutes after this action was reported.

Equipment Damaged

- Turbine generator of Unit 1 and its accessories, bus ducts and excitation panels.
- Electrical cables, that led to the following:
  - Electrical power buses Class I and II (station blackout)
  - Automatic Liquid Poison Addition System (ALPAS)
  - Emergency D_2O injection
  - Circulation and cooling of moderator and end-shields
  - PHT circulation including shutdown cooling
  - Auxiliary feed to boilers
  - Loss of all indication on the emergency control panel outside the Main Control Room

Damaged Areas

The turbine building experienced severe fire damage. The turbine-generator, its support structure and portion of the slab around the turbine-generator set suffered damage from intense heat. A number of window glass panes of the turbine building were shattered. The fire propagated to the Control Equipment Room. Smoke entered the Main Control Room and rendered the room inhabitable.

Impact on Core Cooling

Core cooling was maintained at all times. At no time during the fire, core cooling function stopped. Fuel cladding, the primary envelope and the containment were not adversely affected by the fire. Core cooling capability remained available through secondary side cooling and natural convective recirculation in the primary side. The steam generators were supplied with fire water using diesel driven pumps.

Rediological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A23.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Narora 1, March 31, 1993**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubricating oil and hydrogen were the primary combustibles in this event. Cable insulation was a partial contributor to the combustible load. Hydraulic oil also caught fire.	

Fire Scenario Element	**Incident - Narora 1, March 31, 1993**	**Fire PRA Insights**
Presence of an ignition source	The event, that is turbine blade ejection and severe vibration of the shaft, led to shaft stoppage from friction. It is assumed that this led to high temperature surfaces and served as the ignition source.	In a typical PRA, only those sources of ignition are considered that are present at all times. The possibility of an accident creating an ignition source is not generally modeled. Ignition is commonly treated probabilistically based on past experience.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Blade ejection lead to imbalance of the turbine, that led to severe vibration. This led to breaks in several oil pipes and generator seal failure. Oil and hydrogen ignited on hot shaft surface.	
Fire growth within the combustible or component of original ignition	Hydrogen exploded inside bus ducts and caused damage to the ducts. Oil started burning and created a large fire inside the turbine building.	
Fire propagates to adjacent combustibles	The fire damaged cables inside cable trays that propagated to areas away from the turbine-generator.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information provided	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke propagated into the Main Control Room and caused the operators to leave the room.	This is one of several events in this review that led to smoke in the main control room due to a fire elsewhere. This is the only event identified where this actually led to control room abandonment.
Local automatic fire detectors (if present) sense the presence of the fire	No information provided.	
Alarm is sounded automatically in the control room, locally and / or other places	The control room operators became aware of the fire in a short time because of the noise, a draft of hot air and many different system alarms.	
Automatic suppression system is activated (if present)	No information provided.	
Personnel are present in the area where fire occurs	Personnel were present in the turbine building who observed the occurrence of the explosion and the fire.	

Fire Scenario Element	**Incident - Narora 1, March 31, 1993**	**Fire PRA Insights**
Control room is contacted or fire alarm is sounded	Control room operators became aware of the fire almost immediately because of the noise, vibration of the building, draft of hot air into the room and many system alarms.	
Fire brigade is activated	Internal and outside fire brigades were called. Fire fighting started about 20 minutes after ignition. Outside fire brigades arrived about 30 minutes after ignition.	Note that most of the significant fire damage had already been done before fire fighting activities began. Scenarios such as this tend to dominate fire risk estimates.
Fire suppressant medium is properly applied	Hose streams were used to fight the fire. It took about 1.5 hours for the fire brigade to control the fire, and another 7.5 hours (total of 9 hours) to extinguish the fire	
Automatic fire suppression system is activated	No information.	
Fire suppressant medium is properly applied to where the fire is.	There are no indications of any collateral damage due to fire suppression activities.	
Fire is affected by the suppression medium	See above.	
Fire growth is checked and no additional failures occur	From Reference [23-1] it is inferred that all cable and equipment failures caused by the fire occurred in the first 30 minutes of the fire.	Although the major fire was announced as extinguished in 1.5 hours after ignition, it can be claimed that from fire PRA standpoint, the fire was checked in about 30 minutes after ignition.
Fire is fully extinguished and fire brigade declares it as out	Fire was declared as fully extinguished 9 hours after ignition.	The duration of fire can be considered as several hours. In fire PRA, typically the fire duration is in the order of several 10 minutes. This fire incident demonstrates and it is possible for the fire to last for several hours.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	The turbine-generator support structure and portion of the slab around the turbine-generator set suffered damage from intense heat. A number of window glass panes of the turbine building were shattered. A large number of cables were damaged. Smoke entered several areas including the control room.	

Fire Scenario Element	Incident - Narora 1, March 31, 1993	Fire PRA Insights
Cable failure impacts equipment outside the fire location	The following systems and equipment were failed: . Electrical power buses Class I and II (station blackout) . Automatic Liquid Poison Addition System (ALPAS) . Emergency D_2O injection . Circulation and cooling of moderator and end-shields . PHT circulation including shutdown cooling . Auxiliary feed to boilers . Loss of all indication on the emergency control panel outside the Main Control Room	A fire PRA would have likely identified the potential for loss of multiple and redundant equipment trains given the apparent lack of train separation.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Operators initiated a reactor shutdown almost immediately after the fire. All active components normally used for shutdown cooling were lost because of station blackout. Core cooling was achieved through the use of two diesel engine driven fire water pumps that injected water into the steam generators. Core cooling was then achieved through natural convective recirculation.	Multiple trains were affected by the fire. Impact on redundant trains is a rare occurrence. In fire PRA, proper methodologies are available to identify impact of fire on redundant trains and loss of vital systems.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The operators initiated atmospheric release of steam generators, monitored reactor parameters until they had to abandon the control room because of smoke.	In a fire PRA, if the control room is postulated to be filled with smoke, no credit would be given to proper operator actions from the control room. This incident, demonstrates the validity of this assumption.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators manually adjusted the flow control valves of the fire water pumps into the steam generators. The Gravity Addition of Boron (GRAB) system was activated manually. The system does not require electric power to function.	The operators took actions under time constraints that were in the order of half hour to one hour. In a fire PRA, the human error probability for actions that require such time windows is often close to those used in the internal events PRA.
Structural failures (if occurred) may jeopardize availability of equipment	In the turbine-generator area some structural damage took place and bus ducts melted from the heat. However, none of the structural failure impacted safety components or cables. The cables in the area caught fire and caused all safety related failures.	

Fire Scenario Element	**Incident - Narora 1, March 31, 1993**	**Fire PRA Insights**
Water when sprayed over electrical equipment may fail the exposed equipment	No evidence of water damage to electrical equipment were reported.	
The cooling effect of CO_2 may adversely impact equipment	Only water was used for fire fighting.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The only existing condition was the unavailability of the third diesel engine driven fire pump.	

A23.5 Incident Analysis

The turbine building fire at Narora Unit 1 caused an extended station blackout and extensive damage; hence, it is considered one of the major fire incidents in the nuclear power industry both from a classical fire protection standpoint and from a nuclear safety standpoint. The root cause of the fire is failure of a major equipment item (i.e. the turbine-generator) because of metal fatigue. Since the turbine generators are equipped with lubricating and hydraulic oil systems and the generators are filled with hydrogen, as is the case at several other sites, a catastrophic failure of the turbine generator set often leads to a severe fire. The impact of this fire on plant safety was aggravated by the lack of separation between redundant trains of cables.

In a fire PRA, the possibility of a large turbine building fire is often considered. It is common to model such fires by postulating that an oil spill occurs and is ignited. This, of course, is intended to cover a large spectrum of possible incidents, including blade ejection and turbine generator catastrophic failure. It is also interesting to note that in fire PRA the mechanism of ignition is rarely explicitly treated; however, in those cases where it is treated, only those sources of ignition that are present at all times are typically considered. In this incident, the imbalance in the turbine generator shaft caused the shaft to overheat presenting an ignition source that is not normally present in the plant. This was also seen at Vandellos, for example. The possibility of an accident creating an ignition source is not generally modeled. As mentioned above, in fire PRA an overall fire initiation frequency is used to represent a large spectrum of possible fire scenarios.

Two types of fires occurred at Narora Unit 1 during this incident; namely, an explosion of hydrogen gas and a large oil fire. In a fire PRA, only one type of fire is postulated in a given scenario. Since, extensive damage is often postulated for turbine building fire scenarios, the lack of consideration of simultaneous occurrence of an explosion and a fire would be expected to be of minimal consequence, provided that no ignitions or damage is observed outside the turbine building.

Multiple safety trains were affected at Narora, Unit 1. In particular, all primary and backup trains of safety related power were lost resulting in a station blackout. Current PRA methodologies properly identify the possibility of a fire impacting multiple trains by a thorough analysis of the location of cables important to plant safety. Therefore, in the case of Narora, a fire PRA should have correctly identified the possibility of occurrence of the station blackout from a turbine building fire, as was experienced.

Operators took the proper actions throughout the course of the incident. There were no significant operator errors identified. The alignment (done manually) of the fire water system to the steam generators and use of diesel driven fire water pumps were the main methods for providing core cooling in this incident. Current PRA methodologies do allow for properly identifying the appropriate operator actions. However, PRA methodologies put considerable emphasis on written, available emergency procedures. Little or no credit is given to the possibility of successful completion of actions that are outside written procedures. In this case since the fire water system connection apparently was pre-existing as a part of plant design, one can presume that there was a procedure in place for its use. However, this cannot be clearly established based on the available information.

This is perhaps the only fire incident where the operators have faced a "flying blind" condition (i.e., the operators had lost access to reactor and primary coolant loop instrumentation)[1]. The closest analogue is perhaps the 1975 Browns Ferry fire where plant personnel tapped into containment penetrations (on the outside of containment) to bypass damaged or suspect instrument cables and fed critical data on the reactor conditions to the main control room (see Appendix 3). Somewhat similarly in this case, operators overcame the problem by entering containment and tapping directly into instrument feeds or reading from master gauges. In a PRA it is generally assumed that the result of a complete loss of instrumentation is core damage, operator actions outside of the established procedures are not typically credited, and containment entry would not typically be credited. This incident demonstrates that typical PRA assumptions with regard to operator actions may be conservative.

This is the only fire incident identified in this review where operators had to evacuate the Main Control Room. In fire PRAs, upon the presence of smoke or other adverse conditions in the control room, it is assumed that the operators will not be able to function properly and will have to leave the control room. This incident demonstrates that smoke alone (i.e., there is no fire in the main control room and no direct fire damage to main control room circuits) can lead to main control room abandonment. It is also of interest to note that upon arrival at the emergency (reserve) control room, operators for Unit 1 were still unable to control the reactor because the station blackout had rendered the emergency control panels inoperable as well. This incident demonstrates the possibility of a common cause failure for the two control rooms. It should be noted, however, that regulatory requirements in the U.S. should preclude a similar occurrence.

[1]The nearest similar incident is perhaps the 1975 Browns Ferry fire where operators and electricians tapped into instrument feeds through containment electrical penetrations in order to by-pass fire damaged cables.

Indeed, in fire PRAs it is somewhat common to assume remote shutdown independence based on the Appendix R analyses. However, verification of remote shutdown independence and potential control system interactions continues to be a point of methodological debate. For example, related technical concerns were commonly identified in the USNRC-sponsored reviews of the licensee IPEEE fire analyses.

In the course of the incident, the two diesel driven fire water pumps failed simultaneously well into the incident. No clear cause for this is established in the available reports, but it is inferred that the cause for the failure of both of the available diesel engine driven fire pumps were linked (a common cause failure) and that the failures were not related to the fire itself (i.e., not the result of fire damage). In a fire PRA, the independent failure of equipment is postulated and the probability of occurrence of such events are included in core damage frequency calculations. However, in the case of fire suppression systems, it is common practice to apply a generic system-wide reliability estimate rather than to consider specific mechanisms that might lead to system failure. This was somewhat aggravated by the maintenance outage of the third fire pump, although it is not clear if this pump would have survived while the other two failed. This incident demonstrates the potential importance of independent failure events and equipment outages to core damage frequency evaluation.

In this incident, there is a long time between the fire being brought under control and complete extinguishing of the fire. This is not modeled in a typical fire PRA and is not generally considered as an important contributor to the chain of events. Furthermore, from the available information about this incident, all key failures appear to have occurred within the first half hour of the incident. No additional failures were reported beyond this time. From a core damage modeling point of view, this demonstrates that extinguishing the fire quickly is an important factor. Beyond the first half hour in this case, the impact of fire fighting efforts had little or no apparent effect on the likelihood of core damage, perhaps other than the continued evolution of smoke that may have extended the abandonment time for the main control room. This is consistent with typical results of fire PRAs. PRAs commonly predict that fire damage that might occur very early in the incident is of the greatest risk significance.

The operators successfully took actions under time constraints that were on the order of a half hour to one hour. In a fire PRA, the human error probability for actions that require such time windows is often close to those used in the internal events PRA. That is, it is commonly assumed that the fire will not impact the longer term operator actions, provided those actions take place away from the fire itself. This event appears to be consistent with that assumption, despite the fact that the fire continued to burn for several hours.

A23.6 References

A23-1 International Atomic Energy Agency, Incident Reporting System, “Completed Station Blackout Due to Fire in Turbine Building at NAPS-1".

A23-2 J. S. Rao, “Role of Electrical Problems in the Failure of Narora Power Plant”, Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Volume I, ISBN 0-7803-2795-0.

Appendix 24 - Analysis of Waterford, Unit 3 Fire on June 10, 1995

A24.1 Plant Description

Waterford 3 is a single unit pressurized water reactor (PWR) located near Taft, Louisiana. Unit 3 is the only nuclear power unit on the site. The unit is rated at 1,104 MWE and started commercial operation in September 1985. The fire being reviewed here occurred in one of the non-vital switchgear cabinets. There are two non-vital switchgear trains, A and B, and both are located in one room on the +15 feet elevation of the turbine building. The two buses are separated by a 10 foot high heat shield (a 1-foot thick, partial height, concrete block wall). The ceiling of the turbine building switchgear room is 25 feet above the floor, and the switchgear cabinets are 7 feet tall. There were 36 fire detectors in the room that annunciated on a fire protection board inside the control room, and there was no fixed fire suppression system in the switchgear room.

A24.2 Chain of Events Summary

On June 10, 1995, the unit was operating at 100% power. At 08:58 failure of a lightning arrester on a substation transformer (230kV/34.5kV) caused a severe electrical transient that, in combination with failure of a breaker, led to non-vital switchgear 2A failure and fire in the breaker cubicle for the startup transformer. This led to a reactor trip and a series of other non-safety related equipment trips, signal actuations and equipment activations. [Ref. A24-1].

All 36 fire detectors for the turbine building switchgear room alarmed to the control room indicating panel. However, the control room operators did not become aware of the fire detector alarms because there were other plant alarms sounding at the same time, the fire protection alarm board was in an area not readily visible to the operators and the fire detector alarm panel buzzer had been covered with tape. Hence, control room operators remained unaware of the fact that a fire had started in the switchgear room.

At 09:06 a.m., the control room received a report from an auxiliary operator, who happened to be a trained fire brigade member, that heavy smoke was coming out of the switchgear room. The shift supervisor asked if the auxiliary operator could observe flames or an orange glow. The response was that no flames could be seen but a large amount of smoke was coming out of the switchgear room. The auxiliary operator was instructed to confirm the presence of an actual fire and report back.

Two auxiliary operators donned self contained breathing apparatus (SCBA) and entered the switchgear room to verify the presence of a fire. The control room was notified that a fire was indeed in progress. This exchange of information took place about half hour after the arrival of the first fire alarms in the control room (i.e., approximately 09:30). The shift supervisor, at this point, announced the presence of fire and activated the fire brigade.

The fire brigade arrived on the scene and initially attempted to put the fire out using hand held extinguishers charged with carbon dioxide, Halon and dry chemical. All their attempts proved ineffective. The shift supervisor, according to plant procedures, assumed the leadership of the fire brigade and left the control room for the fire location.

The local off-site fire department was summoned at 09:41and they arrived at about 09:58 (17 minutes later). Upon arrival they recommended the use of water. However, the shift supervisor in consultation with other members of plant operations team decided to continue using non-water suppression media. Permission to use water was eventually given about 90 minutes after fire initiation (i.e., about 10:30). The fire was brought under control within four minutes after initial application of water and was declared extinguished about two and a half hours after initiation.

As noted, the fire was initiated inside of a switchgear panel. The fire propagated out of the top of the panel and ignited vertical cable tray risers above the panel. It can be inferred that the switchgear cubicle fire broke through the steel top of the panel and propagated to those cables. However, whether this was due to heat damage to the top panel or whether the top panel may have been damaged in the initial electrical fault cannot be established. In its progression, the fire jumped over a fire stop installed in the vertical section of the cable tray and continued its propagation. Cables in a 5-foot diameter column up to a height of about 10 feet above the panel top were damaged by the fire. The fire detectors immediately above the fire zone were also damaged by the heat.

The fire eventually reached a horizontal cable tray about 17 feet above the floor (10 feet above the top of the panel). The fire then propagated horizontally until it came to a fire stop installed in the horizontal cable tray about 8 feet from the junction with the vertical trays. From the available information it can be inferred that, for the horizontal segment of the cable trays, the flames were of limited height and/or limited duration. This is because the 6.9 kV power cables that were located a few inches above the burning 4.16 kV cables were not ignited and after the fire were found with only minor surface damage.

Two adjacent switchgear cubicles were also severely damaged by the fire. Four other nearby cubicles experienced exterior damage only. The investigators postulated that the radiative heat reflected from the shield wall separating the two switchgear trains caused the exterior damage to those four cubicles. None of the redundant train cubicles (on the opposite side of the shield wall) were damaged.

It is also interesting to note that, log records indicate erratic behavior of the A2 unit auxiliary transformer breaker that was involved in the fire. A few other erratic indications were also noted on the control board through the course of the incident. The records indicate that the transformer breaker first showed closed and then open. It can be inferred from this that breaker control circuit faults led to inaccurate indications on the sequence of events log.

A24.3 <u>Incident Analysis</u>

The non-vital switchgear fire at Waterford 3 had little impact on safety related functions. It does, however, provide important PRA lessons. Switchgear fires are considered one of the most likely fire scenarios in a nuclear power plant, and many fire PRAs have concluded that safety related switchgear are significant fire risk contributors. Non-safety related switchgear however, are not generally found to be risk significant.

This incident provides an interesting account of what can happen to the switchgear cubicles and the cables above it in the event of a switchgear fault and fire. In this case, three cubicles suffered extensive damage, and four experienced minor damage. Further, the fire propagated through the steel panel top into a vertical cable tray, about 10 feet up the vertical tray to a crossing horizontal tray and about 8 feet along the horizontal tray before being stopped by a raceway fire barrier. The potential for fires inside closed electrical panels to propagate outside of the panel has been a point of significant recent debate. This incident illustrates that under some conditions this potential clearly exists.

A second factor of interest is the fact that fire fighting was delayed considerably in this incident. The delay was caused by three nominally unrelated factors, two relating to decisions made by plant personnel during the incident.

One of these three factors was the decision made by the shift supervisor who insisted on direct observation of flames prior to declaring a fire and activating the fire brigade. It took close to half an hour (from the time of ignition) for two operators to don protective breathing apparatus, enter the room, seek out the source of the fire, verify the presence of flames, retreat from the room and report back to the main control room. This would not be captured in a typical fire PRA. Fire PRAs will almost universally assume that once there are clear indications of a fire underway (e.g., alarms, smoke), the fire brigade will be activated immediately. Indeed in most cases this is what happens observed. In this particular case the plant procedures apparently did call for plant personnel to verify the existence of flames before declaring a fire[1]. This illustrates the importance of a careful review of plant fire emergency response procedures to fire PRA.

The second factor related to the strategy used to fight the fire. Once the fire was declared and the fire brigade arrived on-scene, the fire brigade resisted using water on an electrical fire until multiple attempts to extinguish the fire using portable extinguishers proved ineffective. As a result, the fire was allowed to burn far longer than would typically be assumed in a fire PRA, and the observed damage was perhaps made worse than if prompt and effective fire suppression had been undertaken. Typical PRA practice assume that once the fire brigade arrives on scene, effective fire fighting will begin immediately. Delays caused by the decision to use ineffective fire suppressing agents are not modeled. This incident illustrates that this assumption may be optimistic. It must be noted that current fire PRA methodologies are fundamentally capable of incorporating the possibility of ineffectiveness of the fire suppression attempts and delays caused by management decision. For example, current methods already include the ability to assess fire brigade response based on time - likelihood of suppression distributions which could account for some chance that initial fire fighting attempts will be ineffective. However, there is currently no basis for quantifying such behaviors.

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[1]Based on discussions with cognizant USNRC/NRR staff.

The reasons for the failure of carbon dioxide, Halon and dry chemical in controlling the fire in this incident has not been reported. However, other incidents have illustrated similar unsatisfactory results for such efforts, in particular, when the fires involve energized electrical panels. In hind-sight, it also appears likely that the fire had already propagated to the overhead vertical cable trays before fire fighting was initiated (recall the fire had been burning for at least 40 minutes). This would place the fire well above the heads of the fire fighters. Under these conditions it is not surprising that the hand-held extinguishers were ineffective. These devices are designed to fight fires that can be readily approached. The very limited capacity and range of a hand-held gaseous or dry powder fire extinguisher made them poor choices in this particular case, and this was likely a contributing factor in their ineffectiveness in this particular incident.

The final factor contributing to the delay in declaring a fire emergency is the position of the fire protection annunciator panel and the suppressed sound of the alarm. The panel was not readily visible to the operators in the control room and the fire alarm buzzer had been covered with tape. Also, there were many other alarms in the control room that must have diverted the attention from the fire panel. It is important to note that the operators, even after receiving a verbal report of smoke in the switchgear room, did not approach the fire protection panel to verify fire detector conditions.

Such conditions may be addressed in a fire PRA but may well be overlooked. Current methodologies would likely have led to discovery of some of these conditions if exercised fully. In particular, a fire PRA walkdown would have considered the position of the fire annunciator with respect to the location of the operators and would have likely detected the condition of the buzzer. Of course, in such situations as tape over the buzzer, it is quite likely that the tape would be removed as a result of the discovery during the walkdown and the PRA analysts would assume lack of tape as the normal condition. However, this may be an optimistic assumption and a thorough analyst would likely attempt to discern the original reasons for the presence of the tape. Had, for example, plant operators been interviewed as a part of the PRA process, and had they stated that multiple false fire alarms had been a problem at the plant, then the PRA analyst would likely apply a judgmental factor to “degrade” the response time for fire detection and verification. This would, however, be highly dependent on the approach and knowledge state of the analyst. No clear or consistent guidance in this regard is currently available.

Another point of interest in this incident is the fact that a few erratic indications were noted on the control board through the course of the incident. This indicates that control circuits can fail erratically under fire conditions. The exact reasons for the observed behavior was not reported for this incident.

This incident also demonstrates two points related to cable fires and fire stops in cable trays. In this case the fire propagated out of the panel top, up a cable riser for about 10 feet, and along the intersecting horizontal tray for about 8 feet. Second, a fire stop in a horizontal cable tray can be effective in stopping the progression of the fire. In this case, the fire propagation in the horizontal tray ended at a raceway fire stop. Third, fire stops in a vertical cable tray may be ineffective. In this case the fire in the riser jumped past a fire stop and continued to propagate. It is not clear if propagation was delayed by the stop. Fire PRAs will often assume some credit for fire stops in cable trays limiting the extent of fire damage, although practices vary widely.

PRA practices with regard to panel fires vary widely. For example, the EPRI *Fire PRA Implementation Guide* (see report body for associated references) recommended that fires initiated in a closed and unventilated panel could not propagate out of the panel, and such sources could be screened. This was a point of considerable debate in the USNRC IPEEE review process. Indeed, the Waterford fire was one of the incidents cited as the basis for technical concerns regarding this practice. In this case, the fire did propagate out of a nominally closed electrical panel, along a vertical riser and into a horizontal cable tray. Ultimately, EPRI developed revised guidance and licensees were asked to reconsider the potential for fire spread outside of a closed panel for a range of panel types. While this resolved the concerns in the context of the IPEEE process, the more general methodological debate has not been fully resolved.

From the observations provided in the investigation report, it can be inferred that the flames on the horizontal segment of the cables were of limited height and/or limited duration. This is because damage to a tray immediately above was very limited and no propagation of the fire to the next higher tray was observed. The cable combustibility properties would clearly impact this behavior, and it must be noted that these aspects of the incident are not known. Given the age of the plant (construction began in 1974) it is quite likely that the cables used at Waterford are qualified as low flame spread per the 1975 IEEE-383 test standard. In fire PRAs, a large variation of fire propagation patterns are predicted depending on the severity of the exposure fire, cable material characteristics and the approach to estimating fire growth behavior. In some cases fire models are used to predict fire growth, and these models explicitly consider cable material flammability parameters. In other cases, fire spread is based on the results of past fire experiments applied to a given case. This practice has been criticized as a part of the IPEEE review process, and not considered to be well founded. This case does confirm behaviors that have been noted experimentally. In particular, fires propagate much more readily in vertical cable trays than in horizontal trays.

The fire damage to adjacent switchgear cubicles is also interesting to note. Only two adjacent cubicles were damaged severely. Four other cubicles, next to the first two, experienced minor surface damage. It is suspected by investigators that the radiative heat reflecting off of the wall that runs parallel to the switchgear caused the damage to these four cubicles. This demonstrates that despite a severe fire in one cubicle, the fire may not propagate internally in the horizontal direction. In a fire PRA, practices in this regard vary widely. Some PRA's would credit a solid steel barrier with preventing fire propagation. In other analyses, if the cubicles are separated by a single metal sheet, the likelihood of propagation across cubicles is considered to be high. Testing (References [A24-2,3]) illustrates that fire propagation given a solid single wall panel is unlikely unless there is direct contact between the wall panel and a secondary fuel source. It is not clear what the exact configurations involved in this case were. Radiative heat reflecting off of other objects is modeled in some of the existing fire propagation models. Re-radiation and reflection is considered in such models as COMPBRN IIIe (Reference [A24-4]). Another observation of some interest is that the heat shield (partial wall) separating the two trains functioned properly and protected the Train B switchgear from the fire.

This incident also demonstrates that given an energetic failure of a switchgear and ensuing fire, large quantities of smoke may be generated and the smoke will likely not be confined to the compartment of origin. In a fire PRA, the impact of smoke outside the compartment of origin is seldom modeled explicitly. In this particular case, smoke did escape from the room of fire origin, but no direct effects of the smoke propagation were noted.

A final point of interest is that in fire PRAs, if the fire does not impact safety related equipment, it is commonly assumed that the operators would take the proper actions to provide core cooling and reactor shutdown, and such scenarios are screened. This incident demonstrates that the plant may experience a large number of inter-related deviations from the expected chain of events. Such deviations may impact operators' judgement regarding the best course of actions and proper shutdown of the plant. In this incident, the fire was limited to non-vital switchgear but the overall incident did cause considerable operational upset. Nonetheless, the operators took the proper actions for the plant conditions that existed and ultimately there was only a minor challenge to nuclear safety (a plant trip with redundant plant safety systems available).

A24.4 References

A24-1 Inspection Report 50-382/95-15, by U.S. Nuclear Regulatory Commission, of Waterford Steam Electric Station, Unit 3, June 13-16, 1995.

A24-2 J. Chavez, *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets, Part I - Cabinet Effects Tests,* SAND86-0336V1, NUREG/CR-4527/V1, SNL/USNRC, April 1987.

A24-3 J. Chavez and S. P. Nowlen, *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Cabinets, Part II - Room Effects Tests*, SAND86-0336V2, NUREG/CR-4527/V2, SNL/USNRC, October 1988.

A24-4 V. Ho, et al., "COMPRN IIIe: An Interactive Computer Code for Fire Risk Analysis," University of California at Los Angeles, EPRI NP-7282, May 1991.

Appendix 25 - Analysis of Palo Verde, Unit 2 Fire on April 4, 1996

A25.1 Plant Description

Palo Verde Nuclear Generating Station is located outside Phoenix, Arizona. The site has 3 pressurized water reactor (PWR) units rated at 1,270 MWE each. The units each started commercial operation between 1986 and 1988.

A25.2 Chain of Events Summary

On April 4, 1996, Unit 2 was in a refueling outage. At 17:00 a fire watch detected smoke in the back panel area of the control room. Smoke was emanating from the Train B emergency lighting un-interruptible power supply panel. At about the same time, an auxiliary operator discovered smoke and fire in the Train B DC equipment room at the 100 foot elevation of the Auxiliary Building. This second fire was found on the 480/120 volt essential lighting isolation transformer. Multiple trouble alarms on the fire detectors had masked the actual fire alarm coming from this equipment room such that the valid fire alarm signal that had come in was not noticed by the operators.

The fires led to the loss of power to Train B control room emergency lighting circuits, to some of general plant essential lighting, and to plant fire detection and alarm system panels. The circuit breaker supplying power to the un-interruptible power supply panel tripped open when cables in the conduit supplying the power supply panel overheated causing various conductors to short circuit. The circuit breaker trip also de-energized power to the fire detection and alarm panels in the auxiliary building. The fire alarm annunciator monitor (a computer screen) indicated a large number of fire detector trouble alarms and these multiple alarms were scrolling on the monitor. This was attributed to the de-energized fire detection and alarm panels.

The fire in the equipment room was reported to the control room and the onsite fire brigade was activated. They attacked the fire immediately and put it out in a short time. It is not entirely clear if the fire brigade also reported to the main control room or not. The fire in the main control room was apparently handled by the operators. In either case, the control room fire was also quickly extinguished. The direct damage caused by these two fires was limited to the components of origin. That is, neither fire propagated beyond the point of ignition.

A25.3 Incident Analysis

In this incident, the fires were neither severe from a classical fire protection standpoint nor from a nuclear safety standpoint. The most interesting aspect of this incident is the occurrence of multiple simultaneous fires, one of which occurred in the plant's main control room. Incidents involving multiple initial fires have been observed in several other plants (as discussed elsewhere in this report). In some cases, particularly incidents at non-U.S. reactors, the fires have led to extensive damage. PRAs currently do not treat concurrent fires. Rather, only a single fire is postulated in a single location at a given time. This is discussed in detail in the body of this report.

The cause of simultaneous fires at Palo Verde was traced to a fault in the isolation transformer located in Train B DC equipment room. This failure caused a short circuit fault to the station ground through the transformer's panel ground. The neutral leg of the transformer was not connected to ground. Also, an inverter that served as the alternate essential lighting un-interruptible power supply was grounded improperly. The ground connection of the inverter served as the return path for the isolation transformer's ground fault that passed through the essential lighting power supply panel. The conductors that carried the fault current were not designed to handle the high currents caused by the fault. As a result they overheated and ignited the combustible materials around them. Clearly, the common factor leading to the multiple ignitions was a common overloaded electrical conductor.

It is also interesting to note that the fires in this case were, in effect, self-ignited cable fires. An electrical fault led to an ampacity overload on a particular cable, and the cable was ignited in two locations as a result. The units at Palo Verde are relatively new (construction began on Unit 2 in 1976 and the current U.S. cable flammability standard, IEEE 383, was adopted in 1975); hence, it can be assumed that the cables installed in the plant are of a low-flame-spread type. This incident is one of the very few incidents, if not the only incident, where a self-ignited cable fire in low-flame-spread cables has not self-extinguished. In typical fire PRAs, the potential for a sustained self-ignited cable fires is typically considered vanishingly small provided the cables are certified as low-flame-spread. This incident appears to illustrate that the possibility of such fires does exist at some level, though the actual frequency of such fires remains uncertain. If this is, indeed, the only such event in the experience base, then the assumption of low frequency would still be justified.

A25.4 References

A25-1 NRC Information Notice - IN 97-01, "Improper Electrical Grounding Results in Simultaneous Fires in the Control Room and the Safe-Shutdown Equipment Room", U.S. Nuclear Regulatory Commission, January 8, 1997.

NRC FORM 336
(2-89)
NRCM 1102,
3201,3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See Instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6738
SAND2001-1676P

2. TITLE AND SUBTITLE

Risk Methods Insights Gained From Fire Incidents

3. DATE REPORT PUBLISHED

MONTH	YEAR
September	2001

4. FIN OR GRANT NUMBER

Y6037

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6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (if NRC, *provide Division, Office or Region, U.S.* Nuclear Regulatory Commission, *and* mailing *address; provide name* and mailing *address.)*

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9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(if NRC, type "Same as above"; if contractor provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

IO. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

This report presents the findings of an effort to gain new fire probabilistic risk assessment (PRA) methodology insights from fire incidents in nuclear power plants . The study is based on the review of a specific set of 25 tire incidents including fires at both U.S. and foreign reactors. The sequence of actions and event s observed in each fire incident is reconstructed based on the available information. This chain of events is then examined and compared to typical assumptions and practices of fire PRA. The review focuses on two types of actions and events . First are events that illustrate interesting insights regarding factors that fall within the scope of current fire PRA methods. Second are events observed in actual fire incident s that fall outside the scope of current fire PRA methods. Fire PRA insights are then drawn based on these observations. The review concludes that the overall structure of a typical fire PRA cant appropriately capture the dominant factors involved in a fire incident. However, several areas of potential methodological improvement are identified. A few factors are also identified that fall outside the scope of current fire PRAs including the occurrence of multiple initial fires or secondary fires, multiple simultaneous initiating events, and some aspects of the smoke control and human response assessment.

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

Fire, Probabilistic Risk Assessment, PRA, Fire Events, Fire Incidents, Event Analysis

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)
unclassified

(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)

This form was electronically produced by Elite Federal Forms. Inc.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

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