NUREG/CR-6738
SAND2001-1676P

# Risk Methods Insights Gained From Fire Incidents

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Manuscript Completed: August 2001
Date Published: September 2001

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**NRC Job Code Y6037**

# 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.

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# 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-specificdecision 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 tasksin 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 riskassessment 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?

[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.

[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) | | | Manual Suppression Used | Automatic Suppression System | Suppression System Overwhelmed |
| | | | | Last Damage | Fire Under Control | Fire Out | | | |
| 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:

Insights

- 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

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[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.

[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

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[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.

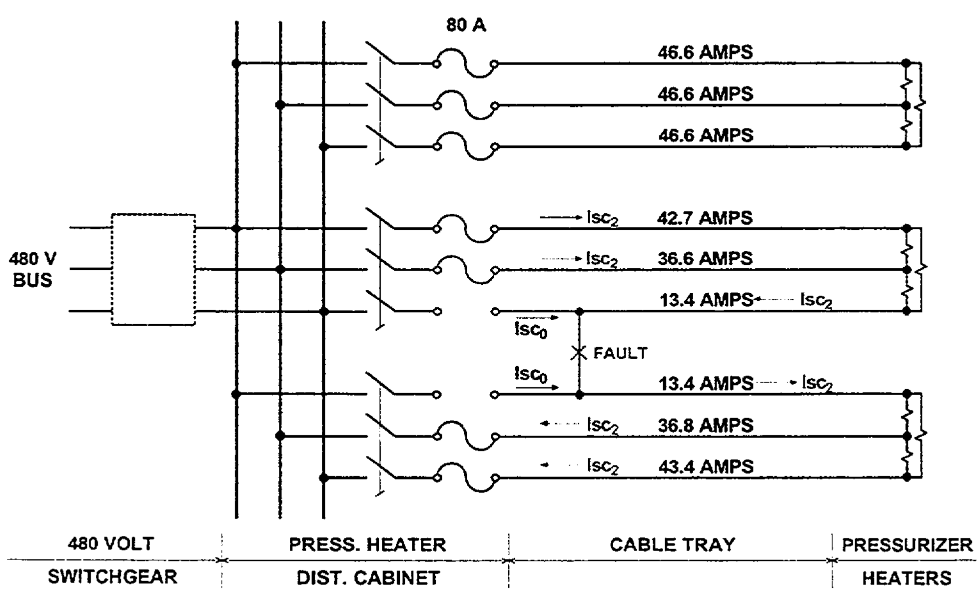


Figure A1-1: Schematic of Pressurizer Heater Circuits.

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

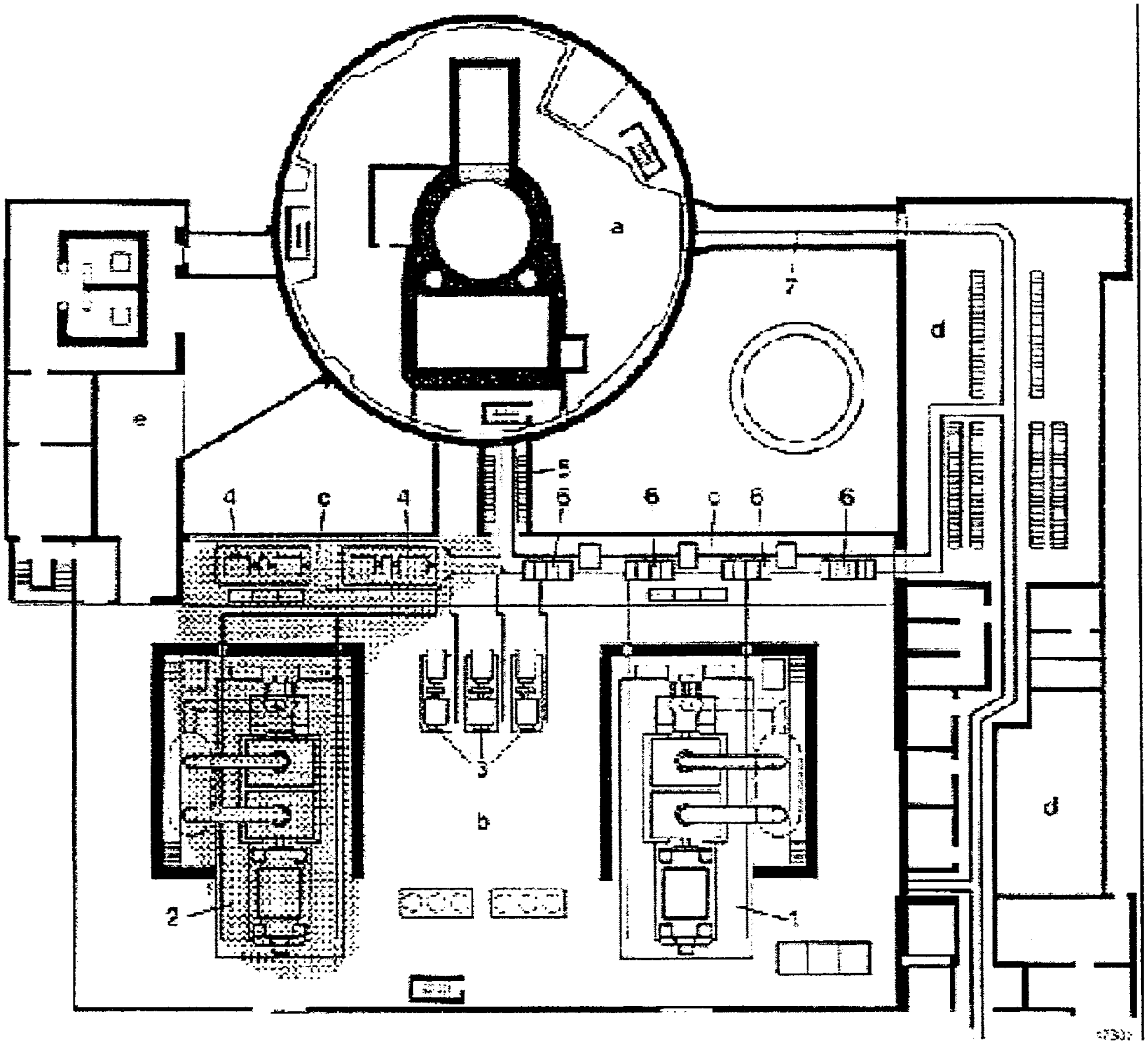


Figure A2-1 Location of Fire at Mühleberg (from Reference [2-1])

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.<br><br>A second alarm was received "Core Spray, RHR Pumps Running". A third alarm "Core Cooling System Diesel Generator Initiate" was received.<br><br>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.<br><br>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.<br>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.<br><br>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.<br><br>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 .<br><br>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.<br><br>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.<br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>Some separation requirements had not been met during construction.<br><br>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).

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## 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 References


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 -47°C. | 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.<br><br>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.<br><br>The fire in cable shafts spread rapidly upwards. It is estimated that the flame propagated vertically at the speed of 0.7m/s.<br><br>A large number of control and power cables at elevations 12.35m and 16.40m were damaged.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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°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.<br><br>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 - Belovarsk, 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

A5-1 Heikki Aulamo, Jouko Martilla and Heikki Reponen, "The Full Stories on Aremenia and Beloyarsk", *Nuclear Engineering International*, July 1995.

A5-2 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, *Energoatomizdat*, Moscow, 1990.

A5-3 Soloviev.P.S. "Accidents and incidents in nuclear power plants", *Obninsk*,1992.

A5-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A5-5 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

## 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.<br><br>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.<br><br>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:<br>- Neutron capacity exceeded 20%<br>- Neutron flux period less than 20 sec.<br>- 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.<br><br>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.<br><br>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.<br><br>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 300m² 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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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.<br><br>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. |

| Fire Scenario Element/Issue | Incident - ANPP, Oct. 15, 1982 | Fire PRA Insights |
|---|---|---|
| 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.<br><br>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.<br><br>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. | 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. |
| | 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 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 150°C. 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 Incident Analysis

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 <u>References</u>

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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.