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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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FIRE RISK ANALYSIS, FIRE SIMULATION, FIRE SPREADING AND IMPACT OF SMOKE AND HEAT ON INSTRUMENTATION ELECTRONICS

State-of-the-Art Report

English text only

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA) is an international committee made up of senior scientists and engineers. It was set up in 1973 to develop, and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety among the OECD Member countries.

The CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of the programme of work. It also reviews the state of knowledge on selected topics on nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus on technical issues of common interest. It promotes the co-ordination of work in different Member countries including the establishment of co-operative research projects and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences and specialist meetings.

The greater part of the CSNI's current programme is concerned with the technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment, and severe accidents. The Committee also studies the safety of the nuclear fuel cycle, conducts periodic surveys of the reactor safety research programmes and operates an international mechanism for exchanging reports on safety related nuclear power plant accidents.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

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ABSTRACT

Numerous fire PSAs (probabilistic safety assessments) have shown that fire can be a major contributor to nuclear power plant risk. However, there are considerable uncertainties in the results of these assessments, due to significant gaps in current abilities to perform realistic assessments. These gaps involve multiple aspects of fire PSA, including the estimation of the probability of important fire scenarios, the modeling of fire growth and suppression, the prediction of fire-induced damage to equipment (including the effects of smoke), and the treatment of plant and operator responses to the fire.

This SOAR provides an overview of Fire PSA methodology, Fire simulation models and codes applied or available, the impact of smoke and heat and cover application issues.

FOREWORD

The SESAR reports have emphasized the impact of high temperature of fires and the spreading of smoke on electrical equipment and electronics as important issues in fire risk assessments. The fact that fire risk analysis has become an integral part of PSA and the fires have been recognized as one of the major contributors to risk of nuclear power plants was also well reflected. Accordingly SESAR reports recommended CSNI to tackle the issues in fire risk assessment.

In 1996 PWG5 submitted CSNI a proposal to undertake such a study and the task 97-3 was initiated in 1997. Accordingly, the prime focus of the task was to concentrate on some special issues such as fire simulation, fire spreading, and impact of smoke and heat on instrumentation electronics. A questionnaire for acquiring information was sent to all nuclear energy using OECD countries. The prime questions of the questionnaire concerned issues such as:

- Characterization of fire risk PSA Applications
- Fire simulation codes applied or available
- Review and assessment of fire ignition data
- Modeling of fire spreading on cables or other equipment
- Modeling of smoke production and spreading
- Impact of smoke and heat on instrumentation electronics or electrical equipment
- Impact of cable fires on safety systems

Task Force included Mr. R. Virolainen of STUK (Chairman), Dr. Lanore of IPSN, Mr Cunningham and Mr. Murphy of USNRC, Mr. Wilmart of TRACTABEL, Mr. Hirano and Mr. Fukuda of NUPEC, Dr. Köberlein of GRS, Dr. Shepherd of NII, Dr. Raina of Ontario Hydro, Dr. Yllera of CSN, Mr. Keleman of ETV ERÖTERV and Dr.Czako of VEIKI,

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1. INTRODUCTION

Numerous fire PSAs (probabilistic safety assessments) have shown that fire can be a major contributor to nuclear power plant risk. However, there are considerable uncertainties in the results of these assessments, due to significant gaps in current abilities to perform realistic assessments. These gaps involve multiple aspects of fire PSA, including the estimation of the probability of important fire scenarios, the modeling of fire growth and suppression, the prediction of fire-induced damage to equipment (including the effects of smoke), and the treatment of plant and operator responses to the fire.

In response to recommendations of /VIR 93/, CSNI/PWG5 established a Task Group to review the present status and maturity of current methods used in fire risk assessments for operating nuclear power plants. The Task Group issued a questionnaire in May 1997 to all nuclear power generating OECD countries. The prime focus of the questionnaire (see Appendix A) was on a number of important issues in fire PSA:

- Fire PSA methodology and applications
- Fire simulation codes
- Ignition and damageability data
- Modeling of fire spread on cables or other equipment
- Modeling of smoke production and spread
- Impact of smoke and heat on instrumentation, electronics, or other electrical equipment
- Impact of actual cable fires on safety systems.

The questionnaire requested specific information on these topics (e.g., computer codes used in fire PSAs, the physical parameters used to model ignition).

Responses to the questionnaire were provided by Finland, France, Germany, Hungary, Japan, Spain, Switzerland, United Kingdom, and the USA. This report summarizes the questionnaire responses and thereby: a) provides a perspective on the current fire PSA state of the art (SOAR) with respect to the issues listed above, and b) provides numerous references for more detailed information regarding these issues.

The main responsibility for writing different chapters of this report was divided between some OECD countries. The contents of each chapter are based on the writers' knowledge on his or her national practices and on the results of the questionnaire. The emphasis in the descriptions of the national practices also reflects the information supplied by the responding countries. Fire PSA is also used in other OECD countries, but the scope of this report is limited to those countries which responded to the questionnaire.

The contents of this report are as follows.

Fire PSA methodology overview - Based on a review of fire risk studies performed in the contributing countries, the report addresses different methodology and applications issues. Methodology issues, treated in Chapter 2, include the treatment of physical barriers, fire detection and suppression systems and fire fighting. They also include the treatment of operator actions and dependencies (both direct and indirect) between a fire and the plant's safety systems, definition of initiating events, and screening methods. Key assumptions and the effect of plant operational state (i.e., full power vs. low power operation) are dealt with in the report as well.

Fire simulation models and codes applied or available - Chapter 3 of the report identifies which fire simulation codes have been used in actual PSAs. The models and scenarios used in different codes are described. To build confidence on fire simulation models, validation against experimental results in different types of fires is necessary. Fire experiments and the pre- and post experiment calculation used for code validation as well as ongoing fire simulation code development projects are discussed. Examples of fire scenarios and typical modeling assumptions are treated and numerous references are given in Chapter 3. References for experimental case studies and related simulation models and codes used for analyzing the production and spreading of smoke are also provided.

The impact of smoke and heat - The immediate consequences of fires are caused by heat, smoke, and soot. The failure thresholds, modes, and attendant disturbances are treated in Chapter 4.

The chapter provides references for statistical and phenomenological information relevant to ignition and component damage, and also for fire events. References are given modeling of fire spreading, the ignitability, damageability, and heat release rates of components such as cables, printed circuit boards, and electronics cabinets. Some experiments and simulations on the development of cabinet as well as cable tray fires are also described.

Specific examples are given on the impact of smoke and heat on instrumentation electronics, electrical equipment. References are given on relevant experiments studying the impact of smoke and heat on electronics and/or electrical equipment. Some cases where cable fires have resulted in threats to plant safety or caused power and I&C circuit failures are discussed. References concerning the habitability of main control room are also provided.

Applications Issues - The essence of fire PSA is discussed in Chapter 5. The scope and completeness of fire PSA may vary according to the strategy and stage of the overall PSA studies. For the identification of the main vulnerabilities of a plant, rough models are sufficient, whereas in a full scope fire PSA for detailed evaluation and comparison of risks more sophisticated methods have to be applied. Purpose and contents of the fire PSAs, as well as the uses made of these studies in different OECD countries are described in Chapter 5.

It should be noted that the report is intended to serve as a resource to fire risk analysts but is not intended to serve as a fire PSA procedures guide. References for fire PSA guidance are provided in Chapter 2.

2. CURRENT FIRE PSA METHODOLOGY: OVERVIEW AND ISSUES

2.1 Fire PSA Overview

Conceptually, the general framework of fire PSAs for nuclear power plants is little changed from that underlying the earliest fire PSA studies performed some 15 years ago. In this framework, the core damage frequency (CDF) contribution due to a given fire scenario[1] can be represented as being comprised of three elements:

- the frequency of the fire scenario,
- the conditional probability of fire-induced damage to critical equipment given the fire, and
- the conditional probability of core damage given the specified equipment damage.

Formally accounting for the possibility of different levels of equipment damage and different plant responses following fire initiation,

$$\mathrm{CDF} = \sum_i \lambda_i \sum_j p_{ed,j|i} \sum_k p_{CD,k|i,j} \qquad (1)$$

where λ_i is the frequency of fire scenario i, $p_{ed,j|i}$ is the conditional probability of damage to critical equipment set j given the occurrence of fire scenario i, and $p_{CD,k|i,j}$ is the conditional probability of core damage due to plant response scenario k given fire scenario i and damage to critical equipment set j. Note that the second term addresses the issues of fire growth, detection, suppression, and component damageability, and that the third term addresses the unavailability of equipment unaffected by the fire and/or operator failures.

We note that the three-term decomposition of fire risk presented in Eq. (1) is not unique; alternate decompositions can be found in the literature. For the purposes of this report, the three-term decomposition is useful because each of the terms tend to be addressed differently in current fire PSAs. In particular, the fire frequencies are generally estimated using simple statistical models for fire occurrences, the likelihood of fire damage is estimated using combinations of deterministic and probabilistic models for the physical processes involved, and the likelihood of core damage is estimated using conventional probabilistic risk assessment systems models. Note also that the three-term decomposition directly corresponds with the traditional fire protection definition of defense-in-depth, whose elements are fire prevention, fire detection and suppression, and fire mitigation.

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[1] For the purposes of this discussion, a fire scenario is defined by the location and burning characteristics of the initiating fire. Both fixed and transient combustible fires are considered.

The general process used by the analyst to apply Eq. (1) is also quite similar to the processes used in the earliest fire PSAs. Plant familiarization activities (including design reviews and plant walkdowns) are performed to identify and characterize, for each fire area[2] in the plant, potentially important fire initiation scenarios and potentially important target components (especially cables[3]). Iterative approaches using progressively more accurate models are then employed to focus analysis resources on those scenarios which contribute most to risk. Note that in many analyses, the term $p_{ed,j|i}$ is not quantified initially; it is only addressed for those areas where a detailed analysis is needed (see Chapter 5). The results of the analysis are typically presented on a fire area by fire area basis.

Despite the same general framework and analytical process, the results of fire PSAs can vary significantly (see Table 1, which presents the results of a number of fire PSAs performed for U.S. commercial nuclear power plants). Part of this variability is due to variations in plant design, as expected. However, a significant part of the variability appears to be due to differences in the specific analytical processes and assumptions employed. Key issues underlying this variability are discussed later in this chapter.

Descriptions of the general fire risk assessment FRA methodology currently used can be found in a variety of references, including /APO 82/, /KAZ 85/, /ANS 81/, /BOH 90/, /NRC 91b/ and /PAR 95/. The Fire-Induced Vulnerability Evaluation (FIVE) methodology, used in numerous ***U.S.*** Individual Plant Examinations of External Events (IPEEEs) and used in a modified form in ***French*** fire PSAs, is documented in /PLC 92/. ***German*** fire PSA guidance published by the regulatory authority BfS and by GRS is provided in /FAK 97/, /FAK 97a/, and /GRS 97/. Widely available references documenting plant-specific FRA studies (including the study methodologies and data) include /BOH 90a/, /LAM 93/, /MUS 94/, /GRS 90/, /GRS 93/, /HOF 96/, /MEY 98/, /MEY 98a/, /TAI 89/, /BRE 99/. More narrowly focused references relevant to specific aspects of the FRA methodology include:

/KAZ 82/, /BER 95/, and /HOU 97/ (fire frequency analysis);
/SIU 82/, /HOV 91/, and /BER 96/ (fire modeling in FRA);
/SIU 86/ (detection and suppression analysis);
/BRA 89/ and /SIU 92/ (uncertainty analysis); and
/LAM 89/, /VIR 93/, and /SIU 97/ (FRA methods, tools, and data issues).

In Finland, the Regulatory Guide YVL 2.8 requires that fire risks have to be analyzed in plant PSAs. When the fire PSAs were started at the late 1980's, a review of the state-of-the-art procedures and fire study reports was carried out. Full power operation fire PSAs have been carried out for both Finnish NPPs (Loviisa and Olkiluoto). Fire PSAs for shutdown and low power states are under way. The methodology is continuously developed according to national and international studies and research results. The methodology development and the findings of the authority reviews are incorporated in the updated revisions of the PSA studies within the living PSA framework.

National practices in fire PSA have been lately described, for example, in the OECD/NEA International Workshop on Fire Risk Assessment, (Helsinki, June 1999) /NEA 99/.

Note that many of the general FRA methodology and application references mentioned above also provide useful (and sometimes detailed) discussions regarding these specific issues. Also note that there are many

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[2] In this report, the term «fire area» will be used generically to refer to fire compartments or fire areas (plant areas generally separated by rated fire barriers) and fire zones (subdivisions of fire areas which may or may not be separated by rated fire barriers).

[3] Note that for a 900 MW_e French PWR, approximately 10,000 cables associated with safety related systems have to be taken into account.

useful references on the general issue of fire modeling and experiments; these are provided in later chapters of this report, as appropriate.

2.2 Specific Topics and Issues

This section discusses current fire PSA methods for addressing each of the three terms in Eq. (1). The discussions include descriptions of the general approach (or approaches) for addressing each term, as well as an identification of potential issues. The section also includes a discussion of control room fires. Applications issues, e.g., screening analysis practices, are addressed in Chapter 5 of this report.

2.2.1 Fire Frequency Analysis

A fire frequency analysis involves the definition of representative fire scenarios for the fire area of interest, and the estimation of the frequency (i.e., the «quantification») of these scenarios. Depending on the objectives of the fire PSA (see Chapter 5) and the potential risk significance of the fire area, the scenarios can be defined in a broad or detailed manner. For example, for areas where a relatively crude analysis is sufficient, the representative fire scenario can be defined as a fire anywhere in the area. For areas where a more detailed analysis is needed, multiple fire scenarios defined in terms of the precise location and initial magnitude may need to be specified.

The quantification process generally involves: (i) the statistical analysis of historical data, and (ii) the application of judgement. The statistical analysis is generally done on an area basis or a component basis. The first approach involves the estimation of fire frequencies for different fire areas (e.g., main control room, cable spreading room, switchgear room) or groups of fire areas (e.g., auxiliary building, turbine building). The second approach involves the estimation of fire frequencies for different component types (e.g., pumps, electrical panels, transformers, transient combustibles). In both approaches, it is typically assumed that fire frequencies are constant over time, i.e., that fire occurrences are Poisson events. Note that /HOU 97/ shows that the frequencies of fires in key U.S. nuclear power plant compartments have not changed dramatically when comparing the periods 1965-1985 and 1986-1994. Most fire PSA analyses have assumed that the fire frequencies are also constant over plants; some have performed plant-specific assessments.

In the U.S., a number of fire PSAs have developed plant-specific estimates for fire frequencies using standard Bayesian procedures. Generic data (screened to exclude such events as fires during construction) are used to develop a prior distribution, which is then updated using plant-specific data. An analysis which statistically accounts for plant-to-plant variability in the generic data is described in /KAZ 82/. The results of these analyses include a quantification of the uncertainties in the fire frequencies.

In many other U.S. fire studies, however, simple generic point estimates are used for fire frequencies. This is the approach used in most (but not all) of the Individual Plant Examinations of External Events (IPEEEs), discussed in Chapter 5. The use of generic fire frequencies clearly can mask problems in plant-specific administrative programs intended to prevent fire occurrences, but is otherwise not expected to affect the identification of fire vulnerabilities, which is the primary concern of the IPEEE program.

Fire-frequency estimation issues identified in /SIU 97/ include: the effects of plant operations (e.g., maintenance activities) on fire frequency, the frequency of self-initiated cable fires involving flame retardant cable, and the potential significance of unreported fires.

In ***France***, point estimate calculations are generally used for fire frequencies /BAR 96/. The estimates are different for each of the two PWR classes; but are treated as being generic within a class. Similar to U.S.

studies, construction fires and fires in non-safety related buildings are not included in the fire frequency estimates. Similar to the FIVE methodology, the fire frequencies are developed for component classes (or «ignition source family») on a reactor-year basis. Example classes include: batteries, diesel generator sets, relay cabinets, and electrical switchboards or cubicles. Thus, for example, the fire frequency analysis will produce an estimate for relay cabinet fires per reactor-year. Note that in cases where there is no fire experience for a particular ignition source family, the χ^2 relation for a 50% confidence level is used (i.e., the estimate is derived as if 0.7 fires had occurred).

The procedure used in ***Germany*** for revealing fire frequencies is based on the method of Berry /BER 79/ as outlined in more detail in /ROE 97/ with some additional treatment due to methods described in /PES 95/. The approach starts with frequencies for the differing plant locations derived from plant specific information taking into consideration generic fire occurrence data as far as available and applicable. It furthermore considers geometric factors (e.g. for fire loads as point source, fire load homogeneously or inhomogeneously distributed over the fire compartment) and fire severity depending on type and amount of combustibles as well as on the safety related equipment potentially affected. A further improvement of this approach is to be developed in the near future by GRS.

Regarding the role of analyst judgement in fire frequency analysis, it is especially significant when estimating the frequencies of detailed scenarios, e.g., fires in a particular portion («location») of a cable spreading room that have a particular severity. Judgement is needed to partition the statistically estimated frequencies (e.g., for cable spreading room fires) when analyzing detailed scenarios because the available fire data are too sparse to allow direct estimation of the frequencies of such potentially challenging fires.

In the U.S., «location fractions» are employed in some fire PSAs to reduce plant area-based fire frequencies to account for geometrical factors; other fire PSAs use plant component-based fire frequencies for this same purpose, as described in /PLC 92/ and /SAI 95/. Regarding fire severity, «severity fractions» are widely used to address the fraction of fires (in a given compartment or involving a given component) that have the potential to cause significant damage in a relatively short amount of time.

The use of severity and location factors has reduced the fire area frequencies in a number of ***U.S.*** fire PSAs by one or more orders of magnitude. However, as discussed in /SIU 97/ and /SIU 99/, the basis for these reduction factors is not strong. The most significant issue concerns the treatment of fire severity. The potential problems include: ambiguity in qualitative event narratives used to determine fire severity; possible double-counting of the impact of suppression in the data (effective suppression may be the reason why a particular fire was not reported as being severe, but fire suppression is modeled separately in the fire PSA); neglect of possibly significant differences between conditions (e.g., fuel bed geometry) of the event and those of the situation being analyzed in the fire PSA which can affect the severity of the fire; and scarcity of data for the large, transient-fueled fires that have been predicted to dominate fire risk in a number of studies. Also of concern is the ambiguous interface between the fire frequency and equipment damage analyses; the lack of definition of the physical characteristics of the fire scenarios quantified in the fire frequency analysis means that the analyst has significant flexibility in establishing the initial conditions for fire modeling.

In ***France***, location-related frequencies for component-based fires are developed in the same manner as FIVE; it is assumed that the fire frequency in a compartment is proportional to the number of potential ignition sources. Therefore, knowledge of the distribution of components throughout the plant provides a means for allocating component fire frequencies. The fire frequency in a compartment due to equipment is obtained by summing the contributions of the frequencies of the different ignition source groups. The contribution to room fire frequency caused by human action is assessed assuming that their contribution is uniform throughout the facility. An adjustment factor is used in the case of transient-fueled fires to deal with the likelihood that the fire is near the target of interest.

Fire frequencies have, to date, been treated as empirical parameters which can be directly estimated from data. The issues discussed above show that this treatment may need to be re-examined, especially if fire PSA is to play a stronger role in risk management. A more mechanistic, systems modeling approach which specifically addresses the possible scenarios leading to fire ignition and the different outcomes of these scenarios, and does so within the constraint of available data, appears to be needed for detailed assessments. A possible starting point is provided in /BER 79/, which employs a number of subjective ratings of relevant factors (e.g., availability of fuel) to develop an index for the likelihood of fires of different severities.

In **Finland**, modifications of Berry’s model have been used for allocating proportional fire ignition frequencies of rooms, especially at the Olkiluoto plant. In the Loviisa fire PSA, the ignition frequencies of rooms have been mainly estimated on the basis of component fire event data.

2.2.2 Equipment Damage Probability

Given a fire in a nuclear power plant compartment, the conditional probability of damage to key equipment (i.e., $p_{ed,j|i}$) needs to be determined. In a detailed fire PSA, the assessment typically involves: (i) a prediction of the fire-induced environmental conditions; (ii) an assessment of the equipment response to these conditions; and (iii) an assessment of the likelihood that the fire will not be detected and suppressed before equipment damage occurs (see Figure 2.1). Note that the index j in $p_{ed,j|i}$ accounts for the possibility of multiple equipment damage scenarios due to a single initiating fire scenario. Therefore, as appropriate, the analysis also assesses the effectiveness of fire barriers in preventing fire damage to protected equipment in the room of fire origin and in preventing fire growth to neighboring compartments.

Based upon the results of the fire environment, equipment response, and suppression analyses, the probability of equipment damage is, in principle, given by /APO 82/

$$p_{ed,j|i} = p\{T_{d,j|i} < T_{s|i}\} \qquad (2)$$

where $T_{d,j|i}$ is the damage time for equipment set j given fire scenario i and $T_{s|i}$ is the suppression time for fire scenario i. Current approaches used to perform these analyses and quantify $p_{ed,j|i}$ are discussed below.

2.2.2.1 Fire Environment

Characterization of the fire-induced thermal environment for the purposes of fire PSA requires the estimation of the time-dependent temperature and heat fluxes in the neighborhood of the safety equipment of interest (i.e., the «targets»). This requires the treatment of a variety of phenomena as the fire grows in size and severity, including the spread of fire over the initiating component (or fuel bed), the characteristics of the fire plume and ceiling jet, the spread of the fire to non-contiguous components, the development of a hot gas layer, and the propagation of the hot gas layer or fire to neighboring compartments. It also requires an appropriate treatment of uncertainties in the structure and parameters of the models used to perform the analysis.

Chapter 3 of this report discusses the fire models that either have been used in NPP fire PSAs or can be used in these studies, as well as sources of uncertainties in the model predictions. /SIU 97/ provides additional discussion on issues in fire modeling for fire PSA. It should be noted that potentially risk significant NPP fire scenarios have a number of special characteristics which may or may not be directly addressed by fire models not explicitly designed to model these scenarios. These characteristics include a variety of source fires (including cable tray, electrical cabinet, and oil pool fires), the possibility of propagation through fuel arrays (e.g., cable tray stacks) prior to flashover, the lack of openings to the environment, and local obstructions and barriers. Furthermore, fire models not designed for NPP fire PSAs may not have integrated component response models (discussed in the following subsection), which are convenient for an efficient analysis.

From an applications viewpoint, it should be noted that fire models may need to be exercised for a number of potentially significant fire scenarios within a compartment. Different fire scenarios can be defined depending on the number of fixed and transient combustible sources and the variety of ventilation conditions (including possible changes, e.g., the opening of a fire door). The number of scenarios can be quite large. In ***France***, during screening analyses (see Chapter 5) for a given target, the «worst case» (in probabilistic terms) is adopted. In other words, the analysis focuses on the scenario for which damage of the target is the most probable

It should also be noted that, although uncertainty analysis is a standard part of many detailed PSAs, uncertainties in fire modeling are not always treated carefully in current fire PSAs. In the ***U.S.***, only a few studies (e.g., /PLG 82/) explicitly identify and propagate parameter uncertainties and model uncertainties. In a number of other studies (e.g., /BOH 90a/, /LAM 93/), uncertainties in the overall fire model output are assessed on a more subjective basis. /SIU 82/, /BRA 95/, and /SIU 92/ describe a number of formal methods for addressing uncertainties in fire modeling.

2.2.2.2 Equipment Response

Given a predicted environment for a piece of equipment, a detailed fire PSA needs to assess the equipment response and determine the likelihood of equipment failure and the mode of failure. Because of the common cause failure potential of cable fires, the key concern is the fragility of electrical cables. However, the fragilities of other potentially vulnerable equipment, e.g., electro-mechanical and electronic components in electrical cabinets, are also of interest.

Current fire PSA treatments of equipment failure due to heat are very simple; it is generally assumed that damage will occur if a representative temperature (e.g., the surface temperature of a cable) exceeds a threshold value. In some analyses, component damage is also assumed if the incident heat flux exceeds a critical value. When component temperature criteria are used, conservative approaches (e.g., assuming the component is at the local environment temperature) or simple heat transfer models (e.g., lumped capacitance models or one-dimensional transient heat conduction models in the case of cables) are employed. Chapter 4 of this report discusses available information relevant to the estimation of thermal fragilities of key equipment. Cable damageability and failure modes are treated in Section 4.2.2 and Section 4.4 provides information relevant to the estimation of smoke fragilities of sensitive equipment. Note that smoke effects are not yet explicitly addressed in detailed fire PSAs.[4]

Regarding the treatment of failure modes, all fire PSAs address fire-induced circuit failures that lead to loss of function; some also address failures that can lead to spurious actuation of plant equipment or to an alarm. The latter failure mode, typically assumed to be caused by «hot shorts» (i.e., electrical faults between cable conductors without a loss of conductor integrity or a simultaneous short to ground), has been shown to be an important and sometimes even dominant contributor to fire risk in a number of U.S. studies. In such cases, the scenarios often involve the spurious opening of one or more valves in the primary system boundary and a subsequent loss of coolant accident (LOCA).

In the ***U.S.***, the probability of a single hot short is commonly based on a generic probability distribution derived subjectively in 1981 from a limited amount of information /KAZ 81/. (The distribution, assumed to

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[4] It can be argued that, for those fire PSAs where it is conservatively assumed that any fire within a compartment will damage all equipment within that compartment, the potential effects of smoke and fire suppressants are indeed addressed.

be lognormal, has a 5th percentile of 0.01 and a 95th percentile of 0.20; its mean value is 0.07.) The probability of multiple hot shorts is often obtained by multiplying this probability an appropriate number of times. The latter procedure ignores the potentially significant impact of state-of-knowledge dependencies. More importantly, these hot short distributions do not reflect such presumably important issues as the circuit design, the function of the cable, and the characteristics of other cables in the vicinity. Research is being conducted on developing an improved technical basis for estimating hot short probabilities /SIU 99/, /LAC 99/.

2.2.2.3 Fire Barriers

As part of determining the immediate environment of equipment potentially affected by a fire, the fire PSA needs to consider the effectiveness of fire barriers.[5]

In the U.S., the most extensive investigation of multi-compartment fires and the effect of inter-compartment barriers was performed by the LaSalle fire PSA /LAM 93/. In that study, which was intended to extend the PSA state-of-the-art in a number of areas, the possibility of fire propagation across rated fire barriers between up to three fire areas was treated explicitly. Screening analyses using barrier failure probabilities of 0.10 and assuming the loss of all equipment in all affected fire areas were employed to eliminate unimportant combinations of fire areas. (The computer code SETS was used to perform the logic calculations.) More refined analyses employing less conservative barrier failure probabilities[6] (but still assuming the failure of all equipment in all affected areas) were then performed for the remaining combinations of fire areas. As it turned out, no combinations passed the study's CDF screening criteria of 10^{-8}/yr, and so multi-area fires were determined to be insignificant contributors to fire risk for the LaSalle plant.

More recently, many of the IPEEEs have investigated the potential for fire vulnerabilities associated with the spread of fire between compartments in a single fire area. (Fire spread between fire areas has not been treated by these studies - it is assumed that the 2- or 3-hour rated fire barriers generally separating fire areas will contain the fire.) Some of the IPEEEs have used the FIVE methodology /PLC 92/, which employs engineering judgement in conjunction with a number of screening criteria. Other IPEEEs have used the more quantitative, PSA procedure described in the EPRI Fire PRA Implementation Guide /SAI 95/. This procedure addresses fire modeling concerns (the potential for hot gas layer formation) as well as barrier, fire protection, and safe shutdown reliability concerns. None of the IPEEE studies investigating multi-compartment fires has concluded that these fires are sources of fire risk vulnerabilities; only a very small number of studies have identified multi-compartment scenarios which are potentially visible contributors to fire risk.

Regarding the treatment of local fire barriers (i.e., separating equipment within compartments) in ***U.S.*** fire PSAs, the barriers are usually either assumed to be completely reliable or are entirely neglected. Even when physical models for barrier performance are employed (e.g., COMPBRN /HOV 91/ provides a one-dimensional steady state heat conduction model), these models do not address such behaviors as gross

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[5] Note that the often-quoted fire duration ratings of fire barriers (e.g., as determined by the ASTM E-119 furnace test or similar tests) should be taken as relative indications of barrier effectiveness. The fire sciences community has agreed that the quantitative model relating fire loads and fire severity that underlies these ratings is obsolete (see p. 7-111, /NFPA 86/; also /COO 96a/). This means, for example, that a 3-hour barrier will not necessarily prevent the spread of fires with an «equivalent severity» (as computed from the fire load) of less than 3 hours.

[6] As discussed in /SIU 97/, the technical basis for these reported failure probabilities is weak and needs to be re-examined.

distortion and mechanical failure of the barrier system. Fire tests have shown that such behaviors are strongly affected by installation practices (e.g., the method of sealing joints). Furthermore, the physical properties of the barriers needed to address such complex issues are not readily available.

In ***France***, it is generally assumed in screening analyses that, for a fire barrier which has a resistance rating greater than a calculated fire duration for the room of fire origin, fire spread through the barrier to an adjacent compartment will not occur. The fire duration can be based on the fire loading (e.g., in MJ/m^2 floor area) for the room. Information on the ventilation system (e.g., locations of fire dampers) and fire barrier elements (e.g., fire doors, cable penetration seals) is needed for the analysis. Figure 2.2 provides an example of a loading/duration curve which can be used. In detailed analyses, performed on critical zones, the fire propagation through fire barrier is studied. These analyses involve active barrier elements (e.g., fire doors and dampers), the possibilities of mechanical failures or human failures (e.g., when a fire brigade opens a door) are addressed in fault trees for fire event tree top events (see Section 2.2.2.4 below).

The fire duration versus barrier resistance method for treating fire barrier effectiveness is also used in ***Germany*** (see Figure 2.3 for an example loading duration curve which depends on the distribution of combustibles within the compartment), ***Japan*** and ***Spain***. In ***Japan,*** a physical barrier is assumed to have a 50% likelihood of failure in the absence of suppression when the fire severity is equal to the barrier rating. In ***Spain***, fire propagation from one room to another room is assumed if either, a fire barrier installed between them is unavailable or the burning time is longer than the time the barrier can stop fire progress. The reliability of barriers was initially assessed using generic data from NRC inspection reports. However, it was recognized that this approach did not take into account the actual surveillance, maintenance and control practices exercised at the plants concerned and so attempts were made to base reliabilities on actual plant practices.

The treatment of fire barriers, both within and between compartments, is a continuing source of uncertainty in fire PSAs due to concerns with: a) the obsolete fire duration-based barrier effectiveness model still used in many fire protection evaluations, b) the data used in earlier studies to estimate barrier failure probabilities, and c) the available tools to deterministically evaluate the performance of a number of realistic barrier systems /SIU 97/. (Note that the behavior of barrier systems under challenging fire conditions can be fairly difficult to model mechanistically. Depending upon the barrier material and installation practices employed, such issues as material ablation and the effect of assembly techniques on mechanical distortion may need to be addressed.) The results of recent fire protection inspections in the ***U.S.*** indicate that improvements in available tools and data may be needed.

2.2.2.4 Fire Detection and Suppression

Within the context of a fire PSA, the objective of a detection and suppression analysis is to determine the likelihood that a fire will be detected and suppressed before the fire can damage critical equipment. This requires an assessment of the performance of automatic systems and of the effectiveness of manual fire fighting efforts.

In the ***U.S.***, /SIU 86/ describes a state-transition methodology which assesses the likelihood of multiple detection/suppression scenarios and their associated suppression times using generic fire protection system reliability estimates and detection/suppression time data obtained from nuclear power plant fire events. A condensed and somewhat simplified version of this methodology which employs data from operational experience is presented in /SIU 85/; the methodology has been used in a few FRAs (e.g., /MUS 94/). An alternate methodology which: a) does not explicitly identify different detection and suppression scenarios, b) uses physical models included in FPETOOL /NIS 92/ to estimate detector and sprinkler actuation times, and c) uses expert judgement to estimate other characteristic delay times in the fire detection/suppression process, has been used in the LaSalle fire PSA /LAM 93/.

Most ***U.S.*** fire PSAs have used a simpler model in which automatic systems, if they are credited and actuate, are assumed to be immediately effective. (See the guidance provided in /SAI 95/.) The results of calculations for equipment damage times are sometimes compared with the results of FIVE /PLC 92/ worksheet calculations for fire detector and sprinkler actuation times to determine if automatic systems should be credited. If automatic suppression is unsuccessful, the likelihood that manual suppression efforts will be effective before equipment damage is then determined. A possible weakness with this simpler model is its neglect of delays in fire suppression following fixed system actuation observed in real events (e.g., the Browns Ferry fire). However, because the fire growth models used in fire PSAs do not account for the retarding effects of suppression activities, the risk impact of this neglect is not clear.

In ***French*** screening analyses (see Chapter 5 and /BON 96/), fire suppression is not taken into account to determine the likelihood of component damage. In other words, as long as fire models show that component damage can be caused by the «worst-case» fire for the area, the possibility of automatic or manual suppression before damage is not credited.

In the ***French*** detailed analyses, event trees are used for modeling the progression of the fire scenario, including the effects of detection and suppression. The trees are based on a state-transition model for the detection and suppression process that is similar to the state-transition model described in /SIU 86/. The analysis explicitly addresses ignition, detection (including delays for local confirmation of the fire), and extinguishing (i.e., total control of the fire). Multiple modes of detection (automatic, equipment inoperability, local, and late detection due to eventual appearance of fire symptoms) are addressed, as is the likelihood of local operator presence (including the effect of room inaccessibility). The suppression model accounts for automatic and manual suppression. Regarding the latter, the different phases of manual suppression modeled are: the first-line response (due to field operators or others in the vicinity), the second-line response (due to plant staff using extinguishers and fire hoses), and a phase involving joint efforts by site and external fire brigades, see also Fig 2.1. It is assumed that, for the last phase, the fire extinguishing strategy consists of preventing the propagation of fire outside the compartment and ensuring that it remains limited to the compartment involved. Regarding automatic (and manually actuated fixed) suppression systems, the reliability of the fire suppression systems is assessed using appropriate fault trees.

Regarding the treatment of human actions in these event trees, the field operator, in case of fire, has to follow a procedure involving: (i) the confirmation to the control room that there is a fire, (ii) verification of the closure of fire doors, (iii) closure of the fire dampers, (iv) activation of the fixed extinguishing system, and (v) opening of the valves of the smoke reducing system and then asking the control room to activate this system. The error probabilities for these steps are estimated from fire experience (e.g., in the case of fire detection, fire confirmation, activation of the fixed extinguishing system) or from an application of the Technique for Human Error Rate Prediction (THERP) /SWA 83/. These detailed analyses permit to identify the consequences of each fire scenario that occur in a compartment (equipment or electrical cables lost and their damage time). In addition to the estimation of conditional probability of equipment damage, a functional analysis of these consequence establishes the information needed to identify the initiating events that can be induced by fire, to quantify human error of operating team and safety engineer, to estimate the probability of core damage sequences. This information is notably:

- alarms initiated in control room,
- operating procedure applied by operating team,
- alarms not transmitted in control room and needed for the implementation of the operating procedure,
- equipment unavailable and needed to reach a safe shutdown state.

In ***Japan*** human reliability has been taken into account within the suppression failure probability assessment (which uses the COMPBRN-IIIe code /HOV 91/ in the competing risks formulation of Eq. (2)).

In ***Spain*** a systematic and detailed analysis of human actions associated with external event analysis has been required for the more recent PSAs. A document addressing the relevant factors for human reliability for external event analysis (in this case fire detection and suppression) has been developed by CSN for utility application.

Issues with current fire PSA detection and suppression analyses include /SIU 97/: the use of generic data which can account for plant practices (e.g., installation and maintenance) in only an average manner; the potential for over-crediting of suppression efforts in studies which employ «severity factors» (see Section 2.2.1); the sparsity of data for detection times; the lack of data to quantify the dependence of suppression times on such issues as location, severity, and accessibility of the fire; the integration of expert judgement regarding suppression effectiveness with actual data; the lack of treatment of the effects of smoke and loss of lighting on manual fire fighting; the lack of tools to assess the effectiveness of compensatory measures (e.g., fire watches) for temporary fire protection deficiencies; and the lack of tools to assess the effect of interactions between the fire growth and suppression processes on the likelihood of suppression before damage.

2.2.3 Fire Mitigation

For each fire scenario involving damage to a set of equipment, the fire PSA must assess the conditional core damage probability (CCDP). This analysis must address the response of plant hardware and staff under fire conditions.

In the ***U.S.***, most studies employ modified versions of the relevant internal events analyses to determine the CCDP. The modifications performed include the forced failure of equipment directly damaged by the fire and, in many studies, increases in human error probabilities (HEPs) to account for the additional «stress» induced by the fire. Most studies do not take credit for ex-main control room actions in the affected fire area (due to heat and smoke), or for the repair of fire-damaged equipment.

In ***France***, at the screening analyses, all equipment (including cables) present in the propagation zone are assumed to be lost. (A propagation zone is considered to be a compartment or a set of compartments whose boundaries withstand the spread of fire. By definition, the fire is limited to the extent of the propagation zone.) All HEPs are assigned a value of 1 for the operating team actions. But if the information needed to apply the ultimate operating procedure is available, it is considered that the safety engineer can recover the situation. It is considered that the repair of equipment damaged by the fire is not possible before to reach the safe state. The analysis is performed by modifying the appropriate internal events models (event trees and fault trees for the appropriate initiating events).

During the detailed analysis, human errors in a fire situation have been quantified with the same model that the one used for internal event PSA with some adjustments. Notably, the probability of human errors takes into account unfavorable factors due to the stress induced by fire and, for the field actions, the difficulties to perform them when smoke can reach the zone where these actions have to take place. It is considered that an unfavorable factor has to be taken into account if the action has to be performed before 4 hours from the beginning of the initiating event. If the time is greater than 4 hours, it is considered the fire is extinguished and the stress due to the fire disappeared. In this case, the same value that the one used for internal event PSA is adopted. One of the issues induced by the fire is the inadvertent alarms, the alarms not transmitted to the control room or the first alarm that can lead the operating team towards a wrong operating procedure. In this case, it is considered that the probability to not perform the adapted actions is 1 if these actions are not asked by the procedure applied.

In ***Germany***, human factors are only partly taken into consideration in current fire PSAs, (see /FAK 97/ and /FAK 97a/). A more detailed consideration of human factors is foreseen in the recent research activities on fire PSA and actual PSA studies to be carried out.

In ***Japan*** human reliability for actuation of accident mitigation systems is analyzed in the same manner as for the internal event PSA.

In ***Spain*** a systematic and detailed analysis of human actions, including fire mitigation, associated with external event analysis has been required for the more recent PSAs /YLL 99/.

In the ***United Kingdom,*** human factors have been addressed with the support of task analysis to identify the important influencing factors on the HEPs, such as time pressure, quality of indications and procedures. Assessment methods taking into account these performance shaping factors have been used to quantify human error probabilities. Dependency of human errors is assessed in terms of the failure logic, the need for diagnosis, and the relevance of the operator to the actions.

A number of concerns raised with the analysis of CCDP in many studies are as follows /SIU 97/. First, the risk associated with «control systems interactions» associated with main control room fires is still not well understood /NRC 97/. These interactions (e.g., the loss of control power before the transfer of control from the main control room to the remote shutdown panel) /LAM 89/ are generally not quantitatively addressed in current studies. Second, as shown by a recent IPEEE, there can be fire-specific situations where the equipment unavailability is significantly higher than the generic values typically used in PSAs (because the safe shutdown methodology relies on the use of equipment from a different unit/plant, which may be shutdown). Third, the HEP adjustments to account for fire effects may not adequately address such plant-specific issues as the role of fire brigade members in accident response or the complexity of fire response procedures,[7] nor are they universally agreed upon. Fourth, as is true with PSAs in general, fire PSAs do not address errors of commission very well. In particular, they do not address possible effects of fire (including fire-induced faulty instrumentation readings and spurious equipment actuations) on operator situation assessment and decision making, nor do they address incorrect operator actions stemming from incorrect decisions. Using the terms of /COO 96/, fire PSAs do not address the likelihood of «error forcing conditions» being caused by a fire or the likelihood of «human failure events,» given these error forcing conditions.

2.2.4 Control Room Fires

Main control room (MCR) fires are potentially dominant contributors to risk because they can cause instrumentation and control failures (e.g., loss of signals or spurious signals) for multiple redundant divisions, and because they can force control room abandonment. The analysis of these fires is highly uncertain, due, in part, to the weaknesses in the current state of knowledge regarding: (i) the likelihood of severe fires in MCRs (which are continuously occupied), and (ii) the likelihood of successful operator actions in the event of a severe MCR fire (which will require MCR abandonment and shutdown operations from, depending on the plant design, one or more remote panels with varying safe shutdown related indications and capabilities). This section briefly outlines the analysis requirements and associated issues.

2.2.4.1 MCR Fire Frequency

In general, the analysis of MCR frequency is the same as that for any other plant area (see Section 2.2.1). Historical data are used to estimate the overall area fire frequency, and judgement is used to determine the relative frequencies of specific fire scenarios within the area.

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[7] Work on self-induced station blackout (SISBO) and a number of recent IPEEE studies appear to indicate that complexities in procedures designed to mitigate possible fire-induced hot shorts can be significant contributors to risk.

In the ***U.S.***, a small number of MCR fires are recorded in current fire events databases. Based on five reported fires[8] over the period 1965-1994, /HOU 97/ estimates a mean fire frequency of 2.6 x 10^{-3}/reactor-year. None of these reported fires appears to have been especially severe; it appears that the fires are electrical in origin and typically limited in terms of damage extent. Judgement therefore plays an important role in partitioning the total MCR fire frequency among specific locations (especially panels) and fire severities. It can be noted that, some U.S. studies have partitioned the overall generic MCR fire frequency to other fire areas in the plant, per the guidance in /SAI 95/. This procedure recognizes that a few plants place many of their safety-related control circuitry cabinets in non-MCR rooms (e.g., «relay rooms» or «auxiliary electrical rooms») rather than in the MCR (as is the case in most plants). However, this approach does not address factors that may increase the plant-specific MCR fire frequency over the generic value.

In ***France***, no fire occured in the control room, so the fire frequency is estimated by the χ^2 relation for a 50% confidence level is used. This frequency has been broken down to estimate the fire frequency in each control desk /INA 97/. This breakdown is made on the basis that the fire frequency is proportional:

- to the number of components (controls, relays etc.) and thus is roughly proportional to the area of the panels,
- to the mass of fuel represented by each control desk.

2.2.4.2 Equipment Damage and MCR Abandonment

Most current fire PSAs do not use fire models and component response models to explicitly determine if equipment is damaged in a severe MCR fire. Instead, the direct effects of fire are either addressed through the use of severity factors (with some probability, cabinets within a certain radius of the fire origin are damaged prior to MCR abandonment). The severity factors are typically assessed based on a subjective evaluation of the magnitude of previous MCR fires. Most analyses assume that if the fire is severe enough to force MCR abandonment, as discussed below, all equipment in the MCR will be damaged and will not be recoverable.

According to a number of SNL experiments /CHA 87/, /CHA 88/, in the event of a severe MCR fire, there may only be a few minutes available to operators before they are forced to abandon the MCR. Using the results of these tests as the basis for determining the time available to operators, and using available historical evidence on the time to suppress MCR fires, the likelihood that the fire is not suppressed before abandonment is required can be determined.

/SAI 95/ describes such a procedure; it assumes that: (i) the SNL experiments show that 15 minutes are available before smoke impairs visibility, and (ii) the available data on MCR fire durations[9] supports a lognormal distribution for the suppression time. Using this information, /SAI 95/ derives a best estimate value of 3.4 x 10^{-3} for the probability of MCR abandonment. This is significantly lower than values used (typically on the order of 0.10) in earlier studies (e.g., /BOH 90a/).

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[8] Note that /HOU 97/ builds upon previous U.S. databases and reflects their screening rules. For example, it incorporates data from a proprietary EPRI database, which does not include fires with a duration less than five minutes. Many of the previous databases also rely upon Licensee Event Reports, which do not include many fire events not involving non-safety systems.

[9] According to /SAI 95/, there are five relevant fires. One had a duration of 0.5 minutes, one had a duration of one minute, two had durations of two minutes, and one had a duration of five minutes. /SAI 95/ discounts a small, five-minute kitchen fire, although the kitchen was apparently within the MCR envelope.

There currently is a controversy concerning this procedure, including the interpretation of the time available (/LAM 97/ indicates that only 7 minutes may be available if the MCR cabinets are not supplied with in-cabinet smoke detectors) and the ability of the sparse suppression time data to support the lognormal distribution. We note that a direct severity factor use of the MCR data (0 large fires in N events, where N may be 5 or 12, depending on the data set examined) does not provide strong support for such a small abandonment probability.

2.2.4.3 MCR Fire Mitigation

Given a severe MCR fire which forces control room abandonment and plant shutdown from one or more remote shutdown panels, a detailed analysis must consider a number of issues. These issues, identified in /LAM 89/, include the following:

- electrical independence of the remote shutdown control systems;
- loss of control equipment or power before transfer of control from the MCR to the remote shutdown panel(s); and
- spurious actuation of components (prior to control being taken at the remote shutdown panels) leading to component damage, loss-of-coolant accidents (LOCAs), or interfacing systems LOCAs.

In addressing these issues, the analysis needs to consider the nature and location of the shutdown panel(s), the types of control actions that can be taken, the available procedures for transferring control, and the time and indications available.

In ***U.S.*** fire PSAs, such an analysis is generally performed qualitatively (if at all) due to its complexity. A number of studies employ a nominal failure probability for post MCR-abandonment actions; many others simply do not take credit for these actions. Improved analysis tools (and technical bases for these tools) are needed to support routine PSA evaluations of the likelihood and consequences of severe MCR fires.

In ***France*** /INA 97/, to determine the foreseeable consequences of each fire, have been identified:

- the failures of basic components, directly associated with the thermal effects of the fire or associated with the secondary effects (suppression agents, aggressive combustion products, deposits of particles etc.),
- spurious commands which can give rise to transients not taken into account in control room design or to a configuration of systems making control of the installation more complex,
- loss of information needed to reach the safe shutdown state.

With regard to the first two items, all the controls in the control room, to locate them, then to analyze the consequences of a fire damaging them.
Due to the long duration of the control room unavailability, the risk of core damage during the period when the control room is unavailable following evacuation due to fire has been assessed. This involves identifying initiating events independent of fire which can occur when the unit is maintained in the shutdown state from the emergency shutdown panels, but which cannot be managed from these panels. For instance, such initiating events include:

- primary breaks,
- loss of off-site power,
- loss of the heat sink.

Concerning the duration of the control room unavailability, a study is in progress to define the time to take into account. This study examines the possibility to unload the core, if this is possible in case that the control room is unavailable. If not, it is necessary to estimate the time necessary for repair and re-qualification, even partially, of the control room after a major fire.

Table 1 - A Partial List of Fire PSAs for U.S. Nuclear Plants (Not Including IPEEEs)

Plant	Sponsor	Date	Fire CDF (1/yr)	Total CDF (1/yr)	Important Contributors[(a)]
HTGR (design)	USDOE	1979	1.1E-5[(b)]	4.1E-5[(b)]	CSR (only the CSR was analyzed)
Zion ½	Utility	1981	0	0	Electrical equipment room, CSR
Big Rock Point	Utility	1981	0	0.001	Station power room, cable penetration area
Indian Point 2	Utility	1982	2.0E-4[(c)]	0	Electrical tunnels, switchgear room
Indian Point 3	Utility	1982	6.3E-5[(c)]	0	Switchgear room, electrical tunnel, CSR
Limerick	Utility	1983	0	1.5-5[(d)]	Equip. rooms, switchgear room, access area, MCR, CSR
Millstone 3	Utility	1983	0	0	MCR, instrument rack room, CSR
Seabrook	Utility	1983	0	0	MCR, CSR
Midland	Utility	1984	0	0	Switchgear room
Oconee	Utility	1984	0	0	
TMI-1	Utility	1987	0	0.001	MCC area, switchgear room, cabinet area
Sav. River K Rx	USDOE	1989	1.4E-7[(e)]	3.1E-4[(e)]	MCR, maint. area, cable shaft, DG rooms
S. Texas Project	Utility	1989	< 1.2E-6[(f)]	0	MCR
Diablo Canyon ½	Utility	1990	0	0	CSR, MCR
Peach Bottom 2	USNRC	1990	0	2.8E-5[(g)]	MCR, switchgear rooms, CSR
Surry 1	USNRC	1990	0	7.6E-5[(g)]	Switchgear room, MCR, aux. building, cable vault/tunnel
La Salle 2	USNRC	1993	0	0	MCR, switchgear rooms, equip rooms, turbine building, cable shaft
Grand Gulf 1	USNRC	1994	< 1.0E-8[(h)]	6.7E-5[(g,b)]	No areas found to contribute
Surry 1	USNRC	1994	2.7E-4[(h)]	4.3E-4[(g,b)]	Switchgear room, cable vault/tunnel, containment, MCR

a) Area contribution > 1 % total fire CDF; contributing areas prioritized by contribution (most important first); MCR = main control room, CSR = cable spreading room
b) Frequency of core heat-up
c) Prior to plant modifications identified by risk study
d) Internal events only
e) Frequency of severe core damage
f) Total contribution from external events
g) Seismic contribution calculated using EPRI seismicity curve
h) Mid-loop conditions; instantaneous CDF is presented

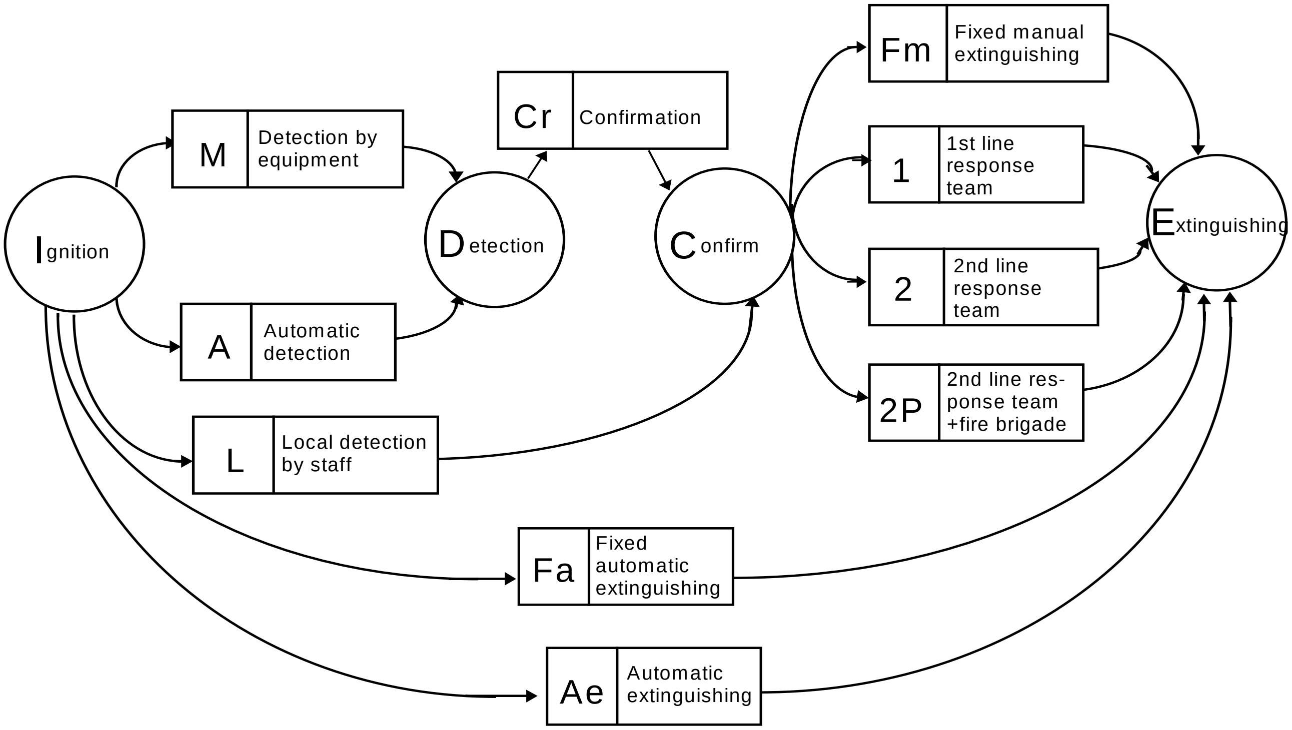

Figure 2.1 - Schematic of Equipment Damage Analysis Contributors

EMBED

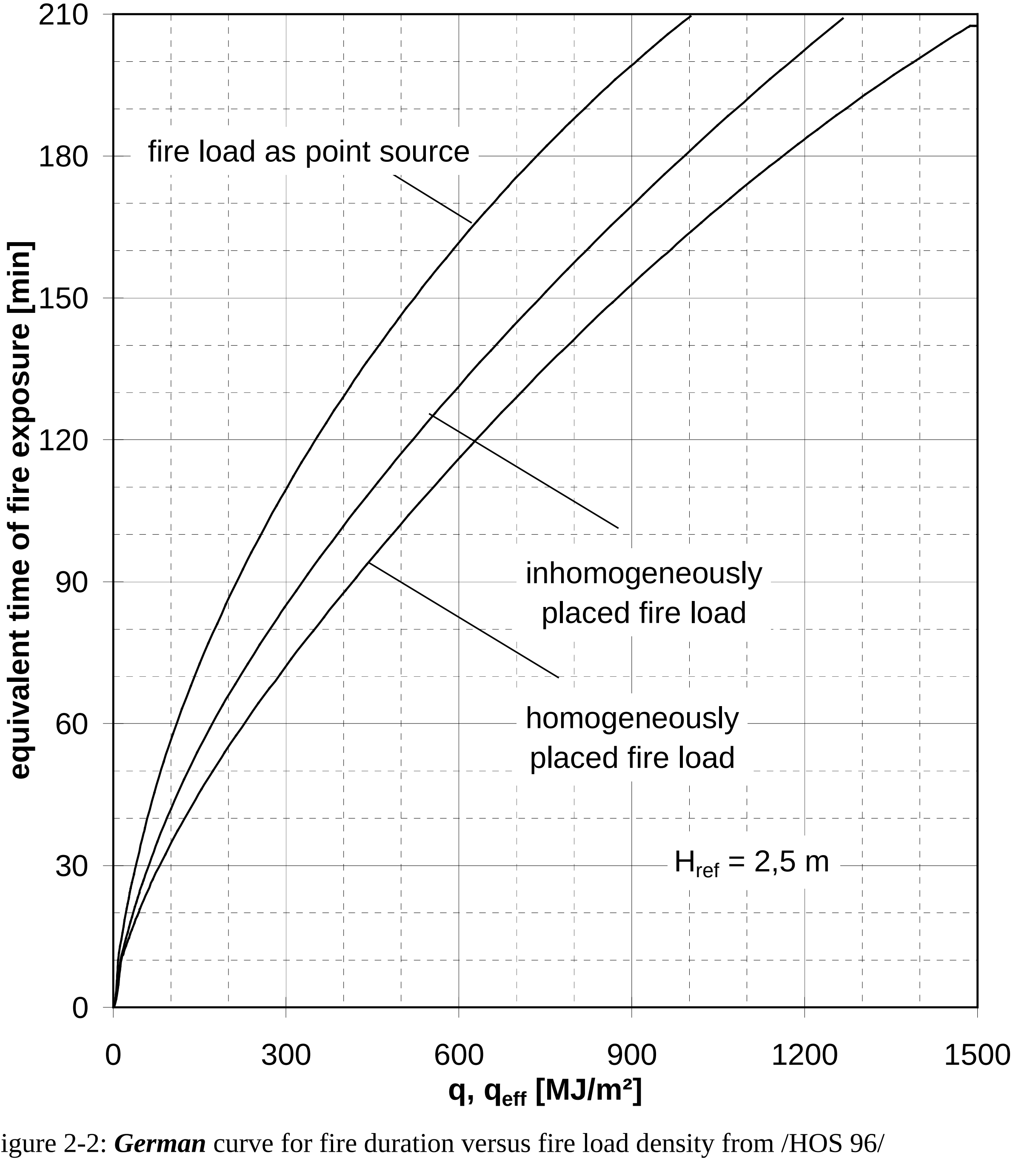

Figure 2-2: ***German*** curve for fire duration versus fire load density from /HOS 96/

3. MODELING OF FIRE, SMOKE AND HEAT SPREADING AND ITS IMPLICATION TO PSA

3.1 Simulation Models and Codes Used for Analyzing Fire Spreading

World-wide, several types of fire simulation models and codes are applied for analyzing the fire development including the fire and heat spreading in the framework of probabilistic safety analysis (PSA) at nuclear power plants (NPPs).

In principle the assessment of fires at NPPs can be performed by physical experiments, physical models or numerical models. Since NPPs are huge buildings consisting of thousands of different complex rooms, real size experiments can be used only in a few specific cases. Physical modeling can be used in certain cases. The numerical modeling of fires is a promising tool to handle fire problems in complex buildings. Writing equations for fire phenomena and solving them numerically allows also the comparison of theoretical predictions with experimental results from small correlation experiments up to full-size experiments.

The numerical fire modeling codes follow several routes of development. Those codes are often divided into three classes:

- zone models
- system models (lumped parameter models)
- CFD-field models (Computational Fluid Dynamics)

In zone models a compartment is divided into two horizontal layers, each of which is at the same temperature throughout. The lower layer is close to ambient temperature and the upper layer contains hot gases from fire.

In system models the building is divided into nodes which are connected to other nodes with branches building a network. This type of modeling is suitable for complicated buildings consisting of small compartments connected with each other by corridors, doors, and other type of ducts.

Field models calculate multidimensional fields of temperature, flow velocity, gas concentrations, pressure etc. by solving numerically the conservation of equations for several variables under given boundary conditions.

The main features of the models and the particularities of the different codes are principally outlined in the references for each model/code given in the text.

Germany

The following fire simulation models/codes were used in Germany in the framework of fire hazard and fire risk analyses:

- the zone model COMPBRN /SIU 83/ has been used to calculate fire source term for fully developed (post-flashover) fires together with the lumped parameter model CRDLOC /JAH 86, /JAH 88/, /JAH 88a/ (PWR, DRS-B /GRS 90/) for simulating the fire effects and consequences,
- the 3-dimensional lumped parameter code CRDLOC /JAH 86/, /JAH 88/, /JAH 88a/ developed by GRS, mainly used in the German Boiling Water Reactor Risk Analysis (BWR risk study) and further GRS studies,
- multi-zone models, such as CFAST and HAZARD /POR 92/, /PEA 93/, for more recent GRS risk studies,
- the multi-compartment, multi-zone code FIGARO (see /KAR 93/) for a PWR study including risk analysis, developed by iBMB of TU Braunschweig.

The main features of these codes can be found in /KAR 93/, /KFK 91/, and /KFK 89/.
Some examples of those scenarios applied to the different codes in Germany are listed in the following:

- oil fire (multi-compartment, large/smaller amount),
- cables fire,
- combined oil and cables fire,
- main coolant pump (MCP) lubrication oil fire,
- MCP lubrication oil fire combined with cable fire,
- turbine oil fire,
- cable fire in a cable spreading room,
- fire in the switchgear area.

Several fire simulation models/codes (analytical models after fire hazard analysis (FHA)) are also able to be applied to modeling those fire scenarios resulting from the failure of active fire protection measures (including fire detection, suppression and extinguishing systems and manual means) covering:

- fire development and effects without active fire protection measures,
- reliability/availability/failure rates of active fire protection measures,
- analysis of the influence (efficiency as well as effectiveness) of fire protection measures on fire impact on safety systems.

Furthermore, these analytical tools are able to model fault tree diagrams resulting in CDF.

France

In France, the objective of fire simulation codes is to predict more accurately by using a numerical fire calculation how long it will take to damage the equipment subjected to fire effects in the critical zones.

A two tear approach is applied by IPSN for the development of computer codes in the domain of fire studies. On the one hand, a zone model called FLAMME-S /CAS 96/ is developed for the present safety assessment and allows to perform engineering calculations, with a low CPU time. On the other hand, a 3D code, called ISIS /AUD 99/, is under development, in order to provide a research tool able to overcome the limitations of the simple tool and to extend the configurations accessible to the simulation.

The FLAMME-S fire computer code developed by IPSN is used in the frame of safety assessment and in the frame of fire PSA. The code calculates the effects and thermodynamic consequences of a fire in a compartment and/or in several compartments (fire extension). FLAMME-S can be used to analyze the following phenomena:

- temperatures of the gases in the compartment (cold gas layer, hot gas layer, plume), of the walls and of any equipment (e.g. electrical cabinets, cables, solid structures), inside the compartment
- heat flux emitted by the fire source and received by the equipment,
- time to malfunction of safety related equipment,
- pressure inside the compartment,
- inlet and outlet gas flow rates,
- oxygen concentrations and combustion products in the two zones.

The main input parameters of the code are:

- for the compartments: dimensions, thermal and mechanical characteristics,
- for gas dynamics: convection heat exchange coefficients between gases and walls, heat exchange coefficient between fire plume and ceiling, energy loss coefficients for mechanical ventilation, ventilation rates,
- for the combustibles: surface, position (center, against a wall, in a corner), orientation (horizontal or vertical for solid combustible), mass loss rate, combustion efficiency,
- for the equipment: position and dysfunction criteria (critical temperature and/or critical heat flux).

Some of the particularities of FLAMME-S make it different from existing zone codes:

- the integration of a back flow being done in the upper part towards the lower part, a phenomenon which was experimentally observed,
- the possibility of performing a three dimensional calculation for the walls, notably for the ceiling,
- a good level of qualification, by comparing the calculated results and the experimental ones from roughly twenty tests and this for a complete set of variables.

A digital code data base is created, including characteristic data of common combustibles used in nuclear installations.

For the time being, the code FLAMME-S is qualified for studying the fire spread inside a room where the fire can be considered as confined (that means a room where a hot gas layer is created by the fire). One example of a fire growth simulated by FLAMME-S is given in paragraph 4.3.2.2.

A model for fire spreading from the affected room to adjacent rooms has been recently introduced in FLAMME-S code. The qualification of this model is in progress.

The computer code FLAMME-S is equipped with specific models simulating the fire barriers (walls with their thermal inertia, dampers, etc.).

The intrinsic limitations of the zone models lead IPSN to take an interest in an more detailed approach of the fire simulation which is based on the Navier-Stokes applied to turbulent flows with buoyancy effect at which it is added balance equations for chemical species and energy of the gaseous mixture. The 3D, field modeling, ISIS code is based on the Computational Fluid Dynamics (CFD) theory. This type of model solves the mass, momentum and energy balance equations. In order to determine the solution of these equations, the compartment is divided into a three-dimensional numerical grid of typically several ten of thousand of elementary control volumes filling the domain of interest.

The two codes described above complete each other with regard to the advantage and disadvantages of their use: global (FLAMME-S) and local (ISIS-3D) approaches, simple (FLAMME-S) and complex (ISIS-3D) geometry, and CPU times very different.

FLAMME-S code allow a lot of calculation for a simple scenario with some parametric studies. ISIS code will treat a complex scenario taking into account local phenomena. Furthermore, ISIS code could propose and validate correlations for FLAMME-S code.

USA

In the U.S. nuclear power plant fire PSAs, a variety of fire modeling tools have been used to address the potential effects within the framework of a PSA. In the recent Individual Plant Examinations of External Events (IPEEEs), the most commonly used tools are those provided by the FIVE methodology /PLC 92/, COMPBRN IIIe /HOV 90/, and the methods described in the EPRI Fire PRA Implementation Guide /PAR 95/. The scenarios addressed include cable fires, switchgear fires, oil pool fires, and transient fueled fires.

The FIVE fire models are designed to be used in a vulnerability analysis, and are intended to be conservative. They are generally used to determine if, given a specified fire and targets, fire damage is possible. The models consider three key regions within the room: the plume, the ceiling jet, and the hot gas layer. Radiant transfer to targets outside of these regions is also considered. Fire growth is not modeled explicitly; the user is required to specify the physical characteristics of the fire.

The COMPBRN IIIe zone modeling code, similar to its predecessors (see /SIU 83/), is designed to be used as an integrated part of a fire PSA. Thus, its output (the predicted time to component damage) is compared with the suppression time, as shown in Eq. (2) of Chapter 2. Moreover, recognizing that there are significant uncertainties in the model parameters (e.g., see /BRA 89/), the code explicitly propagates these uncertainties through the model to develop a distribution for the time to damage. (Uncertainties in the model structure are treated separately, as discussed in /SIU 83/, /SIU 85b/, and /SIU 92/.) An applications-oriented description of the process for integrating code results into a network-based model for fire scenarios (including detection and suppression) is provided in /SIU 85a/.

COMPBRN IIIe explicitly addresses fire growth over fuel arrays (including lateral spread over cable trays), and allows for the possibility of growth to non-contiguous fuel cells (which will lead to multiple, interacting flames). It models radiative and convective transfer both inside and outside of the fire plume(s) and hot gas layer. Target heat-up is addressed using a 1-D transient heat conduction model. The hot gas layer is treated quasi-statically (note that it does change as the fire changes). Inter-compartment fire spread is not treated. The COMPBRN codes have undergone a limited amount of validation (e.g., see /SIU 81/, /HOV 88/).

The fire models recommended in /PAR 95/ are either based on FIVE (e.g., for the prediction of hot gas layer temperatures) or upon a re-interpretation of existing experimental data (e.g., for the prediction of fire growth through a stack of cable trays). A review of /PAR 95/, including a discussion of the recommended models, is provided in /LAM 97/.

Finland

In Finland, fire simulation codes have been used both, to create relevant room-specific scenarios and to assess the time-dependent course of fire as well as to give insights on the fire development and effects on a more general level. Thus, using simulation, the dispersion in results obtained purely by expert judgement have been reduced significantly. The following models and codes were applied:

- For power companies' fire risk analyses:
  - zone models as COMPBRN IIIe /HOV 91/ and BRI2 /TAN 89/, time-dependent temperature rise in fire compartments
- In the frame of analyses for independent review purposes (by authority, research institute):
  - field models (CFD): PHOENICS /CHM 91, SPA 81/;
  - zone models: BRI2 /TAN 89/, COMPBRN /SIU 83/, /HOV 91/, CFAST /POR 92/, /PEA 93/;
  - lumped parameter (network) models: FIRAC /NIC 86/.
- State of the art of CFD modeling in Finland:
  - Fire modeling based on computational fluid dynamics (CFD) has been used in Finland since 1986 for analyzing fire risks on Finnish nuclear power plants. Commercial general purpose codes – in the early simulations PHOENICS and in recent simulations FLUENT – have been used. In both codes it is essential, that the user is able to add his own coding to the simulation.
  - Generally simulation predicts the time dependent flow and temperature field induced by fire when the fire source has been predefined. The fire source can be given as a mass and heat source but usually only the fuel source is defined and combustion is calculated using the local conditions for fuel vapor, oxygen, temperature and turbulence. In some cases also heat conduction inside structures has been calculated. Radiate heat fluxes on structures are also calculated. The temperature field and induced heat fluxes can be used in estimating the potential damage area due to the fire at a given time step.
  - CFD-based simulation is as its best in cases where the detailed flow field has an essential influence in the phenomena (smoke and heat spread, stratification) or where the area of interest has a complex geometry. Special questions considered include stratification of flow due to density, air condition, and heat exchangers as part of the process.
  - Simple fire spread models have been developed. In these the aim is to calculate fire spread starting from a small initial fire. However, the complete feedback between fire spread and simulation requires rather accurate calculation of pyrolysis, heat transfer and combustion and is still under development. Educated estimate of fire source is used at the moment in most cases.

The Finnish fire simulation by CFD codes at VTT Energy (nuclear technology) is outlined in several reports, most of these written in Finnish. All simulations are based on computational fluid dynamics. Codes used are PHOENICS /CHM 91/ (older simulations) and FLUENT /FLU 97/. The CFD codes were widely applied to the analysis of fire spreading, e. g.:

- Simulation of an oil pool fire on a floor of turbine hall: Early simulation with about 10.000 computational cells /HUH 88/, /HUH 89/.
- Cable fire simulation in the stem generator room of the Loviisa reactor building: The simulation model includes effects of ventilation and air cooling and pressure relief to the other parts of the reactor building. It seems that the ventilation and air cooling has an essential role in restricting the temperature in the case of a fire. Due to the air cooling it might be difficult to identify the fire on the basis of the temperature rise.
- Simulation of a cabinet fire: The simulation (model included ventilation air cooling units in the room) provided estimates the general thermal conditions in the room and the local thermal conditions in the adjacent cabinets (adjacent cabinets side to side and opposite) in case of a cabinet fire /KES 95/.
- CFD simulation of the German HDR-fire experiments (oil pool fire) and comparison with the experimental values: The main flow field was predicted properly, but the simulation suffered from

discrepancies in modeling of the geometry (11.000 m3 complex building, some obstacles were too restrictive) and the lack of computational cells (3000 cells) /HUH 90/, /HUH 93/.

Hungary

In Hungary, ETV-ERÕTERV Co. uses the U.S. fire simulation zone model FIRST /MIT 87/. The goals of the model are to determine whether an object starts to ignite due to a defined fire inside the fire compartment and to determine the time period between pilot fire ignition and detector response and object ignition.

This code is mainly used for the locations primary loop compartments and cable rooms.

Japan

In Japan, the zone model COMPBRN-IIIe /HOV 91/ is applied to get critical radius between transient fuel and target cable tray and time margin to damage, which are used to estimate geometry factor and non-suppression factors.

NUPEC has introduced one of US IPEEE fire PSA methodologies /PLG 89/ and has made its trial application to a Japanese PWR /UCH 96/, /FUK 97/, where failure probability of adjacent equipment due to fire (called »severity factor») is estimated based on US fire experiences /DOC 92/, /MUS 94/. The trial application shows that the severity factors are too conservative for Japanese plants which are designed under Japanese fire protection codes /JEA 86/. On the other hand, there are very few fire events in Japan. Therefore it is quite difficult to make Japanese specific severity factors only based on Japanese fire experiences. At the time being, in NUPEC a project to obtain Japanese specific severity factors using three dimensional fluid dynamic code alpha-FLOW (CFD: computational fluid dynamic code) /TAK 92/ and the zone model code COMPBRN-IIIe /HOV 91/ is ongoing. The alpha-FLOW code will be validated through detailed fire experimental analyses for fire experiments conducted by Japanese utilities /TAN 85/, /FUJ 85/. The alpha-FLOW code could be helpful in making COMPBRN-IIIe input data. Uncertainty analysis of COMPBRN-IIIe could evaluate failure probability of adjacent equipment due to the fire (so-called severity factor). In this project lubricant oil, cable and electric board are coped with as fire source, and cable and electric boards as target components, respectively.

United Kingdom

In the United Kingdom, no fire simulation codes are currently used in the reactor safety cases. However, one of the research projects currently being undertaken is to review the software packages which are available to identify those which are applicable to the potential fire scenarios found on nuclear power plants in the United Kingdom and to identify the extent of their validation and the limitations to their use. The first phase of the program is to identify generally available field and zone models and assess their capabilities, limitations and flexibility for use on nuclear power plants.

In addition, within the HSE mainstream research program on major hazards and risk assessment, work has been undertaken on upward flame spread on inclined surfaces, jet-fire interactions with pressure vessels and simulation of fires in enclosures.

For the Sizewell B safety case, work was carried out to calculate the duration of fires and the temperatures to which barriers were exposed within all fire zones, so as to demonstrate the adequacy of structures and fire barriers provided. These calculations were based on calculations used within the HARVARD V zone model /MIT 81/.

Switzerland

In Switzerland, the computer code COMPBRN III/MC was used to analyze all scenarios requiring physical models for the behavior of fires in rooms.

HAZARD I (CFAST) /POR 92/, /PEA 93/ was used in deterministic analyses to simulate several scenarios in all Swiss NPPs.

Spain

In Spain, PSAs have been developed using different versions of COMPBRN. The more recent PSAs have used COMPBRN III /COMPBRN III/, introducing corrections to avoid some simulation deficiencies, e.g. at the calculation of radiant heat transfer.

A limited number of fire scenarios accounting for typical cable tray and room geometry cases are studied. Fire scenarios are analyzed using such previously studied cases changing specific parameters, such as distance, fire loads, etc. if necessary.

3.1.1 Simulation Models and Codes Used for Analyses of Fire Spreading on Cables and Other Equipment

One particular Issue of the fire modeling in the frame of fire PSA is the fire spreading on cables and other equipment.

In ***Germany***, the most recent codes are able to consider fire spreading on cables and other equipment. Several results of scientific studies accompanied and verified by experiments on NPP specific cable fires carried out at iBMB of TU Braunschweig are available. /WIL 94/, /WIL 95/, /WIL 96/, /HOS 97/, /HOS 98a/.

The ***French*** PEPSI fire tests carried out by IPSN showed that a fire does not propagate on cables installed in French NPP of 900 MW_e. Furthermore, these tests indicated a cable damage temperature of approx. 220 ^{o}C. This assumption has been verified, for control cables (DC 48 V) and for power cables (AC 380 V) by analytical fire test (see chapter 3.3.1). It is foreseen to perform EPSILON tests (see paragraph 3.3.1) to confirm the non propagation of fire on electrical cable.

For fire propagation on other equipment, the most sensitive material (lowest ignition temperature) is taken into account.

In the ***USA***, information on fire-related cable properties (e.g., ignition and damage thresholds, mass burning rates, heat release rates) contained in several reports, such as /TEW 79/, /LEE 81/, LUK 82/, /WAN 85/, /JAC 86/, /WHE 86/, /NOW 91/, /VIG 95/, and /TAN 96/, is used for cable fire modeling. Other required information, e.g., thermal conductivity, specific heat, density, are estimated using either data for specific cables when available, or, more often, data for generic materials. All of this information is used in COMPBRN analyses to model fire spread (in a discrete, cell-to-cell manner) along and among cable trays. Fire spread from other equipment (e.g., major pumps, switchgear) is generally addressed using pool fire models. In some cases (e.g., for pump fires), the pools are taken to represent spilled lubricants; the properties of the fire are then dictated by the relevant properties of the lubricants. In other cases, the pool is used as a simple representation of the actual fuel bed; the properties of the fire are determined by the assumed flammability properties of the component. Discussions on appropriate heat release rates for electrical cabinet fires, based on experimental data provided in /CHA 87/ and /CHA 88/, are provided in /PAR 95/ and /LAM 97/.

In ***Finland***, fire experiments have been carried out for solid materials, e.g. cable coatings, electrical boards, to define input parameters for computational fire models. The phenomena to be modeled, for example, in a cable fire simulation include ignition thresholds of target material, velocity of flame front and rate of the heat energy. On the basis of full scale fire experiments for cables and connected blind fire simulations by the Fluent code /FLU 97/ the validation and development of the existing cable fire model is ongoing /KES 97/, /MAN 97a/. Examples are:

- The fire spreading on cables, cable trains, cable tunnels, cable spreading rooms /HUH 98/ as well as on significant electrical equipment and other equipment;
- Separate studies on near field effects using engineering formulae to evaluate spatial separation principles between redundant cable trays in sprinkler-protected cable tunnels and compartments.

The ***Hungarian*** simulations take into account that cable loose their function at approximately. 80 °C - 100 °C and that a cable ignition occurs at approx. 340 °C - 370 °C. Velocity of flame front and rate of energy released have not been calculated.

In ***Japan***, simulation codes used by NUPEC for analyzing fire spreading on cables are also alpha-FLOW code and COMPBRN-IIIe /HOV 91/ as well as for oil fires. Analytical models for fire spreading process with melting, pyrolysis and gasification of cable will be introduced into alpha-FLOW and the models will be validated by some fire experiments such as IEEE-383 and -384 standard cable fire experiments. Failure probabilities of adjacent cables due to a cable fire will be estimated by uncertainly calculation of COMPBRN-IIIe. The approach for analyzing fire spreading on electric board is under investigation, referring to domestic board fire (relay and switch fire) experiments.

In the ***United Kingdom***, fire spread analysis has not been carried out and has not been considered necessary. This is because the safety case approach has been to provide adequate segregation or separation of essential plant systems into fire zones and sufficient redundancy and diversity of plant such that, even allowing for complete burn out of all cables and other equipment within a fire zone, risk targets are met.

In ***Spain***, a comparative analysis has been made of parameters given or used in several sources, such as /BOH 90/, /LAM 89/, /SIU 81/, /MCC 85/, /AZA 85/, /HOV 86/.

Values from /BOH 90/ and /LAM 89/ are mostly used in Spanish PSAs. However, some parameters may be slightly different from one PSA to another, depending e. g. on the fire source considered (solvent, oil, etc.) and the target material (cable type). For the parameters provided by Japan in the report using also COMPBRN IIIe, the Spanish values are:

Cable ignition threshold:	500 °C (/BOH 90/), (equivalent to Japan),
Cable damage temperature:	350 °C (/BOH 90/), (equivalent to Japan),
Combustion heat of cables:	2,67 · 10^7 J/kg (/LAM 89/).

3.2 Simulation Models and Codes Used for Analyzing the Production and Spreading of Smoke and Heat

Up to the time being, only in some countries the production and spreading of smoke is simulated. Most of the fire PSA studies do not include modeling of smoke.

In ***Germany***, smoke generation is included in analytical fire simulation modeling but was not yet considered in the fire PSAs carried out.

Smoke production was experimentally analyzed in all HDR fire experiments as well as in actual cable fire experiments by iBMB of TU Braunschweig, the results were implemented in codes participating in the HDR studies and in codes used by iBMB of TU Braunschweig. At the time being, the models used are still under development.

For the time being, the ***French*** FLAMME-S code /CAS 96/ models the spreading of smoke in the following way:

- for each fire, a quantity of soot, depending of the burnt material, is produced in a room. This quantity of soot is used to estimate the smoke concentration in the hot zone which is considered to be homogeneous,
- due to air exchange between hot and cold zones, the smoke concentration in the cold zone, considered homogeneous, is evaluated,
- in the adjacent rooms the smoke concentration is also calculated taking into account the flow rate exchange between the different rooms by the openings.

The smoke impact is taken into account for its impact on the radiation heat exchange.

To date, no ***U.S.*** nuclear power plant fire PSAs have explicitly modeled the production, transport, and deposition of smoke, and resulting equipment damage from this process. Experiments on some of the basic physical processes have been (e.g., see /JAC 86/) or are being performed (e.g., see /TAN 96/), and simple transport codes (e.g. CFAST) are available, so a credible analysis may be possible in the near future. At present, analyzes use experimental information (e.g., from /CHA 88/) directly in simplistic models.

In ***Finland***, experimental case studies and related simulation codes are used for analyzing the production and spreading of smoke:

- PHOENICS code /CHM 91/ (numerical field code) and developed heat transfer and fire and smoke product models (CO2, H2O, N2, HCl),
- Smoke spreading and content of smoke (fire gas) product components can be calculated as a part of the fire simulation /HST 98/.

Some cases are simulated at NPPs, e.g., a main control room, an electrical room, two different cable spreading rooms. The results of the simulations can be used for evaluating the following issues:

- habitability of a main control room,
- toxic products,
- fire fighting environment in electrical and cable rooms,
- visibility.

Examples of the application of recent CFD codes are:

- Simulation of a cabinet fire in a control room of a nuclear power plant (4 cases): The simulation provided estimates for the smoke and hydrochloride concentrations in the control room and the impact of ventilation and flow obstacles to the local conditions near the control desk.
- Simulation of smoke movement in a room with no ventilation system: The initial temperature stratification (which is enhanced due to structural objects) may restrict smoke movement so that smoke does not rise to the detectors at the ceiling if the fire source is weak. It may be beneficial to move the detectors to a lower position (depends on the obstacles).

For the time being, in ***Japan*** the effects of smoke production and spreading have not been taken into account implicitly in the level 1 fire risk analysis by NUPEC. However, a detailed sub-scenario analysis for the main control room fire will be carried out in the near future. The respective code (/TAK 92/), an advanced fluid-dynamic analysis code, the alpha-FLOW code, has the capability of analyzing the production and spreading of smoke. Namely, the time dependent flow and temperature fields induced by fire can be simulated to solve mass conservation equations, mass conservation equations for chemical species, momentum conservation equations, energy conservation equations and equations of states for compressive fluid. The mass conservation equations for chemical species consist of transport equations, which dominate production and consumption, diffusion and convection of chemical species. The alpha-FLOW code has no generation models of smoke but if generation rates are given, it can analyze smoke spreading using the above transport equations. This code will be used on occasional demands.

In the ***United Kingdom***, no modeling of smoke production and spread has been carried out in the PSA. In the reactor safety cases, the spread of smoke has been considered deterministically as a hazard. Barriers and the shutdown of ventilation systems are provided where appropriate to minimize the potential for damage.

In addition, within the HSE mainstream research program on major hazards and risk assessment, work has been undertaken on fire and smoke spread modeling originally to explain the rapid fire spread in the London King’s Cross Underground Station fire. This work used a Computational Fluid Dynamics (CFD) software code called CFX /HAR 96/ developed by AEA Technology. The CFX code has now been widely used by AEA Technology and its clients and is considered effective for a range of applications including

- low-momentum compartment fires,
- high momentum compartment fires,
- fire and smoke movements in tunnels,
- interactions of fire and water spray,
- gas dispersion at nuclear plants,
- deflagrations.

Other general purpose CFD codes available in the UK have been used for fire modeling, including FIREDASS /GRA 98/, FLUENT /AND 88/, and PHOENICS /SPA 87/, /CHM 91/, /GRE 96/. JASMINE /KUM 83/, /KUM 95/ is a CFD code specifically developed in the UK at the UK Fire Research Station for fire modeling. JASMINE has a wide choice of fire source details, including corrections to the fire source for radiative heat loss and in built abilities to model fire spread, flash-over and the effects of sprinkler systems. Future code developments include implementation of the more advanced DTM radiation model (discrete transfer model) and a two-step combustion model. A limitation of the code is that it is currently restricted to rectangular shaped rooms.

There are no experiments or models being developed in ***Spain*** to consider the effects of smoke generation on electric/electronic components or humans. In the Spanish PSAs it is assumed that in case of fire burning in the control room, smoke will fill the room after 8 to 15 minutes. If this situation is reached, the plant should be shutdown from the remote shutdown panel. Some time before, however, self breathing equipment (breathing apparatus) would be necessary to stay in the control room.

This time period has been obtained from /NOW 88/. It is dependent of several factors, such as room size, ventilation rate, etc.

3.3 Code Development

Code development efforts have been undertaken all over the world in the past, and these activities are still ongoing. Nevertheless, there are strong differences between the different countries.

At the time being several fire simulation codes are further developed by ***German*** institutions. Namely these codes are:

- FIGARO (by iBMB of TU Braunschweig, see /KAR 93/ and /KFK 91/),
- CRDLOC (by GRS) /JAH 86, /JAH 88/, /JAH 88a/, /KFK 89/, /KAR 93/,
- MRFC (by AGB, see /KAR 93/), /KFK 89/, /KAR 93/.

Main objective of the recent development is the capability of the codes to simulate fire and smoke phenomena in a more realistic manner. Another goal of the developments is a better characteristics of the plume. Due to this, different plume models, in particular for interferences of walls, ceilings and the plume, were tested and implemented in the codes. Further developments aim on the easier use of input data (user-friendly codes).

In the frame of the development work in ***France*** a numerical method has been adapted in order to be able to simulate the fire scenario in which several rooms communicate with each other either through openings allowing a natural regime ventilation (e.g. doors), or by ventilation ducts in forced regime, Fig. 3.3.1. The developed model has been qualified with COOPER fire tests. The main objective of the ongoing works is to qualify this model with PEACOK fire test and with DIVA tests (IPSN tests to be performed - see chapter 3.3-1).

Moreover, a model /TOU 98/ permitting to estimate the damage time of an electrical cable taking into account its thermal inertia has been developed and qualified with analytical fire test of electrical cables performed by IPSN.

For the plume, other physical models for the calculation of temperatures and of entrained air flow, which are experimental correlations of the same type, have been studied and one of them, HESKESTAD has been integrated in the version being developed. The vertical wall-plume intersection for the thermal transfers has also been taken into account. Moreover, IPSN performed FLIP (fire in interaction with a wall) fire tests /AUD 97/. The results of these tests will be used to develop and qualify a plume model corresponding to a fire near a wall or a corner.

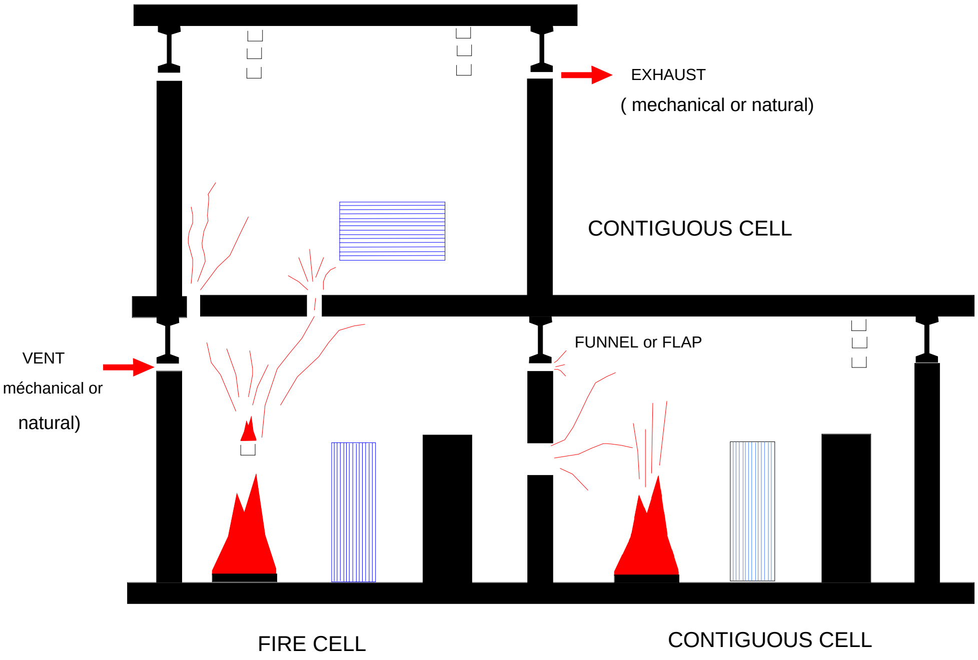

Figure 3.3-1: Example of Multi-room Configuration

A large number of zone model codes have been developed in the ***USA*** for a variety of fire protection applications. For example, the CFAST code /POR 92/, /PEA 93/, which treats multi-compartment fires, has been the subject of development by the U.S. National Institute of Standards and Technology (NIST). Computational fluid dynamics (CFD) codes are being developed at NIST and Sandia National Laboratories to provide more detailed representations of fires (e.g., to treat fire propagation over complex fuel arrays, to address very large scale fires, and to treat detailed heat transfer to targets within a flame). None of the improvements are, to date, explicitly targeted at nuclear power plant fire PSA applications.

Extensive efforts have been allocated in ***Finland*** by the Technical Research Centre of ***Finland*** (VTT) to develop the general-use field model codes to be better applicable to fire simulation purposes (PHOENICS /CHM 91/, FLUENT /FLU 97/). Especially the radiant (discrete-transfer) and conductive heat transfer models have been developed and refined. To better model the combustion process, the two-phase turbulence model has been implemented. Modeling the ignition, fire spreading and heat release rate of solid matter (cables etc.) as a function of physical conditions (ignition temperature, incident heat flux etc.) is under development, too. Usually, the time-dependent heat release rate has been pre-determined.

The Finnish applications of recent developments on CFD codes are listed in the following:

- Model developments: buoyancy effects for turbulence, free boundary conditions, buoyancy and pressure. Comparison with experimental results (experiment series by Steckler & al. /STE 82/, see also MPEG-video at http://www.csc.fi/visualization/graphics_group.html).
- Model development: Two phase reaction model for burning, reaction kinetics, discrete transfer model for heat radiation and soot formation model.

- Simulation of a horizontal cable tray fire in a room containing several cable trays: First simple fire propagation model applied. Model includes feedback from environment to the burning object. Essential results: time frames and mechanisms for cable fire spread, effect of structural objects to smoke and heat transfer.
- Model development: Modification of the discrete transfer method (variable wall surface temperature), documentation of the first simple cable fire propagation model. The above mentioned MPEG-video visualizes the results.
- Blind simulation of four smoke detector tests performed at VTT Fire technology: Comparison with experiments to be added /HUH 98/.
- Simulation of cable tray fire experiment by using a draft version of the flame propagation model. The experiment was performed at VTT Fire technology /HUH 98/.

Concerning the zone models, some limited development has been made, mainly to improve the usability of the codes for engineering applications by implementing a modern user interface and a connection to input and output data bases.

In ***Japan***, the zone model COMPBRN-IIIe /HOV 91/ is used by NUPEC.

The alpha-FLOW code of NUPEC /TAK 92/ is a three-dimensional fluid dynamic calculation code, which consists of mass conservation equations, mass conservation equations of chemical species, momentum equations, energy equations and equations of states for compressive fluid to simulate the time dependent flow and temperature fields induced by fire. The alpha-FLOW code has radiation heat transfer models considering gas absorption, heat conduction models in solid and models for the combustion process of gasified fuel but it has no models for analyzing the process of melting, pyrolysis and gasification of solid and liquid fuel. NUPEC is now developing these models in the alpha-FLOW code.

The models for electric board fires are under investigation. The integrated system for calculating failure probabilities of target components (so-called severity factor) by COMPBRN-IIIe is also under investigation.

In the ***United Kingdom***, two codes have been identified as under development, but not specifically for nuclear industry use, including /TAY 98/, /EWE 98/ with an expert system front end, and SOFIE /SOF 94/. Both these codes are fire specific CFD codes.

SMARTFIRE is funded predominately by the UK Civil Aviation Authority with application aimed at aircraft fires. Currently, the code does not include sub-models for combustion, radiation or soot generation; the fire is modeled simply as a heat and mass source, with no smoke generation. Mechanical ventilation of the room cannot be modeled, and the locations of the openings are restricted to walls only. The major advantage of the code is that it contains a complex artificial intelligence user interface, which is aimed at simplifying and speeding up the specification of the fire details and room geometry.

SOFIE (Simulation of Fires in Enclosures /SOF 94/) is being developed at Cranfield University with the financial and scientific collaboration of a consortium comprising the UK Fire Research Station, Statens Provningsanstalt (Sweden), the University of Lund (Sweden) and VTT (Finland). Additions to the code are being made to enable prediction of complex fire phenomena such as fire spread, toxic emissions, and water-spray injection.»

3.3.1 Experimental Validation

Several of the fire simulation models/codes mentioned before have been verified and/or validated by realistic NPP specific experiments, such as the HDR experimental series, or small scale tests. The experiments have shown the potential application of the codes as well as the problems arising for simulating the various fire phenomena. Furthermore they have shown the significance of the expert knowledge with regard to the scenario boundary conditions and the model limitations.

In ***Germany***, the following experimental series were carried out and additionally used for validation of fire simulation codes:

- HDR experiments (oil, cables etc.) for all types of codes at the Nuclear Research Center of Karlsruhe (KfK),
- cable fire experiments at iBMB of TU Braunschweig.

HDR Experimental Series E42.1 + 2:

It has been the objective of a series of large scale experiments performed within the German Heissdampfreaktor Test Facility (HDR Test Facility) sponsored by the German Ministry for Research and Technology (BMBF) to investigate into the physical processes causing and limiting the extent of a fire should it occur within the Containment of a nuclear power plant. The most recent experiments (E41/42-series) have been performed as the terminating series of experiments researching into the consequences of oil and cable fires. The main aim of these experiments were to study

- the development of a fire and its consequences to adjacent Containment compartments,
- the dynamics of a local cable fire and its impact on adjacent cable tracks,
- the behavior of aerosols released by the fire and transferred into adjacent compartments,
- the efficiency of filters and fire extinguishing equipment, and
- the efficiency of cable isolations,

With the agreement of the German BMBF (former BMfT), the HDR-Project offered the cable fire experiment E42.2 as a basis for an International Standard Problem to be performed under the sponsorship of the Commission of the European Communities (CEC). A variety of differently structured codes was involved in this activity.

The experiment was carried out in January 1992 The following technical specification explains the items of the test facility as far as important for the application of relevant codes.

The calculability of a fire inside a chain of rooms under realistic boundary conditions with codes used for conventional fire scenarios could be tested, too.

The HDR experimental series starting with gas and wood crib fires ended in large scale hydrocarbon and cable fires within the plant. Figure 3.3-2 gives insights on the experimental facility and figure 3.3-3 shows the complete experimental program with the participating codes.

Goals of this fire program were to get an increasing insight in the behavior of a complex closed system during fire; the reaction of sensitive components to smoke and aerosol loading; the temperature histories throughout the plant. Code assessment was performed by comparison of different experimental results and comparison of calculations with different code types concerning one experiment.

The HDR experiments gave for the first time the possibility to compare different code approaches to one experimental set-up. This philosophy was very successful, as different types of codes had to calculate the same problem and to discuss their results. Furthermore fluid-dynamic flow models were taken into this code exercise coming from nuclear safety research, as well as field models.

Thus, a broad platform for discussion was opened, to recheck the importance of fire phenomena taken into account so far. Nearly all HDR-experiments were accompanied by pre-and post calculations by different code types as zone model, lumped parameter codes and field models as to be seen in Fig. 3.3-3.

The results were positive. For the first time, an intensive discussion took place to encircle important phenomena and define weak points of the used codes.

Zone models were enhanced to multi-room calculations and mixing effects were taken into account. The calculation of formation and transportation of gaseous products and soot by fire through the plant was improved as well as the simulation of heat transfer to structures. Lumped parameter codes got 3D-approaches in important parts of the plant. The coupling of source terms or the calculation of heat release rate was included in the models to some extend. Field models were forced to calculate very complex geometric areas instead of the former bride type malls. The handling of nearly all calculations was increased.

Some special effects are still not well understood in detail and have to be included in the codes. One of the most important tasks is to develop models for the calculation of the mass loss rate and heat release rate for the different fire scenarios to be expected in real power plants.

One general conclusion of the code benchmark was that many of the fire simulation codes involved - not only German ones, but also codes developed and applied in the USA, France and Finland - could be validated by these experiments. Further details can be found in /KFK 92/ and /KAR 93/.

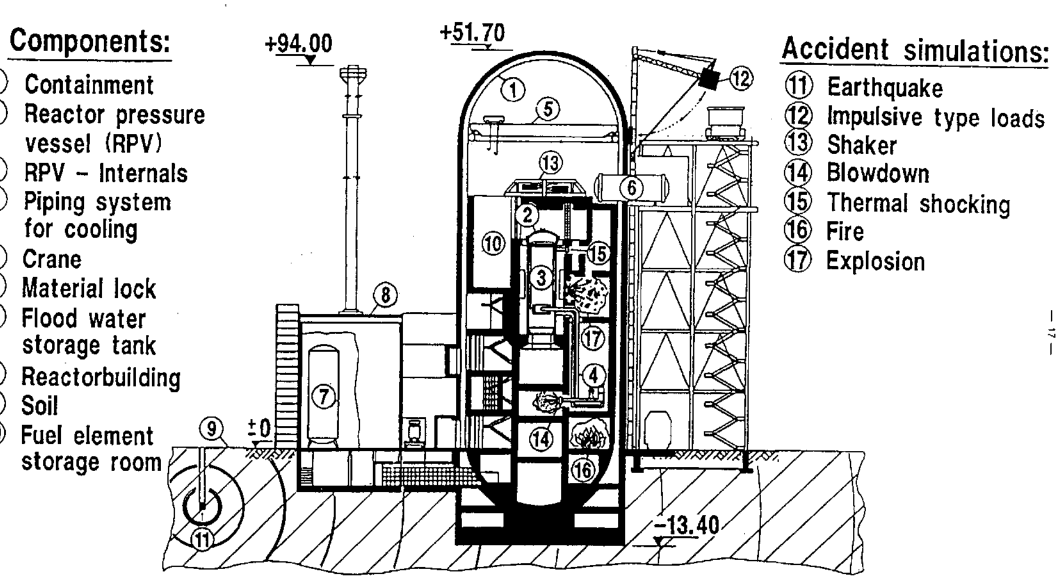

Fig. 1.1 HDR-Test facility and applicated accident simulations

Figure 3.3-2: HDR Test Facility and Applied Accident Simulations

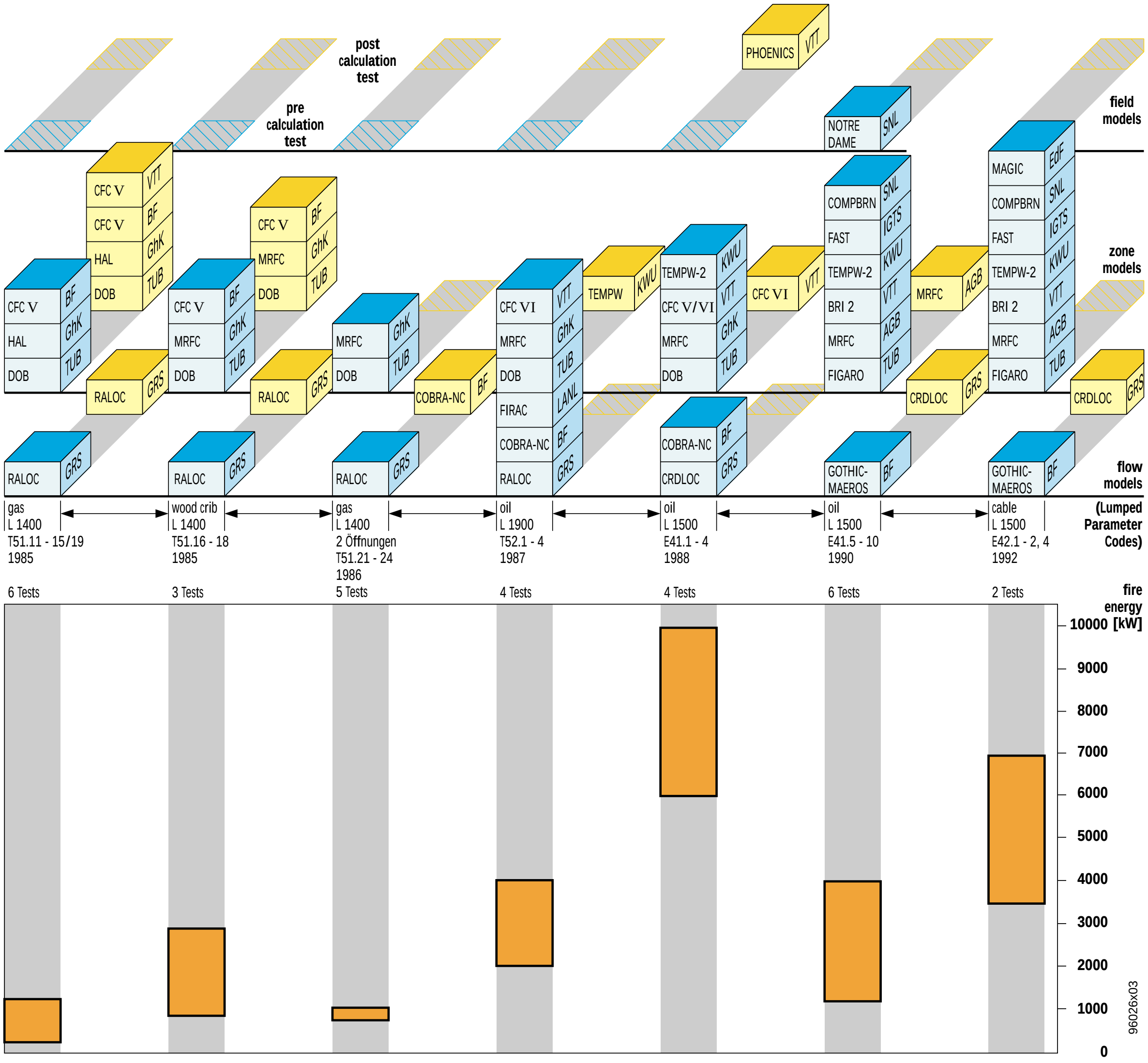

Figure 3.3-3: HDR Experimental Fire Program and Types of Participating Codes

The ***French*** experimental programme with respect to fire risk analysis focused first on the study of the behavior of cables during a fire. This means, at a first stage, to characterize the cable damage (PEPSI 1 test and electrical cable analytical test) and, secondly, to determine the inflammation and propagation conditions of the fire for a given set of cable trays (EPSILON tests). All these elements are used to qualify the physical models of FLAMME-S /CAS 96/. The fire test program foresees to carry out tests related to fire in an electrical cabinet and to the propagation from one room to the adjacent one

PEPSI 1 Test /SUC 97/:

The experimental principle consists in exposing, inside a ventilated room (5 volumes/h), five cable trays to different thermal loads which are directly function of their position in relation to the fire, which is an oil pool fire of 1 m^2. A cabinet is located near the fire (see figure 3.3-4).

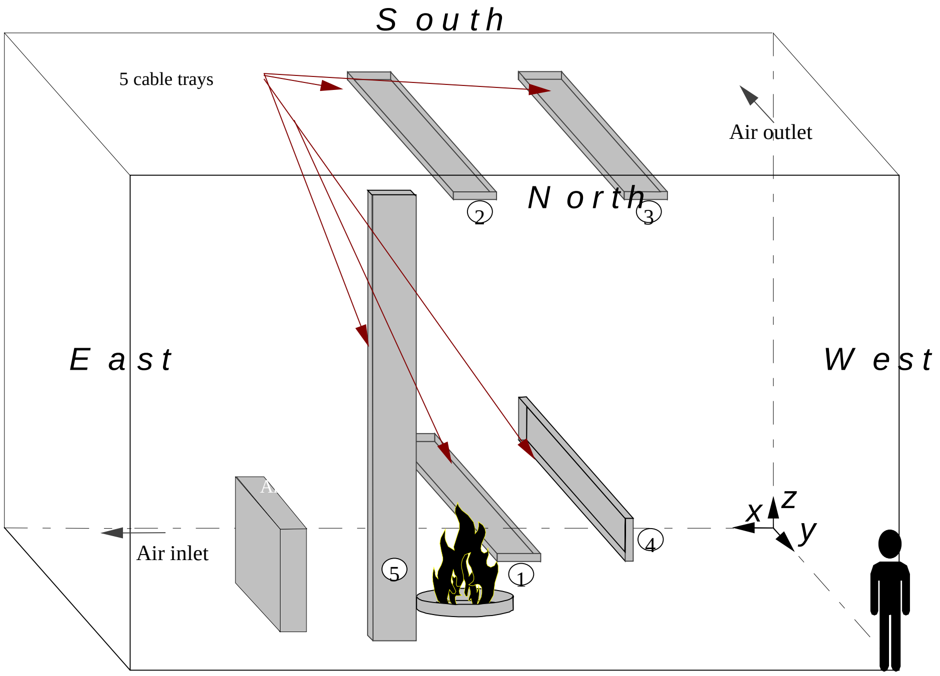

Figure 3.3-4: PEPSI 1 Test

Combustion lasts roughly 1 hour, the temperature of the gases in the room reaching 90 to 210 °C. Apart from tray 4, which seems intact, the others are all damaged over differing length. The east face of the cabinet is slightly deformed. The time at which the damage appears varies between 4 minutes (tray 1) and 40 minutes (tray 3), the temperatures recorded on contact with the cables which were damaged being between 210 °C and 350 °C. Analytical tests related to the cable damage are being defined to get further information on their failure mode and data related to the damage criteria. The calculation with the FLAMME-S computer code for this test leads to satisfactory results, in particular for the instant at which damage occurs.

Analytical fire test of electrical cable damage:

The objective of these analytical tests is to get data to develop a model for FLAMME-S code permitting to estimate the electrical damage time taking into account the inertia of the cable and to confirm the cable damage temperature deduced from PEPSI test. These tests has been carried out for control cables /LOP 98/ and power cables /LOP 98a/ in an oven where two cables are simultaneously introduced. The first one was equipped with thermocouple (internal and external temperature measures), the second one was under voltage in order to detect the moment when took place contact between internal conductors or between internal conductors and the metallic protection. The tests have been performed for different initial oven temperatures (between 200 °C and 400 °C). The results showed that the first failure mode that occurred is the hot short (contact between internal conductor) and that this failure occurs when the internal temperature of the cable reached about 220 °C.

EPSILON Tests /LES 97 /:

These are average scale tests of analytical nature which will allow to show and quantify the influence of the 3 following parameters on the inflammation and the combustion of a set of 4 superimposed cable trays: the position of the cables on the tray, the distance between the paths and the distance between the tray and the wall of the room and this for a type of cable which has been pre-determined.7 The experimental device shown in Figure 3.3-5 is made of a 50 m^3 room with an opening to the outside on the east wall; the cable trays are located near the west wall, opposite the opening. A gas burner is located near the lateral edge of the lowest tray.

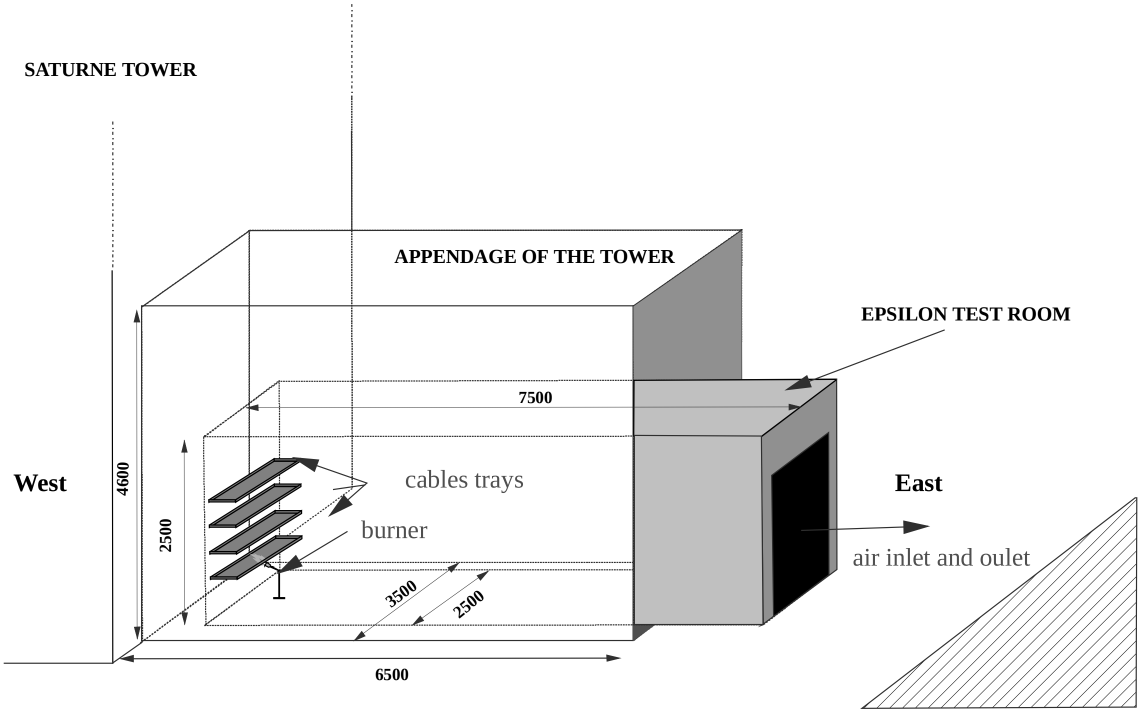

Figure 3.3-5: EPSILON Test Device

The measures used include scales for the monitoring of the mass loss of the cables through pyrolysis or combustion, 50 thermocouples distributed on the 4 trays to follow the propagation of the flame, thermocouples in the gases of the room, a pressure detector, gas velocity probes in the plane of the room opening to determine the inlet and outlet flow-rates and also in the position of the neutral plane. These will be operational in 1998.

CARMELA Tests /TOU 98a/:

The first objective of the analytical CARMELA tests is to establish a data file to develop models permitting to simulate a fire in an electrical cabinet. It is foreseen to study the influence of the ventilation inside the electrical cabinet, the content of this item of equipment and the localization of the ignition point. The first step will consist in determining the evolution of the heat release rate during the burning inside an electrical cabinet. The second step will focus on the study of the damage of the equipment located in the compartment affected by this type of fire.

The second objective is to prepare a global test consecrated to the study of an electrical cabinet fire inside a compartment. This global test will permit to study the burning of a real electrical cabinet and the fire propagation to the contiguous cabinet.

DIVA Tests /TOU 98b/:

Fire propagation tests are foreseen to qualify FLAMME-S version under development. These tests will simulate a set of rooms connected by a ventilation network or by openings such as doors. Figure 3.3-1 represents the configurations that can be simulated. An experimental program has been defined to qualify these more complex situations and the development of the full scale model is in progress

Combustible Tests:

The material characteristics used by FLAMME-S come from either bibliography or fire tests performed with a cone calorimeter.

In the ***USA***, the COMPBRN codes have undergone limited integral validation. (The code's sub-models are largely based on experimental correlations, and are therefore individually validated for those situations where the correlations apply.) The 20-foot separation tests documented in /CLI 83/ have been used to benchmark COMPBRN (see /HOV 88/); COMPBRN has also been applied to the Heissdampfreaktor (HDR) tests (see /NIC 95/). The results of the original version of COMPBRN (see /SIU 81/) were compared to data from a variety of fire configurations (including a set of heptane pool fires, a wood crib, and a vertical cable tray).

Regarding other fire codes in nuclear power plant applications, CFAST /POR 92/, /PEA 93/ has recently been used to simulate some HDR tests. In non-nuclear applications, CFAST is one of 21 computer fire models included in an international program to validate fire models, including FIRST, WPI, BRI2 /TAN 89/ FLAMME-S /BER97, CAS 96/ JASMINE /KUM 95/, and the KAMELEON code of the Norwegian SINTEF Group /HOL 93/. (The last two are CFD codes.) The results of initial validation runs are not yet available. Other validation efforts for the NIST and Sandia CFD codes are proceeding in parallel with code development. It is probably fair to say that, provided appropriate input (the codes do not model combustion from first principles), the codes provide good qualitative predictions at this stage.

It is necessary to experimentally validate the applied simulation codes' and models' calculations and input parameters as well as the applied damage threshold criteria of safety related equipment in order to prove the required accuracy and credibility for PSA purposes.

The following R&D activities in this area are completed or ongoing in ***Finland*** /ROC 92/, /BJO 96/, /HUH 93/, /HUH 90/, /KES 93/:

- Experimental validation for simulation codes and models calculations:
  - simulation of small and full scale experiments,
  - HDR reactor compartment modeling (PHOENICS /CHM 91/, BRI2 /TAN 89/),
  - Steckler standard room fire /STE 82/ (SOFIE /SOF 94/),
  - international simulation development and comparison, pre- and post calculation of experiments,
  - CIB (International Council for Research and Innovation in Building and Construction*)* standard problems;

- Experimental validation of fire simulation input parameters /MAN 94/, /MAN 96/, /MAN 97a/, /BJO 97/
  - cable fire experiments:
    - cone calorimeter tests,
    - small scale fire experiments (cables, trays),
    - full scale fire experiments (cable tunnel),
  - electrical and I&C cabinet fire experiments,
  - field tests of fire detectors,
  - international experiments available,
- Experiments to study failure modes and time dependent damage threshold temperatures, to be applied in simulation-based analyzes:
  - electrical cables,
  - pressure sensors,
  - motor operated valve actuators.

In ***Japan***, validation of alpha-FLOW will be made through lubricant oil fire experiments, cable fire experiments (IEEE-383 and IEEE-384 standard tests) and board fire experiments conducted by Japanese utilities /TAN 85/, /FUJ 85/. The lubricant oil fire experiments have been conducted with parameters of oil pans under open space using turbine oil so as to get empirical equations for burning rates and radiate heat fluxes. In the compartment fire experiments with methanol as fire source, burning rates, room temperatures, radiate heat fluxes, etc. were measured under the parameters of an oil pan of 0.5 m^2, position of fire source and ventilation rate. These experiments showed that burning rate and heat flux are not influenced by ventilation rates and position of fire source.

Compartment fire experiments were conducted 51 times with parameters of oil pan size, compartment size and location of fire source so as to measure room temperatures, radiate heat fluxes, smoke and CO_2 concentrations, where room temperature distributions were observed vertically but not horizontally. The radiate heat flux from hot gas layer and soot was larger than that from the plume. The validation of the alpha-FLOW code is under way using these experiments.

In the ***United Kingdom***, the CFX code has been tested through a number of different validation studies, e.g., /KER 94/, and has been used extensively in the nuclear industry, but almost exclusively for non-fire scenarios. For the JASMINE code /KUM 95/, validation studies have been done against Steckler fire tests and against experimental data from a 1/6th scale model of a pool fire in a sports stadium although the latter example was considered too sparse of data and too selective to be considered rigorous validation of the code. A validation study of SMARTFIRE /TAY 98/, /EWE 98/ compared results with PHOENICS for a Steckler room test and concluded that “results ... compare favorably”. A similar exercise was carried out for SOFIE /HEI 96a/ with the conclusion that ‘the results seem to match experimental results and PHOENICS-simulation results quite well’.

In August 1988 the ***Swiss*** Nordostschweizerische Kraftwerke AG (NOK) together with Cerberus AG performed a series of cable fire tests /LAN 91/ using actual Beznau cables and fire detectors. However, the results of these tests have not been credited in the Beznau PSA.

NOK’s objectives for these tests were to (1) determine the detector sensitivity (1.e., detection time), (2) determine the impact on adjacent cables, and (3) to determine whether a cable fire can propagate from one tray to the next tray. NOK concluded from these tests that (1) the aerosols that are produced in a cable fire cause an alarm well before an open cable flame develops, (2) the probability is low that a single cable fire will affect the adjacent cable, and (3) the fire extinction system prevents propagation of the fire from one cable tray to the next.

The validation of the computer fire simulation codes COMPBRN III/MC (a precursor to COMPBRN IIIe /HOV 90/) and HAZARD I (CFAST) /POR 92/, /PEA 93/ being applied in ***Switzerland*** was published in the literature.

As the COMPBRN III model assumptions are well enough known, no special validation process is done in ***Spain***. Result tendencies of simulated scenarios are analyzed to check if fire spread predictions are reasonable or additional effects not considered by the code could play an important role. If that is the case, conservative assumptions should be made.

3.3.2 Conservative Assumptions Used

The level of conservatism in fire modeling varies with the conservatism/non-conservatism of the assumptions used in the codes. Due to this, there is a variety of conservative assumptions in the different approaches to carry out fire PSAs.

In ***Germany***, the following conservative assumptions in codes have to be mentioned:

- rather conservative assumptions for fire spreading,
- modeling without fire intervention (by fire extinguishing systems as well as manual fire fighting means),
- more conservative hot gas layer,

The level of conservatism varies strongly for the different steps/levels of the analysis:

- initial frequency: relatively conservative (depending on generic data available),
- qualitative screening: conservative,
- quantitative screening: realistic,
- reliabilities: more and more realistic,
- fire growth and spreading: up to now, conservative,
- component impact criteria: conservative.

With respect to the reliabilities of fire protection related systems and components more and more realistic data are applied in the studies.

In ***France***, for the detailed study, the following conservative assumptions can be mentioned:

- the consequences of a fire in the control room have been defined considering that all the hot shorts can be induced simultaneously,
- when tests do not exist, it was considered that the damage of equipment occurred when temperature reach its design temperature,
- the heat release rate and the quantity of combustible has been overestimated,
- the probabilistic assessment of human errors has been overestimated considering that if an inadvertent alarm appears during the beginning of fire and can lead the control room operator towards an unsuited operating procedure there is no chance of recovery,
- the frequency of fire scenarios has been evaluated from the operational experience without taking into account the ratio of fires that extinguish by itself,

- for the solid combustible, the time corresponding to the pyrolysis prior to apparition of flames was not taken into account.

Furthermore, it has to be mentioned that the level of conservatism differs. For the screening phase, the conservatism is notably significant:

- for the functional analysis, it was systematically assumed that a fire damages all the equipment of the fire zone,
- for the estimation of the conditional probability of the core damage (term P2) the human error probability of the shift personnel is assumed to be one,
- for the estimation of the conditional probability of the equipment damage (term P3) the heat release rate of each fire is conservative, the hypothesis of fire spreading is enveloped (for example it is assumed that an electrical cabinet fire can propagate to the adjacent electrical cabinet), the protection of cable, if any, is not modeled, the possibility to extinguish the fire by manual intervention has not been taken into account,
- for the estimation of the frequency of core damage we assumed that each ignition source can generate the worse fire scenario.

In the ***USA***, fire modeling conservatism varies from study to study, depending on the purpose of the study (see Chapter 5) as well as the apparent risk significance of the scenario being analyzed. Potential conservatism can arise in the modeling of fire behavior and its effects. Regarding fire behavior, for example, analyses often ignore the effect of intervening obstacles when calculating heat transfer. (The COMPBRN code uses a “non-communication matrix” to allow the user some flexibility in modeling obstacles, but this capability is not always exercised.) The heat sink effect of room equipment and the impact of local oxygen starvation on heat release rates are also often neglected. In many analyses, it is assumed that the affected room has an open door; this neglects the limiting effect of forced ventilation. Furthermore, most analyses neglect the time required for the fire to reach the “initial” size used to start the fire model simulation. Regarding the effects of fire, a number of analyses ignore the time required for a target to heat up to its damage temperature. Also, it is generally assumed that the fire is sufficiently severe to make the affected room inaccessible to operators (for the purposes of recovery actions). Of course, conservatism may arise in the selection of model parameter values (e.g., for the damage temperatures of components).

It should also be pointed out that non-conservatism can also arise in fire modeling. These can be due to basic modeling assumptions (e.g., the neglect of radiation feedback to the burning fuel, the assumption that fires in closed metal cabinets will stay confined within these cabinets) as well as choices of parameter values (e.g., cable piloted ignition temperatures, electrical cabinet heat release rates).

More generally, of course, it is widely recognized that there are significant uncertainties in the predictions of even the best fire models. These uncertainties have both aleatory (stochastic) and epistemic (state of knowledge) components. (See /APO 90/, /PAR 91/, and /APO 95/ for broader discussions of uncertainty with respect to PSA applications.) They arise because of approximations inherent in the fire modeling tools, lack of definitive data concerning the model parameters, and because of approximations introduced by the analyst when modeling specific scenarios. A useful discussion on the role of uncertainties in the interpretation of fire modeling results is provided in /SIU 89/; a discussion of a general Bayesian framework for addressing model uncertainties is provided in /SIU 99/. It is important to recognize that applications of fire models which neglect the significant uncertainties inherent in such modeling (e.g., applications which neglect the possibility of damage to critical cables because they are a few cm above the damage height predicted by a given model) could easily lead to non-conservative assessments of fire risk.

In the ***Finnish*** probabilistic fire risk analyses some conservative assumptions are applied in the deterministic part of the analysis and in fire scenarios:

- fire growth models, usually t^2-fire chosen (moderate or fast), ignoring the possible smoldering period prior to ignition of flaming combustion, thus underestimating the detection possibilities,
- some simulation parameters chosen to avoid non-conservatism:
  - ignition temperatures,
  - calorific values,
  - burning rates,
- in some zone models the limiting effect of oxygen deprivation on heat release rates is not considered.

With regard to the level of conservatism it has to be stated that the first phase of the fire risk analysis is very conservative. It is assumed that a fire in a room damages all components in it. In the second phase, fire simulation codes and other realistic approaches are used to eliminate the unnecessary conservatism in the fire risk analysis. The corresponding fire frequencies and related conditional core damage probabilities are recalculated using those less conservative assumptions.

It is typical that the level of conservatism is higher at low risk fire areas and lower at high risk fire areas.

In ***Hungary***, the level of conservatism depending on the conservative assumptions in the approach differs a bit from organization to organization involved in fire risk analysis.

For FHA - ETV-ERÕTERV Co. (Hungary) activity it has to be stated:

- Non-conservatism:
  - Only the components of the level-1 PSA-model compartment have been included.
  - Fire spreading between-compartment has not been considered.
- Conservatism:
  - The pilot fire position was defined at the possible worst position in order to get fire damage of the object.
  - In some cases, because of the limitations of the calculation mode, some sheltering effects of components, cable trays other than objects have been excluded.

In the fire risk analysis by VEIKI (Hungary), the following conservative assumptions can be mentioned:

- An assumption is made that all compartments are surrounded by fire barriers. Consequently, the probability of fire propagation from room into another room is low in most cases.
- Some conservative criteria are used so that no potential fire spread will be screened out during quantitative screening within the fire risk analysis. These criteria are concerned with:
  - fire resistance of fire barriers between compartments
  - amount of combustible loading in compartment
  - availability of automatic fire detection and automatic and/or manual fire suppression.
- For the quantitative screening, it is assumed that fire in a given compartment fails all the equipment in that compartment.
- In the preliminary analysis it is assumed that inadvertent signals always occur with a probability of 1 if an I&C cable fails due to fire.

The fire risk analysis methodology developed in ***Japan*** by NUPEC consists of three stages, namely, “spatial interaction analysis”, “screening analysis” and “detailed analysis”. Spatial interaction analysis creates fire scenarios based on plant information. Screening analysis identifies risk significant fire scenarios under conservative assumptions. Detailed scenario analysis reveals sub-scenarios without the conservative assumptions and quantifies core damage frequencies for the sub-scenarios.

In the current detailed analysis, failure probabilities of target components are estimated using US severity factors. These severity factors, which were based on US fire experiences, seem too conservative for Japanese plants which are designed under Japanese fire protection codes /JEA 86/. For example, Japanese physical separation criteria require a minimum of 90 cm between safety cable trays. Even if the plant satisfies these criteria, a cable 90 cm far from an ignited cable tray has still a failure probability of 0.7 according to the US severity factors, which seems to be too conservative. Therefore, NUPEC has pursued Japanese specific severity factors using alpha-FLOW and COMPBRN-IIIe /HOV 91/, which will be validated through some fire experiments conducted by Japanese utilities /TAN 85/, /FUJ 85/.

Conservatism in fire simulations will be coped with uncertainty analyses in which some important parameters such as material data relevant to burning, oil quantity, ventilation conditions will be taken into account. Uncertainty relevant to cable ignition mechanism would get important in cable fire simulation.

The main conservative assumption that has been made in the ***United Kingdom*** analysis is that the significant fire considered will spread within the whole of the fire zone and lead to the failure of all the safety system equipment in that zone.

It has been assumed, conservatively, that the failure probability of a single line of the automatic fire detection and suppression protection system is 0.1.

A degree of conservatism has been introduced by not claiming the benefit of manual fire fighting in the fault scenarios where the initiating event frequency was synthesized. However, this may be small since it has been recognized that the conditions of a fire may limit manual fire fighting to containment of the fire to a single fire zone.

From ***Switzerland*** it was stated that the possible conservative assumptions are dependent on the scenario.

Furthermore, the level of conservatism is dependent on the scenario considered. In general, conservative assumptions are only made, if a lack of knowledge exists. In the first step of the screening it is conservatively assumed that all equipment fails in the room under consideration.

In ***Spain***, the result tendencies of simulated scenarios are analyzed to check if fire spread predictions are reasonable or additional effects not considered by the code can play an important role. If that is the case, conservative assumptions should be made.

With regard to the level of conservatism, it is intended that the analysis should be conservative. This is valid, in particular during the screening process. The most uncertain aspects are most likely fire frequency and fire growing analysis. Uncertainty and sensitivity analyzes are performed to observe the influence of relevant aspects or to cope with data scarcity. Special attention is paid to areas where fire damages can be significant, independently from fire ignition frequency and fire growing calculations.

3.3.3 Insights of the Use of Fire Simulation Codes in PSA

The fire simulation codes applied for PSA studies world-wide have given or are intended to give special insights being useful. These insights differ from application to application strongly.

In ***Germany*** probabilistic risk assessments, such as the German Risk Study, Phase B (DRS-B) /GRS 90/ being carried out for a PWR plant, or the BWR Safety Analysis /GRS 93/, the fire simulation models were mainly used for revealing time-temperature curves for safety relevant areas and compartments being selected in the screening process. In these risk studies, mainly oil fires or combined oil and cable fires were analyzed, for which the applied codes had been validated (e.g. by HDR experiments). Furthermore, the models gave insights on pressure increase in the containment and on the behavior of relevant building constructions (e.g. reactor containment vessel) and components (e.g. instrumentation and control for neutron flux, safety related valves inside the reactor containment).

In a more recent assessment of the risk due to fire in the cable spreading room of a PWR carried out by GRS, fire simulation codes gave detailed insights in the fire, flame and smoke spreading behavior on horizontal as well as vertical cable trays. Furthermore, the results /HOS 98a/ could be used for decisions on the application of additional protective measures for cables, such as protective coatings.

In ***France***, the FLAMME-S computer code, in the frame of fire PSA of 900 MW_e, has been used for studying all the fire scenario in a critical compartment. The main ignition sources studied are batteries, fans and electrical motors, as well as oil and electrical cabinets. Moreover, the thermal propagation from one compartment to another, by ventilation network or open door, is under study.

In the ***U.S.*** fire risk analyses, the usual purpose for modeling fires is to determine:

a) whether a given fire has the potential to damage a specified set of critical components in a compartment, and
b) the time required to damage these components.

In the most thorough studies, it is recognized that the damage time has aleatory (stochastic) and epistemic (state of knowledge) uncertainties; the latter are quantified explicitly.

Some fundamental papers on fire risk analysis which describe the aims of fire modeling and the treatment of uncertainties are /APO 82/, /KAZ 85/ and /SIU 82/. These papers provide some results of analyses (i.e., distributions of damage times) that were performed for early fire risk analysis. Damage time predictions (point calculations) from later PSAs are provided in the studies /BOH 90a/ and /LAM 93/, as well as in a number of IPEEE studies.

The following are among the numerous insights gained from the U.S. fire PSA fire modeling efforts.

- For many of the configurations analyzed in PSAs, fairly severe fires (e.g., equivalent to 1m diameter oil fires) are needed to cause damage to critical components (primarily cables). Furthermore, if the fire is of sufficient severity to cause damage, it usually is predicted to do so in a fairly short amount of time (on the order of ten minutes or less).
- It is important to explicitly treat uncertainties; such an analysis can not only yield interesting results (e.g., the probability that a given fire is incapable of causing damage), it can also indicate whether improvements in fire modeling sophistication are likely to change the risk insights for a given scenario.
- Due to the sensitivity of model simulation results to initial fire size, fire risk analyses should take greater care in defining the initial conditions of fire scenarios (and their likelihood).

In ***Finland***, fire simulation codes have been used both to create relevant room-specific scenarios and assess the time-dependent course of fire as well as to give insights on the fire development and effects on a more general level. Thus, using simulation, the dispersion in results obtained purely by expert judgement have been reduced significantly.

- Power companies' fire risk analyzes
  - Zone models: COMPBRN IIIe /HOV 91/, BRI2 /TAN 89/: time-dependent temperature rise in fire compartments
- Analyzes for independent review purposes (authority, research institute)
  - Field models (CFD): PHOENICS /CHM 91/, FLUENT /FLU 97/
  - Zone models: BRI2 /TAN 89/, COMPBRN /SIU 83/, /HOV 91/, CFAST /POR 92/, /PEA 93/.

In ***Hungary***, the fire risk analysis is going on for the WWER-440 type NPP PAKS, Unit 1. Preliminary sample calculations by the COMPBRN IIIe code were performed up to now. This code will be used further for detailed fire spreading calculations related to the dominating event sequences and scenarios of the fire risk analysis model. These scenarios will be determined by the preliminary quantification and screening of the event logic model.

The purposes of these calculations using COMPBRN IIIe /HOV 91/ is to define and describe the fire events that are particularly dangerous and have an impact on the plant safety. Thus it will be possible to assess in detail those damages caused by fire as well as applicable prevention and recovery actions.

NUPEC in ***Japan*** is now in the stage of making code validation analyses for alpha-FLOW and COMPBRN-IIIe /HOV 91/ using Japanese fire experiments to get Japanese specific severity factors. At the present time the following insights are obtained:

- Fire frequencies should be quantified taking into account the oil quantity of the components.
- Important parameters taken into account in uncertainty analysis are not only material data relevant to the burning process but also boundary conditions, such as oil quantity actually contributed to burning in a real component fire, ventilation conditions, oil pan size, leakage of oil from the oil pan.
- Uncertainty factors relevant to cable ignition mechanism should be clarified under excess-current.
- Fire simulation should distinguish between cables with and without resistance to flame, cables in accordance with and those not in accordance with IEEE-383/384 standards.
- In fire simulations for electrical switchboards, impact of smoke and heat on the board should be analyzed for every board type, considering recent state of the art technology. There are many kinds of boards on which impacts of smoke and heat are different. For example, impact of smoke and heat on boards with modular switches is quite different from those with conventional switches.
- Core damage sequences due to erroneous signal induced by hot shorts of control circuit are dominant in plants with physically highly separated safety systems.

In ***Spain***, the analysts are aware of the uncertainty of fire models, and therefore try to make sure that results are not mainly driven by uncertainties or poorly based hypotheses. In the analysis of many fire zones however, COMPBRN IIIe /HOV 91/ calculations do not drive the results. For instance, if a zone contains two redundant trains, train A and B, and train B is protected by a 1 hour fire rated barrier, COMPBRN may predict damage to train A after 5 to 10 minutes (1st stage). For that short time period credit is given only to automatic fire suppression. If this fails, it is assumed that 1 hour after fire break out train B will fail (2nd stage). Credit is then given to manual fire suppression before stage 2 is reached. This approach provides usually acceptable risk estimations that are not driven by COMPBRN predictions.

3.4 Concluding Remarks

In nearly all member states, fires including fire development and spreading as well as direct and indirect fire effects have been modeled by different types of codes. In the frame of extensive analyses covering deterministic fire hazard analyses as well as probabilistic risk assessment fire simulation models were applied to nearly all types of fires occurring in nuclear power plants.

Several, mainly the more sophisticated fire simulation models and codes could be experimentally validated on a national or partly also on an international basis, including benchmarks. Thus they represent a state-of-the-art and reliable tools in the frame of deterministic and probabilistic fire safety assessment to be performed by nuclear industry as well as by licensing and supervisory authorities and expert organizations.

Up to the time being, conservative assumptions are used in the fire modelling for a number of fire PSAs. These assumptions mainly refer to the initial fire frequency, the fire resistance of barriers, the fire load density and distribution inside the fire compartments, ignition~~s~~ temperatures and burning rates. Furthermore, it is assumed conservatively for nearly all studies that all equipment inside a fire compartment is failed in case of a fire. It has to be noted that non-conservative fire modeling assumptions can also be found in a number of fire PSAs. These include the use of non-conservative parameter values (e.g., for the heat release rates associated with electrical cabinet fires), the neglect of self-ignited cable fires involving cables qualified according to certain tests, and the neglect of fire-induced short circuits. It should also be noted that current fire PSAs do not address a number of issues that have been observed in actual fire events (e.g., the occurrence of multiple fires due to a single cause, the non-thermal effects of explosive electrical faults).

It has to be admitted that the fire modelling still suffers from a lack of knowledge on a realistic burning behavior of several combustibles, e.g. cable insulation materials. Furthermore, the impact of smoke and other fire products on safety related equipment and the effects of smoke and heat on electrical and electronic equipment have not yet been modeled or analytically studied in detail in most countries performing fire safety assessments of nuclear power plants.

There is a need of further developed approaches for the uncertainty and sensitivity studies to be performed in the frame of fire PSA. Only very few papers on fire risk analysis outlining the treatment of uncertainties are existing at the time being. Most of the studies performed up to now, do not consider that the equipment damage time has stochastic as well as epistemic uncertainties. In this area further research activities are seen to be necessary and worthwhile.

4. IMPACT OF SMOKE AND HEAT ON SAFETY RELATED SYSTEMS

4.1 Introduction

In the framework of PSA analysis, the impact of smoke and heat on safety related systems has been analyzed with different methods and analytical depth.

Usually, the analyses take into account cable damage as the main contributor to risk originated from fires affecting safety related systems. The impact of smoke, however, is rarely assessed explicitly. In this chapter, current state of knowledge concerning the impact of smoke on electronics is discussed. Furthermore, electrical cable damageability information and failure modes as well as their consequences are assessed.

In addition, the way in which the impact of smoke and heat on safety related systems is accounted for in PSAs performed in the respondent countries is presented both in general terms as well as with selected samples of the response obtained.

Finally, examples of relevant incidents of smoke and heat impact on electronics and electric equipment as well as cable fires in respondent countries are provided.

4.2 Experimental Studies on the Impact of Smoke on Instrumentation Electronics, Electrical Equipment and Suppression Systems

4.2.1 Impact of Smoke and Heat on Electronics

Experiments on the impact of smoke on analogue and digital electronics have been carried out, for example at the Oak Ridge national Laboratory, Sandia National Laboratories and VTT (Finland). A review of these experiments has been compiled by VTT /BJO 98/.

Investigation of the effects of smoke on the performance of electrical components, especially advanced digital instrumentation and control (I&C) systems, is an important area to be studied. Digital components may be more sensitive to environmental conditions than older relatively robust analogue electromechanical components used in the conventional plant instrumentation, which are considered invulnerable to short-term smoke damage. Digital systems are considered vulnerable due to their closer spacing of electrical traces and contacts, the more precise performance demands of the devices, and the generally less robust nature of the individual components. In case of fire one principal damage mechanism is exposure to smoke.

To date tests concerning smoke damage to electrical components have been carried out in ***USA*** at Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL). Various components were exposed to smoke from burning cable insulation and the nature and mechanisms of smoke damage and critical parameters associated with the problem were investigated. In each test a certain quantity of cable insulation material was burned by external radiant heating. All the smoke was captured and held in a component exposure cell for one hour. The exposure targets included generic chips, optical isolators and computer memory chips. Parameters such as fuel amount (smoke density), fuel mixture (PVC or not), burn mode (smoldering/flaming), humidity level (high/low), coating of targets and target orientation (vertical/horizontal) were varied in the experiments. In one test set functional boards were used to assess the effects of smoke on the real-time performance of four common types of active digital circuits.

The results of the above mentioned tests show that both short-term and long-term damage is possible in a smoke exposure environment. The faults were generally associated with intermittent contact problems and, based on the short time scale over which the faults occurred, they were attributed to circuit bridging problems (induced leakage currents between circuits) rather than to direct corrosive attack on the components or circuit traces by corrosive actions of the deposited smoke particles.

In two series of tests it was observed that short-term degradation from circuit bridging should be expected in such smoke exposures. This degradation develops temporally with smoke generation. However, in many cases a significant recovery is observed immediately upon venting the smoke from the exposure cell. Based on this result, one could conclude that there are two mechanisms of smoke damage:

Actual deposition of particulates, which can lead both to circuit bridging and longer-term corrosive attack.

Simple immersion of the device in the ionized airborne smoke particles, which appears to contribute directly to the short-term circuit bridging problem and is mitigated immediately upon removal of the smoke from the air.

The two most critical parameters are the humidity level and the amount of the material burned or smoke density, which influence the severity of the degradation. Open flame combustion was more severe than a smoldering combustion, which is a bit unexpected observation as well as the fact that the presence or absence of PVC as a part of the fuel mixture seemed to have little influence on the results. PVC and other highly halogenated compounds are often considered to have a high potential for inducing fire or smoke damage.

The results obtained in the USA indicate that the presence of airborne smoke may cause the most serious short-term damage and halogens or PVC may not have any significant contribution to this mode of damage. However, those test results do not give information on longer-term corrosion damage in which halogens and PVC may be a significant factor.

4.2.2 Electric Cable Damageability and Failure Modes

The loss of functionality of electric cables in fire is a complex phenomenon that depends, among others, on cable materials and dimensions, electric and mechanical loads on the cables, as well as on the magnitude of the heat flux and its time of exposure. If the heat flux is small, the insulation material softens in the course of time and disperses away from around the conductors, depending on the mechanical tensions acting on the cable. On the other hand, if heated rapidly, e.g., in a flame, cables may remain functional even beyond the moment when their jackets already have been ignited /KES 97/.

4.2.2.1 Failure modes and consequences

The following text is based on a French study supported by input from other countries.

Fire tests show that electric cables are susceptible to the following failure modes:

- short circuit: direct contact between the internal conductors of multi-conductor cables,
- short to ground: cable conductors become connected with a grounded item,
- open circuit: breaking of cables, loss of electrical conductivity of a conductor.

Short circuit: In the case of damage to electric cables by fire, the first multi-wire cable failure mode to appear is contact between internal conductors. For multi-wire power cables, direct contact between internal conductors causes short-circuiting. A short-circuit can result in inoperability of the corresponding actuator as a result of tripping of a circuit breaker or contactor.

For control cables, the consequences of contact between conductors vary with the type of cable:
contact between conductors of opposite polarity causes short-circuiting and, in principle, disconnection of the affected control part,
contact between an energized and a de-energized conductor can generate a spurious signal (hot short).

Short to ground of single and multi-wire cables: Short to ground of multi-wire cables by contact between conductors and cable tray connected to earth normally occurs eventually after internal contact between the conductors.

On the other hand, for multi-wire cables, the risk of short to ground of this type of cable arises by contact of the single conductor with the cable tray.

The short to ground of alternating current cables causes tripping of the associated circuit breaker or contactor, and hence inoperability.

Open circuit: Breaking of power cables only occurs under exceptional circumstances, in the following two cases:

As a result of failure per demand or undetected inoperability of the thermal protection for over-current, straightforward shorting as mentioned above can persist (non-tripping of the corresponding outgoing feeder cubicle, or possibly the cubicle of the upstream switchboard) and result in melting of the conductors and complete breakage of the cable.

If a fire lasts long enough for a temperature to be reached for failure of the cable tray by slumping. The cable is no longer supported and breaks. It should be noted that in such cases the other failure modes mentioned earlier would have already occurred well before the cables broke.

In addition to the above mentioned failure modes, there may occur intermittent shorting and high impedance shorts that do not necessarily cause tripping of protection devices. Furthermore, the electromagnetic flux occurring in the above mentioned situations may induce voltage spikes in nearby cables and thus potentially affect the function of low-voltage passive, logical and integrated components.

4.2.2.2 Failure Threshold Limits

In experimental failure threshold studies, different criteria are applied to loss of cable functioning that manifests itself as shorts between conductors, shorts to ground or loss of continuity. The phenomena may be monitored by continuous electric measurements during the tests or separate post-test observations.

Various standard test methods have mainly assessed the fire spreading properties of cables, whereas fire endurance (circuit integrity) has been of little concern. Therefore, scenario specific tests have been developed and carried out for cables commonly used in NPPs. Numerous experiments have been conducted to assess the damageability of cables in fires, especially by Sandia National laboratories (US) during the late seventies and eighties. Later on, also ***French*** organizations have been active in this field, as evidenced by the descriptions of test facilities and methods in other chapters of this paper. There have also been some ***Finnish*** and ***German*** activities /KES 97/.

The main test methods are as follows:

- The cable is exposed to a well defined heat flux induced by, e.g., a flame or an oven or a radiant heater. As a result, the time to damage is obtained. In direct flame contact, as for instance in the IEC 331 test, or with a corresponding heat flux produced otherwise, the time to damage is typically of the order of some minutes for conventional cables.
- The temperature of the environment of the cable is increased so slowly that the cable temperature is essentially uniform. As a result, the failure threshold temperature is obtained. With conventional cables, it usually is 150…250 ºC.
- The cable is located in a fire compartment for which the room temperature increases in the course of fire. As a result, the time-temperature history leading to failure is obtained. These tests are usually conducted as a side product of more comprehensive fire experiments where other phenomena and fire protection features are also analyzed.

Usually, in none of the above mentioned tests the cables are under normal operating load current. In the case of power cables, their temperature may exceed the ambient by up to 50 ºC due to the operating current, which is a factor that must not be forgotten when assessing cable damageability in real NPP applications.

In a growing fire, no explicit room temperature causing cable damage may be defined as the phenomenon depends on cable materials and dimensions, electric and mechanical loads on the cables, as well as on the magnitude of the heat flux and its time of exposure. Thus, the heat transfer to the cables should be calculated, which in fact is done, e.g., by the COMPBRN simulation code /SIU 83/, /HOV 91/. Another approach applied is to simply define a critical room temperature or a critical time-temperature history curve and assume the cables damaged if it is shown, e.g., by simulations, that either criterion is exceeded.

4.2.3 Other Safety Related Equipment

Besides the effects of heat on cables and smoke on electronics, some experiments have also been carried out on the effects of fires on other safety related equipment.

For example, in the ***Finnish*** PALOTUB fire research program, experiments were conducted in 1998 to define temperature threshold limits for typical equipment used at the Finnish NPPs. Experiments were done on critical electronic components such as printed circuit boards and relays /BJO 98/, field transmitters and sensors, and motor operated valves.

For electric switchgears and batteries little, if any, information is available. For some types of equipment, useful information may also be obtained from LOCA conditions tests. A conservative approach is to use the environment threshold limits given by equipment manufacturers.

4.3 Models Used in Analyzing the Impact of Smoke and Heat on Electronics and Electric Equipment

4.3.1 General Approaches Applied

The impact of smoke and heat on safety related systems and components is usually analyzed by steps along the general frame of PSA. In the first phase, an usual assumption is that, in case of fire, all equipment in the fire compartment or room (fire zone) is damaged so that its function is lost. This approach has been generally adopted, e. g., in Finland, France, Germany, Japan, Switzerland, United Kingdom and USA.

In the second phase, the impact of heat on safety systems is studied in more detail. In such studies, zone model fire simulation is frequently used, which is the case in ***Finland*** (COMPBRN, BRI2), ***France*** (FLAMME-S), ***Germany*** (CFAST, FIRST, FIGARO, MRFC), Hungary (ERÖTERV: FIRST, VEIKI: COMPBRN), Japan (COMPBRN), ***Spain***, ***Switzerland*** (COMPBRN) and in the ***U.S.***, where COMPBRN also is the most generally used code. The heating of safety related equipment and its time to damage can be assessed by COMPBRN or FLAMME-S codes. In some complicated scenarios of high risk importance, more sophisticated methods such as field model simulation (CFD) has also been applied, as is the case e.g. in ***Finland***, ***Germany***, ***France*** and ***USA***. The use of the simulation tools is comprehensively described in Chapter 3.

In some analyses, also inadvertent signals causing spurious actuation etc. and other active faults are assessed as is the case in e.g. ***Finland***, ***France***, ***Hungary*** (studies by VEIKI), ***Spain*** and also in most ***US*** analyses. The most conservative approach is to always postulate an active fault with the worst possible consequences.

4.3.2 Specific Applications and Approaches

In the following, some interesting applications and approaches applied in different countries are described as per the response obtained. It is noted that especially cable damage temperatures applied in different countries show great variation.

Finland

The impact of smoke is not assessed explicitly. The heat-up of I&C cabinet rooms in the case of big turbine hall fires, and also in the failure of the I&C rooms' ventilation and cooling systems, is considered in the Loviisa PSA, taking into account the allowed environmental temperature of the electronics.

If electrical equipment is exposed to fire effects, it is generally assumed that the cable serving the equipment is the most vulnerable component, thus the equipment itself has not yet been studied in PSAs. However, research programs to study the impact of heat on electrical equipment are ongoing.

The impact of cable fires on safety systems is assessed to some extent in both, Loviisa and Olkiluoto PSAs.

Cables are modeled as parts of the safety systems they serve so that in the case of a fire damaging power cables, the respective safety systems are considered unavailable. In the Olkiluoto PSA, possible failure modes of I&C cabling are considered to be circuit disintegrity or short circuit, with equal probability. In the Loviisa PSA, it is assumed that the failure mode of I&C cables with the worst consequences will occur in a fire. The consequences (false actuation, unavailability) are accounted for in the PSA models.

France

Functional analyses for the cable damage are performed in connection with fire-PSA. Damage to cables can either cause a plant transient or lead to the unavailability of a safety-related item of equipment. Therefore the response of the actuators in the event of cable fire damage has to be analyzed.

There are three types of electric cables to be analyzed: power cables, control cables, and instrumentation cables.

Power cable damage leads, in most cases, to the opening of the circuit-breaker by differential protection or over-current. In some cases, when the number of connections of a switchboard is sufficiently high, the fire can lead to the loss of selectivity of the electrical protection due to simultaneous isolation defects. Fire can, indeed, damage the insulators of several power cables fed by the same switchboard. The resulting leaking currents may not be sufficient to operate the protection associated with each electrical cable. Nevertheless, at the switchboard level, the default current, at least equal to the sum of the currents, can be sufficient to trigger the protection and consequently to lead to loss of the switchboard.

For the multi-wire control cables, the main failure modes taken into account are the following:

- If the two polarities + and - are present in the same cable: it is considered that, by a short-circuit between + and -, the fire triggers the polarity module which will affect several actuators. This is particularly the case for the control cables from the turn-push-light switches, controlling the solenoid valves,
- If only one polarity is present in the same cable: it is considered that, in the most cases, the isolation damage leads to the grounding of the conductor which causes, depending on the cable type, either the lack of a command or an inadvertent signal of an individual actuator

For the instrumentation cables, it is considered that fire leads to a voltage decrease towards a zero value for the control cables of pneumatic control valves, or increase towards a maxi value for cables coming from instrumentation sensors.

The cables of safety related systems are analyzed one by one. The consequences of the damage of each cable are included in a data base which contains the following information:

- for power cables: the item of equipment unavailable, the contactor affected, and, for the rooms with sufficient cables connected to the same switchboard, the loss of this switchboard by lack of selectivity due to isolation defects. Moreover, the user has at his disposal the list of items of equipment connected to each switchboard,
- for control cables: the state of the actuator affected, the inadvertent command triggered, the polarity unity lost and the consequences of this loss, the possibility to operate the actuator from the control room or the circuit breaker compartment.

Moreover, it is necessary to take into account the consequences of the loss of equipment whose damage temperature is lower than electric cables. It is notably the case for electrical cabinets and electrical motors.

As an example, in analyzing a fire in an electrical cabinet, the following damage criteria were applied for simulations with the FLAMME-S code:

Damaged equipment	Damage criteria [ºC]	Damage time with ventilation in operation [min]	Damage time with ventilation stopped at t = 10 min -[min]
Other electrical cabinets	40	8	8
Electric cables in the hot zone	230	60	Not damaged

Hungary

In the preliminary phase of the analysis performed by VEIKI it is assumed that inadvertent signals always occur with a probability of 1 if an I&C cable fails due to fire. The following parameters are used in the damageability studies, to be performed using COMPBRN /SIU 83/, /HOV 91/:

– Cable looses its function:	~ 80 - 100 ºC
– Cable ignition:	~ 340 - 370 ºC

Japan

At present, in the fire PSA of NUPEC failure probabilities of adjacent components due to fire are estimated by US severity factors. NUPEC has now pursued Japanese specific severity factors by a CDF code of alpha-FLOW and a zone model code of COMPBRN-IIIe /HOV 91/. In this approach conceivable failure criteria for target equipment are as follows:

<u>Cable failure criteria:</u> At present the following criteria are adopted, which are used in COMPBRN-IIIe calculation as outlined in /MUS 94/:

– ignition thresholds of the target cable	500 °C,
– damage temperature of cable	350 °C,
– calorific value of cable	2.06×10^7 MJ/kg

The applicability of the above criteria to cables designed under Japanese fire protection codes is now investigated.

<u>Probability of hot shorts accompanying erroneous signal:</u> Erroneous actuation of motor driven pump, motor driven valve and air operated valve are taken into account for control circuit fire. The probabilities of the hot shorts are calculated statistically considering the number of combination of actuating erroneous signal, on the premise that two wires within a cable connecting with the control circuit should invariably contact each other. This approach is adopted in /MUS 94/.

<u>Failure criteria of board due to fire:</u> These criteria are under consideration referring board fire experiments conducted by Japanese utilities.

Spain

Safety related systems are mainly affected by equipment exposure to fire or by damage inflicted on their cables. In addition, heat and smoke can also damage sensitive equipment. Information on cable installations is usually included in a plant data base. Such a data base is modified in order to exclude non-relevant cables and information is added on the equipment affected by a cable fire. PSA and plant design are used to establish which components can be affected by a cable fire due to functional dependencies. The most credible damage type a fire can produce is the loss of power or instrument air supply. Cable shorts by insulation damages normally cause fuses to blow out, or breakers to open by protective actions. However, shorts between wires leading to spurious signals or equipment actuation cannot be excluded and are analyzed, particularly for safety related components, e.g., pressuriser PORVs.

Experience on spurious signals or hardware failures due to temperature increase caused by ventilation failure is available. Therefore, exposure of sensible equipment to fire environment should consider failures due to harsh environment. Assumptions on ventilation conditions made during the internal event analysis have to be reviewed.

Switzerland

An interesting approach to switchgear shorting due to smoke and ionization has been applied in Switzerland: In the Beznau PSA, the data gained from a review of fires reported from nuclear power plants was incorporated in an estimate of the likelihood of smoke damage to the switchgear minimal cut-sets. It was postulated that the likelihood increases with the equipment voltage. It was further postulated that the damage likelihood is related to the voltage by a power law and that damage is certain to occur for voltages of **0,40 kV** or higher.

United Kingdom

Fire spread within a zone was assumed to be complete given a fire initiation and failure of automatic detection and suppression systems. Nominal failure probabilities have been assigned to fire detection and suppression systems based on judgement and included in the initiating event frequency of a fire characterized as failing all equipment in a defined fire zone where judged appropriate. In some cases a more formalized approach has been used for deriving these probabilities, based on methods recommended by USNRC.

Specific consideration of the effects of smoke on instrumentation electronics or electrical equipment has not been addressed. In the safety case, it has been assumed that a fire will lead to failure of all the safety significant equipment within a segregated zone. However, research on this topic is being undertaken to identify the vulnerability of safety systems equipment to the effects of fire and of fire extinguishing agents.

For Sizewell B, a separate deterministic engineering analysis of the cable spreading rooms was carried out in recognition of these zones containing cables common to more than one of the segregated zones. The conclusion of the analysis was that the contribution to the risk from a fire in this zone would be insignificant.

USA

Current ***US*** fire PSAs, as evidenced by the NUREG-1150 studies /BOH 90/, /BOH 90a/, the LaSalle PSA /LAM 93/ and the IPEEEs, treat the thermal effects of fire on plant equipment. It is assumed that all equipment damaged by a fire (where the damage criteria are typically in the form of specified temperature or heat flux levels) are failed. (In the case of electric cables, “failure” is generally considered to cause a loss of function or spurious actuation of associated equipment; many studies address the latter failure mode as being of low likelihood, following the guidance of /KAZ 81/. The NRC is engaged in research activities aimed at providing a stronger basis for assessments of the likelihood of spurious actuations /SIU 99b/.) In the case of cables, the damage criteria are based upon available experimental data. Due to the limited amount of data available, the criteria are uncertain (e.g., see /BRA 89/); the associated uncertainties need to be addressed in detailed fire PSAs. In the case of other equipment, conservative damage temperatures based upon equipment design parameters are typically used. The NRC is developing a database for equipment properties (including damage criteria) for use in future studies /SIU 99b/.

In ***US*** studies, smoke damage has not been treated explicitly, although it can be argued that it is partially addressed in scoping analyses which assume that any fire within a given plant area damages all equipment in that area. The effect of smoke on operators is also typically dealt with in a somewhat rough fashion, through the use of subjectively modified estimates of human error probabilities, and through the prohibition of credit for operator actions in the room(s) affected by the fire. Such an approach, of course, does not cover smoke-induced damage in adjacent areas. Work is being done on the effects of smoke on equipment, as described earlier. It is anticipated that the results of this work will lead to the identification of conditions under which smoke damage to components may be risk significant.

The preceding discussion addresses the direct effects of fire on equipment. It should be noted that current US studies do not explicitly treat indirect effects, e.g., fire induced spurious instrumentation signals which prompt operators to take incorrect actions.

4.4 Examples of Relevant Incidents of Smoke and Heat Impact on Electronics and Electric Equipment and Cable Fires

In response to the questionnaire, several countries reported some relevant fire incidents. Examples of cases where cable fire has caused real or potential threat on plant safety or caused less dangerous but identified harm to the operation of a plant were provided and described in varying detail. Also, fires of other origin that did spread to cables were reported. Information on cases in which smoke caused loss of electronics or electric equipment is sparse. The response is presented in the following sub-chapters.

4.4.1 Finland

4.4.1.1 Short Circuit in 6,6 kV Busbar by Arcing and Fire in Switchgear Cubicles

At Olkiluoto II plant unit (BWR 710 MW_e ABB design) a fire broke out in a 6.6 kV switchgear building on 12 April 1991. The smoldering of the secondary side of a current measurement transformer caused an electrical arc and a fire in a cabinet. The fire spread into three other adjacent cabinets in the cabinet room, but the fire did not spread to other plant rooms. Due to the fire event, the connections to the 110 kV and 400 kV external grids were lost for 7.5 hours. All diesel generators started as planned and supplied electricity to all the diesel-backed switchgears during the fire event. All safety functions and automatic protection systems functioned properly as designed.

The fire in the first cabinet caused a ground short in the 400 kV connection. Although the fire occurred in only one of the four subsystem cabinets, all the subsystems were lost, because the defective cabinet could not be disconnected from the transformer as the only disconnection switch was in the burning cabinet. One of the 110 kV cabinets was in the same row and also caught fire, and the 110 kV connection was lost in a similar way. Because the plant transformers had to be disconnected from the plant switchyard to cut the ground shorts, power could not be supplied to the other subsystems, although six cabinets out of eight were unaffected by the fire.

Causes of the event were as follows:

- maintenance/testing procedures of the current transformers were not adequate,
- fire separation inside and between the switchgear cabinets were not adequate,
- the plant off-site grid connections were not adequate for this kind of event, as regards electrical functional separation by disconnection switches.

It is assumed that in connection with relay testing during the annual maintenance outage in 1990 a break occurred in a faulty test connector of the secondary circuit of a current transformer. A faulty test connector, other damaged connectors and the handling of the damaged connectors were direct causes for the event. The test connector did not close the secondary circuit but left it open after testing. Damaged connectors short-circuited the secondary terminals of a voltage transformer, which were overheated producing smoke and causing ionization of the ambient air. This caused short circuit in one busbar by arcing.

The damaged switchgear was replaced with new cabinets. The checking of the closing of the secondary circuit of the current transformers was added into the relay test procedures. To complete the plant off-site grid connections a second start-up transformer has been installed to both plant units. Fire endurance inside the switchgear cabinets and the fire separation between cabinets were improved and a fixed CO_2 fire extinguishing system was installed in the cabinets. An additional plant transformer was also installed and new switches were added to make possible the separation a damaged part of the electrical systems from the transformers. A cross connection of the diesel- backed switchgears between the plant units was also installed.

4.4.2 France

The French feedback of experience has not identified any cable fire event leading to an impact on safety systems. Nevertheless, the PEPSI test results showed that the heating of a safety cable can provoke contact between several wires and consequently hot shorts being able to induce the loss of safety components.

At French NPPs, three fires concerning electric cables have been reported, but they were not of safety significance:

- a short circuit due to a damage caused by a mechanical aggression (during commissioning) that provoked wire contact that was revealed when the cable was put under voltage,
- wrapping of a power cable (6.6 kV) that induced an overheating,
- a control cable feeding an electrically driven valve of the main feedwater system was in contact with a hot pipe.

At French NPPs, 28 fires have occurred in power electrical cabinets (inverter, rectifier, transformer, switchboard) and eight fires have occurred in control cabinets.

4.4.3 Germany

4.4.3.1 Cable Fire at Greifswald NPP (1975)

From NPP in Germany, one significant incident of smoke and heat impact on electronics and electric equipment and cable fires is to be reported, see also /ROE 93/. In December of 1975, a safety significant fire occurred in unit 1 of the NPP Greifswald in the former Eastern Germany. At that time, 2 units were under operation. Greifswald-1 is a PWR of the VVER-440-V230 type. The reactor had 6 loops and 2 turbine generators of 220 MW_e each. In the meanwhile, this reactor was finally shut down and is under decommissioning.

An electrician caused a triple-pole short-circuit at the grounding switch between one of the exits of the stand-by transformer and the 6 kV busbar of the 6 kV back-up distribution that was not required during power operation. The circuit-breaker on the 220 kV side was defective at that time. Therefore, a short-circuit current occurred for about 7.5 minutes until the circuit-breaker was actuated manually. The overcurrent heated the 6 kV cable which caught fire over a long stretch in the main cable duct in the turbine building.

The reactor building is connected to the turbine building via an intermediate building, as typical in the VVER plants. The 6 kV distribution is located in this building and the main feedwater and emergency feedwater pumps all are located in the adjacent turbine building.

In the main cable routes nearly all types of cables for power supply, instrumentation and control were located near each other without any spatial separations or fire resistant coatings. In the cable route that caught fire there were, e.g., control cables of the three diesel generators. Due to the fire in the 6 kV cable, most of those cables failed.

The cable failures caused a trip of the main coolant pumps leading to a reactor scram and the unavailability of all feedwater and emergency feedwater pumps. The heat removal from the reactor was only possible via the secondary side by steam release. Due to the total loss of feedwater, the temperature and pressure in the primary circuit increased until the pressuriser safety valves opened. This heating was slow, about 5 h, due to the large water volumes of the six steam generators, 45 m^3 in each. In this situation one of the pressurizer safety valves was stuck open. Then the primary pressure decreased and a medium pressure level was obtained so that it was possible to feed the reactor by boron injection pumps. Due to cable faults, the instrumentation for the primary circuit was defective (temperature, pressuriser level). Only one emergency diesel could be started due to the burned control cables. The primary circuit could be filled up again with the aid of this one emergency diesel and one of six big boron injection pumps. With this extraordinary method it was possible to ensure the residual heat removal for hours.

The Soviet construction team personnel incidentally at the site then installed temporarily a cable leading to unit 2. With this cable one of the emergency feedwater pumps could be started and it was possible to fill the steam generator secondary side to cool down the primary circuit to cold shutdown conditions. Fortunately, no core damages occurred.

Regarding the weak points with respect to fire safety, first of all, the cause for the fire has to be mentioned. This fire could only occur because there was no selective fusing of power cables.

Another very important reason for the wide fire spreading concerning all kinds of cables was the cable installation. Nearly all cables for the emergency power supply of the different redundancies as well as auxiliary cables were installed in the same cable duct, some of them on the same cable tray. All the fire barriers were not efficient because the ignition was not locally limited but there were several locations of fire along the cable.

In the common turbine building for the units 1 to 4 of the Greifswald plant with its total length of about 1.000 m there were no fire detectors nor automatic fire fighting systems installed. Therefore, the stationary fire fighting system which could only be actuated manually was not efficient. The design as well as the capacity of the fire fighting system were not sufficient.

Although there were enough well trained fire fighting people, the fire-brigade had problems with manual fire fighting due to the high smoke density as there were no possibilities for an efficient smoke removal in the turbine hall.

4.4.4 Hungary

Three cable fire incidents which occurred at the Paks NPP were reported:

- On the ground-yard there was paint spill during some activity. The paint poured onto the cover slabs of the cable channel of the water intake pumps cables. The paint leaked down through the gaps between the cover slabs onto the cables. Accidentally the paint was ignited and the fire spread into the cable channel causing loss of two out of three trains of water intake pumps.
- In the turbine hall during a flame cutting activity the sparks falling below started ignition of cables in the cable channel. Violating the rules, the cable channel was open and the precautions of workers were not satisfactory. There was no direct effect on safety.
- In the turbine hall during welding the filling material poured down and the cables of the oil system of make-up water pumps was jeopardized, as the fill material ignited an oil spill near the cables.

4.4.5 Japan

An example which has resulted in potential threat on plant safety is presented. A non-safety class power cable ignited by excessive electric current during some test mode at RHR operation, which caused a short circuit of a switch-gear between safety class power and non-safety class power. This short circuit caused an electric over-current in the safety class power resulting in loss of safety class electric power of one out of two trains.

4.4.6 Spain

A major fire occurred in Spain at Vandellós I NPP. The plant is located at the seaside, 140 km south of Barcelona and was designed to produce 250MW_e using natural uranium as fuel, graphite as moderator, a concrete reactor vessel, carbon dioxide as primary coolant and 2 turbine generators. The boilers are mounted below the core with all steam and feed water penetrations beneath the pressure vessel. The cause of the fire was a mechanical failure in a high pressure turbine causing the sudden projection of 36 blades from a wheel due to undetected stress corrosion phenomena. High vibrations occurred leading to several lubricating oil pipe breaks. Spilled oil was ignited by contact with high temperature surfaces. Oil pumps started by low pressure signals leading to an oil spill of 12000 litres in a few minutes. In addition, the turbine vibrations caused a hydrogen leak through the generator’s seal followed by a deflagration.

The fire caused the loss of instrument air and power supply to several safety related components. The fire affected the high pressure turbine area and the lower levels of the turbine building, seriously damaging turbine generator no. 2 and auxiliary equipment, main condenser, control valves and electric cables. Affected cables caused the loss of turbo blower no. 4 and turbo blower no. 3 after 7 and 10 minutes of accident beginning. Main heat exchangers 3 and 4 became also inoperable due to loss of power supply to their auxiliary water pumps caused by cable fires. In the same way, cable fires led to loss of 1 out of 2 trains plant cooling circuits. During the first 2 hours after the accident the operators had problems to control auxiliary feed water flow to main heat exchangers no. 1 and 2 because of control valve inoperability due to loss of instrument air. The fire also affected two main circulation water pipe expansion joints causing the entrance of sea water to the turbine building. The flooding propagated to the reactor building because of an open door. This flooding was fed by sea water, fire protection water, and the overflow of the unbalanced plant cooling circuit remaining in service damaging 4 shutdown cooling pumps and threatening the 2 turbo blowers that were operable. Sump pumps were inoperable due to the fire.

4.4.7 Switzerland

Two Swiss fire events are reported:

- In July 1971, before the plant started commercial operation, an oil fire occurred in the turbine house of the Mühleberg plant during tests. Oil leaking from a loose piping connection had ignited in the insulation of the live-steam line due to a catalytic reaction.
- In July 1988, a fault in the control electronics of one of the two generators of Beznau unit II disabled the generator and caused a turbine trip. The fault resulted from a small fire in the cabinet hosting the electronics, burning off the insulation of adjacent cables which in turn caused a short-circuit. The fire was put out with a hand-held CO_2 fire extinguisher.

No incidents involving smoke and heat impact on instrumentation electronics or electric equipment are known to have occurred in Switzerland, neither are cable fires known to have occurred in any Swiss NPP.

4.4.8 United Kingdom

Regarding information on operating experience, there have been no fires on United Kingdom nuclear power station which have led to a serious nuclear incident or notable degradation of safety system equipment. Neither are there any examples of incidents at nuclear power stations in the United Kingdom where the effects of smoke or heat have led to significant failures of instrumentation electronics or electrical equipment in the safety systems.

There have been no incidents in the United Kingdom of any significance of cable fires impacting on safety systems. There have been incidents involving electrical equipment (rotary converters, transformers etc.) where failure has included heat and smoke but the most significant effects arose from the plant failure itself in terms of its effect on electrical systems through operation (or malfunction) of electrical system protection.

4.4.9 USA

The Browns Ferry fire (March 22, 1975) provides the classic example of how loss of function and spurious signals can occur due to a cable fire /NRC 76/. In that fire, which was initiated by a candle flame igniting polyurethane foam in an improperly sealed penetration, control power was lost to a significant amount of emergency core cooling system (ECCS) equipment. The most intense part of the fire, which involved burning stacks of horizontal cable trays, covered an area roughly 3.3 m by 2.5 m in dimension. (Due to reluctance to use water, fire suppression was considerably delayed; the fire was declared out some 7 hours after it started). Power to all Unit 1 ECCS motors and valves was lost at one point in time. Furthermore, many instrument, alarm, and indicating circuits provided “false and conflicting indications of equipment operation”. For example, one panel indicated that all the ECCS pumps were operating, whereas another panel indicated that there was no need for this operation. The Browns Ferry fire represents one of the most serious events ever experienced at a U.S. commercial nuclear power plant; the conditional core damage probability, given that event, has been estimated to be about 0.4 /MIN 82/.

Regarding the effects of smoke, a recent NRC study /HOU 97/ indicates that none of the roughly 500 U.S. nuclear power plant fire events reviewed (covering the period 1965-1994) has involved risk significant equipment damage due to smoke. Note that most of these fires have not occurred in locations where sensitive electronics are expected to be common. Regarding the effect of smoke on less sensitive electrical equipment, some of the fires covered by /HOU 97/ have occurred in switchgear rooms, and “heavy smoke” has been noted in some of the associated Licensee Event Reports; however, equipment damage due to smoke was not noted in these reports. On the other hand, there have been some notable smoke-related outdoor fire events involving high voltage equipment. On November 14, 1983, a 34.5 kV bus explosion and subsequent substation fire at Oyster Creek caused the loss of 1 of 2 offsite power sources. Further, the deposition of smoke on cables and insulators of various substation components resulted in arcing and “affected the redundant offsite power supply”. The affected buses were isolated, de-energized, and grounded. On November 4, 1984, a catastrophic failure of an auxiliary transformer and a subsequent fire at Duane Arnold caused damage and carbon deposits on insulators for the startup transformer; this led to tripping of the transformer.

5. FIRE PSA APPLICATION DIFFERENCES

Probabilistic Safety Analysis is being applied within member countries for a variety of reasons and, in nearly all countries, against differing regulatory backgrounds. These differences can lead to significant differences in fire PSA approaches and emphasis. This chapter discusses a number of sources of these application differences. Note that the discussion does not cover fire PSA applications differences associated with different reactor ages, designs and operational practices; these differences can, in principle, be addressed using the methods described in Chapter 2. Note also that the discussion is not meant to be comprehensive or extremely detailed; it is intended to provide a quick overview of issues that can affect the interpretation and comparison of member countries' fire PSA results.

5.1 Objectives of Fire PSA

PSAs, as discussed by the Committee on Nuclear Regulatory Activities (CNRA) at its 1995 Special Issue Meeting, can be performed to address the following objectives:

- identification of weaknesses and possible modifications,
- support of plant operations (e.g., scheduling of maintenance),
- support of regulatory activities (e.g., prioritizing inspections),
- off-site risk management,
- other applications, e.g. prioritization of research and development activities.

Among the member countries, fire PSAs have generally been performed to satisfy a limited subset of these objectives. For example, fire PSAs have been undertaken in a number of countries in the context of backfitting and these have given insights resulting in plant modifications. In these situations fire PSA was found useful in identifying weaknesses and allowing the benefit of solutions to be assessed.

We note that the regulatory requirements regarding nuclear power plant fire protection in most member countries are deterministic, aided to a limited extent by probabilistic risk insights. Only in a few countries do probabilistic safety criteria play a more dominant role in the decision making process. Where probabilistic safety criteria are being used, an impact on the approach to fire PSA can be expected. This may show itself in terms of the need to demonstrate completeness of consideration. Where there are difficulties in meeting probabilistic criteria this may have a tendency to direct effort into increased deterministic analysis. In case of very conservative assumptions applied for the fire PSA the level of conservatism of the probabilistic assessment may be checked.

Within the ***U.S.***, where the first detailed NPP fire PSA (for a proposed gas reactor design) was performed in 1979 /FLE 79/ and commercial NPP fire PSAs have been performed since the early 1980s, fire PSAs have generally been performed as part of larger PSA or PSA-related efforts. To date, studies have been performed, either by the licensee or by the NRC, for every commercial NPP. A number of these studies have been performed to assess the fire contribution to CDF and, in some cases, public health risk. Many studies have been performed as part of the Individual Plant Examination of External Events (IPEEE) program, which was initiated in 1991. The primary goal of the fire risk portion of the IPEEE program was for plant licensees to identify plant-specific vulnerabilities to fire-induced severe accidents that could be fixed with low-cost improvements. Four supporting objectives were for licensees to, with respect to external events: 1) develop an appreciation of severe accident behavior; 2) understand the most likely severe accident sequences that could occur under full-power conditions; 3) gain a qualitative understanding of the overall likelihood of core damage and fission product releases; and 4) reduce, if necessary, the overall likelihood of core damage and radioactive material releases by modifying, where appropriate, hardware and procedures that would help prevent or mitigate severe accidents. Additional information on the objectives of the IPEEE program can be found in Supplement 4 to Generic Letter 88-20 /NRC 91a/.

At present, although only two IPEEE studies have identified fire protection vulnerabilities, over half of the IPEEE submittals have identified cost-effective improvements /NRC 97/. It is important to note that the IPEEE objective of identifying vulnerabilities (as opposed to estimating risk) has important implications on the study methods employed. This subject is discussed later in this chapter.

More recently in the ***U.S.***, interest has increased on the parts of both the NRC and industry in the broader use of PSA technology to deal with fire protection issues. This interest, which is consistent with the NCR's policy statement on the use of Probabilistic Risk Assessment (PRA) /NRC 85/[10], is supported by activities in a number of areas. One important general (non-fire specific) activity is the development of a risk-informed[11] framework for supporting licensee requests for changes to a plant's licensing basis, described in Regulatory Guide (RG) 1.174 /NRC 99/. This framework uses core damage frequency (CDF) and large early release frequency (LERF) as measures of risk. Among other things, it "requires"[12] evaluation of fire impacts during operation and shutdown, even for non-fire protection related changes (although it does not require a detailed fire PSA). Recent fire-protection specific applications activities where fire PSA is being used include the evaluation of the safety significance of certain fire protection issues (e.g., fire-induced circuit failures) and the evaluation of the safety significance of fire protection inspection findings. An industry consensus standard (NFPA 805) which uses risk information in evaluating a plant's fire protection program, is being developed under the auspices of the National Fire Protection Association (NFPA) /NFPA 98/. It is anticipated that the completed standard will use risk information in a manner that is compatible with RG 1.174 /NRC 99/.

In ***Germany*** and the ***United Kingdom***, fire PSAs have been performed within the context of a Periodic Safety Review. The main goal of the German fire PSA in this context is to supplement the deterministic analyses for a comprehensive overall fire safety assessment. The analysis includes a two-step process involving qualitative and quantitative screening.

In ***France***, the general objective of fire PSA is to supplement the deterministic analyses on which the reactor design and the plant's fire protection are based, in order to get a better appraisal of nuclear risks related to fires. The fire PSA highlights the strong points and the weak points of the installations and their operation in their various operating states, with respect to potential fire hazards. The fire PSA includes a screening study to provide such useful information as the zones for which the fire-induced contribution to the probability of core meltdown is not negligible. The fire PSA includes a detailed study of critical zones

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[10] /NRC 85/ states that the NRC intends to increase the use of PRA technology in "all regulatory matters to the extent supported by the state of the art in PRA methods and data."

[11] The NRC defines a risk-informed approach as follows: "A risk-informed approach to regulatory decision making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety" /JAC 99/.

[12] As with all regulatory guides, RG 1.174 /NRC 99/ describes an approach acceptable to the NRC; it does not impose requirements on licensees. In this discussion, the term "require" is used to indicate what the licensee should do to employ the RG 1.174 approach.

which provide useful supplementary information, e.g., the particular fire scenarios that have a dominant contribution to the core damage frequency. Sensitivity studies are also performed to identify modifications that can significantly reduce the probability of these scenarios.

In ***Finland***, fire PSA has been used to identify significant accident sequences, gain probabilistic insights, and compare alternative design improvements; to assist plant staff in gaining an understanding of their plant and the physical and time dependent progress of accidents; and to assist staff in recognizing the role of well timed measures to prevent accidents and mitigate their consequences, should they occur.

5.2 General Guidance for Performing Fire PSAs

Within the ***U.S.***, most fire PSAs performed to date have used the general methodology described by /APO 82/, /KAZ 85/, and the PRA Procedures Guide /ANS 81/. Additional guidance is provided in conjunction with the NUREG-1150 studies /BOH 90/ and the Risk Methods Integration and Evaluation Program (RMIEP) analysis of the LaSalle plant /LAM 93/. Note that the latter study explicitly accounts for the possibility of fire propagation between compartments. More recently, the Electric Power Research Institute (EPRI) has developed fire PSA guidance, one of whose objectives is to support the performance of IPEEEs /SAI 95/. This guidance builds upon previous fire PSA guidance and upon the EPRI-sponsored Fire-Induced Vulnerability Evaluation (FIVE) methodology /PLC 92/.

Guidance on performing the IPEEE assessments is provided in NUREG-1407 /NRC 91b/. The results of a preliminary review of IPEEE results /NRC 97/ show that most IPEEEs are being performed using the above fire PSA methods (especially /SAI 95/) or a combination of the FIVE methodology and fire PSA methods. In general, the identification of fire-induced vulnerabilities, which is the objective of the IPEEE program, does not require the same degree of analysis sophistication as the estimation of fire-induced CDF (although the two are clearly related). Therefore, fire protection issues are being treated in IPEEE analyses using methods with varying degrees of accuracy and conservatism or even, in some cases, with qualitative analyses.

Note that although the general guidance in /SAI 95/ is consistent with previous fire PSA guidance, NRC has, as part of the IPEEE review process, raised concerns with some of the specific guidance in that report. /LAM 97/ identifies a number of issues that can affect the ability of IPEEEs to identify fire protection vulnerabilities. The issues involve:

- human error probabilities used in screening,
- heat loss factors (used in FIVE and /SAI 95/ when determining if hot gas layer temperatures can reach damaging levels),
- fire growth modeling using experimental results,
- main control room (MCR) abandonment,
- dependencies in the suppression process,
- seismic-fire interactions,
- control system interactions associated with MCR fires,
- effects of smoke on manual fire fighting effectiveness,
- effects of fire suppressants on safety-related equipment,
- fire-induced special initiators (e.g., loss of service water),
- scenario screening criteria involving enclosed ignition sources,
- electrical cabinet heat release rates,
- scenario screening criteria involving transient ignition sources,
- scenario screening criteria involving non-combustible shields, and
- scenario screening criteria involving multiple targets.

An additional issue raised during the IPEEE review process concerns the piloted ignition temperature for IEEE-383 rated cables; tests at Sandia National Laboratories indicate that this temperature can be significantly lower than the values used in many fire PSAs to date /NOW 91/ (see Chapter 4). As a result of discussions between EPRI and NRC, EPRI will revise /SAI 95/ to support the completion of the IPEEE review process.

Many other member countries have based their fire PSAs on the above-mentioned procedures. In some cases, they have produced new procedures based on the above and other NRC documents.

In ***France***, the fire PSA screening study has been performed using a methodology derived from FIVE. This methodology has been adapted to take into account the French operational experience and the deterministic rules related to the fire protection of French NPPs. Concerning detailed fire PSA studies, the methodology involves, as described in Chapter 2, the establishment of a fire event tree which takes into account the possibility of fire or thermal propagation outside compartments. This fire event tree is quantified using detection and fire suppression probabilities based on operational experience and also the results of the fire modeling code FLAMME-S /FLAMME/. Another characteristic of this study is the detailed functional analysis that has been performed. This permits to quantify the human error of the operating team with a methodology similar to this of internal event PSA. The screening and the detailed study have been performed for BLAYAIS, unit 1 which is a 900 MW_e PWR. Due to the standardized plant series, only some differences of cabling exist. So this study will be easily extended to all the French 900 MW_e PWR plants.

In order to stipulate a uniform procedure within the Federal Republic of ***Germany*** and to define a clear frame with regard to objective and scope of the periodic safety review, regulatory guides have been developed supplemented by more detailed technical reports. These technical reports covering also fire safety aspects have been developed by a PSA specialists group. The documents have been published by the regulatory authority BfS /FAK 97/, /FAK 97a/ and also by GRS /LIM 97/; the guidance is based on an evaluation of state of the art PSAs.

In ***Spain*** a procedure has been developed for fire PSA based mainly on the NRC documents mentioned above. Information from other sources, including /MCC 85/ and /LAM 89/, has also been included.

5.3 Selected Issues

Although most fire PSA studies use the same general structure and approach, the differences in study objectives identified in Section 5.1 naturally lead to differences in specific applications. This section discusses a number of differences which can significantly affect the fire PSA results and insights. These include differences in the level of detail of analysis, screening procedures used, how multiple units and plants are treated, and the modes of operation addressed.

5.3.1 Fire PSA Level of Detail

As evidenced by the numerous fire PSA studies performed to date, differences in study objectives can easily lead to differences in the level of analysis detail among studies. For example, in the ***U.S.***, a number of IPEEE studies aimed at identifying fire protection vulnerabilities have been able to use conservative (and highly simplifying) analytical assumptions to demonstrate that fire does not contribute inordinately to overall plant risk. On the other hand, a number of studies intended to support risk-informed decision making have used state-of-the-art analyses to obtain more accurate estimates of the absolute risk contributions of different fire scenarios, in order to determine the risk impact of potential changes. Recalling that fire PSA is an iterative process that employs progressively finer tools, it can be seen that the differences in study objectives can lead to different analyst choices as to when the iteration process can be terminated. Consequently, great caution must be exercised when the results of current fire PSAs are used to develop risk perspectives and support decision making. In extreme cases, as demonstrated by one IPEEE, conservative analyses can yield entirely misleading pictures of risk, leading to unnecessary alarm on the parts of both the licensee and the regulator. (That IPEEE is currently being revised.)

Generally speaking, when simplifications are made in the fire PSA analysis, the most significant ones involve the equipment damage and plant response analyses, i.e., the $p_{ed,j|i}$ and $p_{CD,k|i,j}$ terms in Equation (1) of Chapter 2. In the equipment damage analysis, two common simplifying assumptions with potentially major impacts on the fire PSA results are: (i) all components in the room of fire origin are lost (which means that detailed fire modeling is not required); and (ii) cables whose exact routing is not known are assumed to be lost for all fire scenarios. In the plant response analysis, a common assumption with potentially major impact is that, given fire damage to key equipment, only a single success path can be credited. (This has been used by a number of IPEEE studies which do not couple their fire vulnerability analysis with a full internal events PSA model.) Of course, other simplifications that reduce the level of analysis detail, e.g., the use of simple, conservative fire models to predict equipment damage, can also affect the fire PSA results.

The preceding discussion focuses on assumptions and simplifications which lead to a conservative bias in results. It should be cautioned that there are also a number of common analysis simplifications, e.g., the neglect of smoke damage and the neglect of operator errors of commission, which lead to an optimistic bias. However, these simplifications tend to involve the fire PSA state-of-the-art and are beyond the scope of routine quantification efforts.

5.3.2 Screening

All fire PSAs, both detailed and coarse, employ some method of screening to eliminate rooms or areas not considered to generate significant nuclear safety hazard. The method of screening used can affect the results of the analysis. For example, a scenario screening frequency of 10^{-6} /ry may be adequate when identifying vulnerabilities, but screen scenarios whose cumulative contribution to risk may be important. Qualitative screening assumptions, e.g., that flame retardant cables cannot be involved in self-ignited cable fires, can lead to the screening of rooms that may be very important if a serious fire were to occur. A fire PSA that screens such a room may not adequately address the defense in depth considerations raised in such risk-informed decision making processes as that described in RG 1.174 /NRC 99/.

Both qualitative and quantitative screening studies have been carried out (***USA, Spain, Netherlands, Japan***), often based on the Fire Induced Vulnerability Evaluation (FIVE) methodology /PLC 92/. In ***U.S.*** fire PSAs, screening is typically done in a progressive manner. Qualitative screening is first done for fire areas and scenarios based on such issues as the potential for fire to either initiate a plant transient or damage equipment (including cables) needed to mitigate a transient. Quantitative screening is performed based on CDF considerations. Commonly used rules are provided in /PLC 92/) and /SAI 95/.

In ***Switzerland***, rooms considered for detailed analysis are sometimes determined by spatial dependencies analysis. When the failure of all equipment in a single location represents failure of the core cooling systems such that core damage or core damage and containment failure would be possible, then detailed fire analysis is carried out.

A similar approach is used in ***Finland***, where the first phase (Phase 1) of screening is performed by calculating conditional core damage probabilities for each fire event using the internal event PSA, taking into account the internal event dependent safety system failures and assuming that a fire in a specific room destroys all components. Fire suppression measures within the room are not credited. The dominant fire events identified during Phase 1 are analyzed in detail during Phase 2 when recovery actions, fire extinguishing systems and the failure criteria of the critical components as a function of time and temperature are taken into account.

In ***Germany***, the approach follows the existing guidelines for performing NPP specific PSA /FAK 97/. The screening process is based on a systematic qualitative screening followed by a quantitative screening (based on frequency). This results in an identification of critical rooms or pairs of rooms.

The systematic check of all rooms/room pairs of the plant can be done in two different ways: The critical fire zones can be identified in a qualitative or in a quantitative process (qualitative screening or screening by frequency). The qualitative screening allows - due to the introduction of appropriate selection criteria - the determination of critical fire zones with a limited effort. Applying the quantitative screening method, the critical fire zones are identified in a simplified event tree analysis.

The systematic examination of all rooms/room pairs or fire zones in the plant requires detailed knowledge of the plant specific situation.

The determination of critical fire zones starts with the identification of all rooms for which at least one of the following criteria is fulfilled:

(L) fire load higher than 25 kWh/m^2,
(S) room contains safety related equipment or cables of such equipment,
(O) room contains operational equipment, or sensing/control equipment of the reactor protection, or power limit control system, or cables of such equipment with the potential that a fire caused damage may lead to a plant transient/initiating event or to a manually operated scram[13],
(V) In case that a fire causes an unintentional opening of a safety valve or of the main steam bypass leading to a loss of coolant accident or a main steam line leak, this fire zone will be classified as a “critical fire zone”.

In a first step, those rooms are identified for which the first three criteria (L), (S) and (O) are simultaneously fulfilled. These rooms will be identified as “essential fire zones /rooms”. In a next step, for those rooms for which two out of these three criteria are fulfilled, adjacent rooms are checked to identify pairs of rooms that fulfil all three criteria. The “critical fire zones/rooms” and “pairs of rooms” are selected based on the further criterion that the fire leads to a safety related initiating event.

In the case that the quantitative screening process is applied, the hazard state frequency will be calculated in a simple but conservative analysis for each room with PSA related components and components leading to initiating events after the occurrence of a fire. The event tree analysis will be carried out for fire zones/rooms or room pairs with fire loads > 25 kWh/m^2. Only two elements are taken into account in this event tree analysis: The fire occurrence frequency and the conditional unavailability of the safety related equipment to mitigate the initiating event. All other branches of the event tree, like fire detection, fire suppression and fire spread to adjacent rooms are not considered. All PSA related equipment within the room is assumed to be damaged (probability of damage equal 1.0). Rooms are screened out, if the product of the fire frequency and the conditional unavailability of the safety related equipment is less than 1 % of the total sum of these products. The sum of contributions neglected shall not exceed 5 %.

A detailed quantitative analysis is performed for those rooms not screened out. For that purpose, a standard fire event tree is developed including elements for fire initiation, ventilation of the room, fire detection, fire suppression, both in the pilot fire phase and the fully developed fire phase, as well as fire propagation. This standard event tree is adapted to each critical fire zone or fire compartment. The tree is used to determine, for each fire event, the fire induced initiating events frequencies, the main contributors, and the calculated hazard state frequencies. This standard event tree must be adapted to each critical fire zone or room.

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[13] Operational equipment, such as hoists, lighting, ventilation, fuel storage pool cooling, coolant purification, etc. are not considered.

For the assessment of fire spread through walls, fire doors, dampers, cable penetration sealings, etc. into adjacent rooms different methods are recommended in /FAK 97/. One methodology applied is a simplified approach for the design of structural fire protection measures in NPP which has been developed based on the estimated overall fire load density and distribution of the fire load inside the fire compartment. The design method needs only a few empirical functions and design features which were derived from systematic fire simulations with an advanced multi-room zone model and which are easily understandable and applicable /HOS 96/.

For each critical fire zone/room the following results are obtained:

- frequency and nature of fire initiating events,
- list of damaged equipment, categorised corresponding to different damage states, and
- damage frequencies.

In ***France***, the plant locations (hereafter referred to as to critical zones) are identified by a process of selection. This process /BAR 98/ is based on the FIVE methodology that has been adapted to take into account the French operational experience and the particularities of the fire protection French approach. It involves: the establishment of the maximum fire propagation zone ("propagation zone") by analysis of the fire propagation risk; the assessment of the fire frequency in each propagation zone (F1); the estimation of the conditional probability of core damage (P2), given that a fire has occurred in a propagation zone and damaged all the equipment inside the respective zone; and the estimation of the conditional probability of fire damaging equipment in a propagation zone (P3). Knowing the values of F1, P2 and P3, it is then possible to estimate not only the probability of core damage (F3 = F1*P2*P3) due to fires in the propagation zone but also to identify those propagation zones requiring more detailed analysis.

Note that it is assumed that a fire occurring in a propagation zone will damage all the devices and equipment within it. Manual suppression is not credited during screening. Furthermore, a human error probability of 1 is used for the operating team ; the possibility of recovery by the safety engineer is credited if the information needed to apply the ultimate operating procedure is available.

The criterion for screening out propagation zone is based on the product of F3 (probability of core damage). The propagation zone is taken into consideration if this product exceeds a specified threshold (10^{-7}/ry). A detailed analysis addressing the competition between fire propagation and suppression is performed only if the compartment passes the screen.

5.3.3 Reference Plant Analysis

In countries with a limited number of plant designs (note that from a fire PSA perspective, the physical plant layout is as important as the nuclear frontline and support system design), detailed studies may not be needed for each individual plant. Instead, it may be sufficient to perform a detailed reference plant analysis, followed by a supplementary analysis of detailed design differences for plants within a particular group.

In ***France***, such an approach is being used. A reference unit is analyzed for each class of PWRs. Once the reference study is completed, the specific differences between units that are mainly differences of cabling are evaluated relative to the reference plant.

5.3.4 Addressing Different Operational States

In general, most fire PSAs performed to date have been for reactors operating at power. Those few studies that have been done to address low power and shutdown conditions have generally used the same basic approaches and tools used for dealing with fire issues (i.e., initiation, growth, detection, suppression, and barriers) during at-power conditions, although they have accounted for differences in model parameter values (e.g., fire frequencies) due to differences in operational states. Of course, the plant response portions of these analyses have accounted for issues unique to low power and shutdown analyses (e.g., changes in water inventory, decay heat level, train unavailabilities).

In the ***U.S.***, statistical studies have been performed to address the issue of differences in fire initiating frequencies due to differences in operating state. A study at Seabrook indicated that differences for fire frequencies in the compartments studied were not dramatically different from at-power to shutdown. A more recent NRC study corroborates this result; for areas outside of the containment, the area-specific average shutdown fire frequencies for 1965-1994 can differ from the at-power frequencies by a factor of 3, at most /HOU 97/. (Most of the variations are significantly smaller.) Within containment, the average shutdown fire frequency for the same time period is a factor of 7 higher. It should be noted that the Seabrook study and the NRC study employed somewhat different models. The Seabrook study distinguished between fires which could only occur during shutdown, those that could only occur during at-power conditions, and those that could occur during either operational mode. Since the last category was determined to have the largest number of events, by far, the lack of difference between operational and shutdown frequencies is not surprising. The NRC study looked at fire occurrences from a purely empirical point of view; fires that occurred during shutdown were used to assess the shutdown fire frequency and fires that occurred during at-power conditions were used to assess the at-power fire frequency, regardless of the cause of the fire.

Regarding fire PSA studies for low power and shutdown conditions, very few detailed analyses have been performed in the ***U.S.*** A detailed study for the Surry plant is documented in /MUS 94/. The study shows that the instantaneous CDF contribution from fire during mid-loop conditions can be significant on an absolute as well as a relative basis; the estimated fire-induced CDF of $2.7 \cdot 10^{-4}$/ry is over a factor of 20 higher than the at-power fire CDF. It is also over 50 % of the total instantaneous mid-loop CDF.

In ***France***, shutdown analyses is in progress. In these analyses, fire propagation zones in which a single train of a residual heat removal system can be lost cannot be screened out. Regarding fire frequency, it is generally considered that fires due to equipment which occur during at-power states can also take place during shutdown states. Therefore, the annualized fire frequency in a compartment for component-based fires is considered to be proportional to the duration of the shutdown state. Note that as maintenance-related human actions are more intense during shutdown, it is important to estimate the corresponding fire frequency. As for the power states, it is considered that the contribution of human action to fire frequency is uniform throughout the facility. The shutdown analyses also account for fire detector unavailability due to maintenance.

In ***Germany***, PSA studies for plant operational states other than full power (low-power and shutdown states), including fire PSA studies, are not regularly performed. In a first low power and shutdown fire PSA study for a German PWR, there were no indications for a significant increase of the fire risk for these plant operational states in comparison to full power operation. Nevertheless, the operating experience of German nuclear power plants indicates clearly that pilot fires occur more frequently during shutdown states, in particular during the annual refueling outage period. This is especially noticeable for the containment of the older type BWR plants, where the containment is protected by an inert gas atmosphere during power operation, a measure for which credit is taken during the fire PSA.

6. CONCLUSIONS

It is recognized that fire PSA provides a systematic, integrated method for evaluating the importance of fire protection issues, although the current fire PSA state of the art is not as mature as that for assessing the risk contributions of many other important accident initiators. The results of recent PSA studies have indicated that fire is an significant contributor to the overall core damage frequency in both new and old plant designs.

In old designs, both the relative and absolute fire risk contribution is considerably greater than in new ones. The absolute fire-induced core damage frequencies (CDF) range is 10^{-3} 1/a through 10^{-5} 1/a for old designs and 10^{-5} 1/a through 10^{-7} 1/a for newer designs. The fraction of fire contribution to the overall CDF is typically 10 - 70-% for old designs whereas it may be less than 10 % for new designs. These results reflect substantial improvements in plant lay-out design, resulting in better separation of redundant safety trains. Since the analyses of newer designs show small relative and absolute fire risk contribution, the major issues in the fire risk analysis concern mainly older plant designs.

To a large extent the main issues of fire PSA lay in the physical part of fire analysis and in the interface between the deterministic and probabilistic analyzes. In order to reduce the associated uncertainties, a lot of research work still needs to be done in the fields of several technologies.

One important area which probably needs more research efforts is the impact of smoke and heat on computerized safety critical I & C systems including components such as fiber optic cables and devices, circuit boards and memory chips etc. This issue is relevant to both new NPPs as well as old ones where analogue I&C systems have been replaced with digital technology.

Several methods of fire PSA are still immature or at least less well established in practical work. A lot of effort is still needed to upgrade the fire risk assessment methodology with focus on the physical fire analysis and on the interface between the probabilistic and physical models. In the following the maturity of different physical fire analysis methods is assessed and some recommendations for further development are given.

Fire simulation codes applied or available - Several fire analysis methods and codes are available and established in engineering use. These analysis methods and codes have been gradually adopted in the general building design, called performance-based design. General code and methodology development, good scientific basis and validation are essential also for progress in the nuclear field. In spite of the development of methodology, physical fire modeling methods are still often too time-consuming to be used broadly in PSAs due to the numerous rooms and failure scenarios to be analyzed in NPPs. Hence the interface between fire analysis codes and PSA needs more effective practical engineering tools. These tools are needed to cover the assessment of fire spreading, the vulnerability of rooms and components, the fire fighting actions´ time scales which are modeled in the full scope fire risk analysis, and also to reduce uncertainties in fire scenarios.

Review and assessment of fire ignition data - Even though -the statistical fire event data are fairly well available in plant scale, the room or component specific data are scarce or lacking. Due to a shortage of room and component specific data, numerous experiments have been performed simulating the development of fires in nuclear power plants. These tests have given relevant information on the behavior of fires in cable tray as well as electrical cabinet fires.

Nevertheless, there is a shortage of −physical parameters needed in the analysis to model the ignition thresholds of the target materials, the velocity of the flame front and the rate of the heat energy released on cables, cable trays, cable tunnels and cable spreading rooms and other electrical equipment (cabinets, control room panel etc.).

Quantitative knowledge of ignitability of cables and other equipment in the NPP environment needs more research effort in order to reduce the uncertainties in the analysis of ignition and fire development of equipment important to safety.

Modeling of fire spreading on cables or other equipment - Plenty of research efforts have been focused on overall cable fire phenomena. Experiments fit fairly well with *a posteriori*_simulations, and the blind *a priori* simulations also give qualitatively correct results. The qualitative understanding of cable fire process has been achieved but the analysis of −disturbances caused and identification of failure modes of cables affected by fire need more effort especially as to -cables of digital control systems.

Modeling of smoke production and spreading - Although references to experimental case studies and related simulation models and codes for analyzing the production and spreading of smoke are introduced in this report, the smoke production characteristics are not yet understood well enough because of many dependencies on materials, mode of combustion, ventilation etc. In principle, many fire simulation codes are suitable tools −for analyzing smoke spreading. So far −such an analysis has mainly been applied to assess the impact of -smoke spreading to control room.

Impact of smoke and heat on instrumentation electronics or electrical equipment **-** Although the report provides specific examples of the impact of smoke and heat on instrumentation electronics and electrical equipment, a very limited amount of data are publicly available and -only a few experimental results have been published. The impact of smoke on digital safety critical systems may cause a direct impact such as sooting and bridging etc. or indirect impacts such as interlocking and false control functions. Qualitative understanding of failure mechanisms of some equipment applications has been achieved and some quantification has been presented in recent PSA-studies. This is a developing field of study in the future because of the differences between equipment of different manufacturers and the rapid introduction of new technology in NPPs.

Impact of cable fires on safety systems - Several real incidents / accidents have occurred in NPPs and the failure mechanisms and consequences are fairly well analyzed and understood afterwards. Comprehensive analysis of all NPP PSA-relevant cables is a huge task if the locations and routes of single cables can not be exactly identified from plant documents by automatic data processing.

The reliability and function of fire protection measures are highly important in fire cases of NPPs. This issue may need more attention in the fire risk assessment so that passive features such as fire barriers (fire doors, cable and ventilation duct penetrations) and fire spreading probability through barriers are taken into account as well as plant operating mode, plant technical specifications, implemented maintenance, in-service inspection and fire protection practices. The active measures need to be modeled, including the reliability/unavailability of fixed fire detection and extinguishing systems and operational fire fighting arrangements (equipment, personnel, training). In this context it may be necessary to consider also the unavailability/performance probability of systems in the case of demand, single failure, performance criteria, time window for extinguishing initiation and respective damage extent of safety related compartments.

It is important to notice that the nuclear risk is dependent on the non-linear character of fire development and spreading. The heavy time-dependence of the consequences of fire emphasizes the importance of effective fire protection measures, which have to be modeled also. It is important to reduce uncertainties in all areas of fire scenarios, including fire protection measures, because well-modeled fire extinguishing activities reduce the need for using the most sophisticated fire models. Early intervention in the phase of pilot or smoldering fire, with fixed/automatic fire fighting systems of high reliability or fire fighters will effectively cut the consequences of fire.

As shown by a recent review of Individual Plant Examinations of External Events (IPEEEs) in the U.S, variations in analytical assumptions can lead to orders of magnitude variation in estimates of fire-induced core damage frequency, and qualitatively different risk insights are possible /NRC 97/. Such uncertainties can clearly affect a decision maker’s confidence in the results of fire PSAs and lead to, in hindsight, sub-optimal decisions.

/NRC 98/ identifies a number of areas where improvements in fire PSA methods, tools, and data will improve the ability of fire PSA to support decision making. These issues are discussed in greater detail in /SIU 97/ and in Chapter 2 of this report. The US NRC’s current research plans for addressing these areas are summarized in /SIU 99/.

One important application of fire PSAs is the identification and evaluation of the need for plant fire safety modifications. In some cases, however, the need for prompt upgrading of a plant system may be so evident that further analysis using sophisticated methods is not required to justify the improvement. In such cases the evident safety improvements should be implemented without delay. The time and cost of an elaborate analysis may even exceed the effort needed to implement the upgrade.

The shortage of fire analysis data is one of the major deficiencies in the present fire risk assessment. In order to facilitate the situation, it would be highly important to establish an international fire analysis data bank, similar to that set up by OECD for the CCF data collection and processing system (ICDE/CCF data bank at OECD). Such a data bank would provide fire event data on real fire cases, pilot fires (smoldering etc.) detected/extinguished before development, dangerous or threatening situations, reliability data on fire protection measures, and the unavailabilities of fire fighting systems, for example, due to component failures or operational errors.

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8. GLOSSARY

Combustion: Exothermic reaction of a substance with an oxidizer, generally accompanied by flames, glowing or emission of smoke or a combination thereof. /NFP 97/

Critical Zone: Propagation Zone where core damage is not negligible

Field Operator: Shift operator that carries out local actions

Fire: A process of Combustion characterized by the emission of heat accompanied by smoke or flame or both and/or rapid Combustion spreading in an uncontrolled manner in time and space. /IAE 92/

Fire Area: Used in a similar meaning as fire compartment (see fire compartment).

Fire Barrier: Walls, floors, ceilings or devices for closing passages such as doors, hatches, penetrations and ventilation systems, etc. used to limit the consequences of a fire. A fire barrier is characterized by a Fire Resistance rating. /IAE 92/

Fire Cell: A subdivision of a fire compartment in which fire separation between items important to safety is provided by fire protection features (such as limitation of combustible materials, spatial separation, fixed fire extinguishing systems, fireproof coatings or other features) so that consequential damage to other separated system is not expected. /IAE 92/

Fire Compartment: A building or part of a building comprising one or more rooms or spaces, constructed to prevent the spreading of fire to or from the remainder of the building for a given period of time. A fire compartment is completely surrounded by a Fire Barrier. /IAE 92/

Fire Damper: A device which is designed, by automatic operation, to prevent the passage of fire through a duct, under given conditions. /IAE 92/

Fire Load: The sum of the calorific energies which could be released by the complete Combustion of all the combustible materials in a Plant Location, including the facings of the walls, partitions, floors, and ceilings. /NFP 97/

Fire Resistance: The ability of an element of building construction, component or structure to fulfill for a stated period of time, the required load bearing function, integrity and/or thermal insulation and/or other expected duties specified in a standard fire resistance test. /IAE 92/

Fire Zone: Used in some Guidelines in the sense of subdivision (used in a similar meaning as fire cell) of larger fire compartment (fire area) or a separated zone of concentrated fire load within a fire compartment (fire area).

Non combustible materials: A material that, in the form in which it is used and under the conditions anticipated, will not ignite, support combustion, burn or release flammable vapor when subject to fire or heat. /IAE 92/

Physical Separation:

1. Separation by geometry (distance, orientation, etc.), or
2. Separation by appropriate barriers, or
3. Separation by a combination thereof. /IAE 92/

Propagation Zone: Plant Location where the spreading of fire to or from the remainder of the building is possible.

Protection system: A system which encompasses all electrical and mechanical devices and circuitry, from sensors to actuation device input terminals, involving in general those signals associated with the protective function. /IAE 92/

9. ACRONYMS

BfS: Bundesamt fuer Strahlenschutz (German federal sub-authority)

BMBF: Bundesministerium für Bildung und Forschung (German Federal Ministry for Education and Research)

BMU: Bundesministerium fuer Umwelt, Naturschutz und Reaktorsicherheit (German Federal Ministry for Environmental Affairs, Nature Conservation and Reactor Safety)

CDF: Core Damage Frequency

CFD: Computational Fluid Dynamics

CIB: International Council for Research and Innovation in Building and Construction

CSN: Consejo de Seguridad Nuclear (Nuclear Safety Council, Spain)

ECCS: emergency core cooling system

EPRI: Electric Power Research Institute (USA)

FHA: Fire Hazard Analysis

FIVE: Fire Induced Vulnerability Evaluation (USA)

FRA: Fire Risk Assessment

GRS: Gesellschaft fuer Anlagen- und Reaktorsicherheit (Germany)

HDR: Heissdampfreaktor

HSK: Hauptabtailung für Sicherheit der Kernanlagen (Swiss Federal Nuclear Safety Inspectorate)

IAEA: International Atomic Energy Agency

iBMB: Institut fuer Baustoffe, Massivbau und Brandschutz (German testing institution for building construction, materials and fire safety)

IPEEE: Individual Plant Examination of External Events (USA)

IPSN: Institute de Protection Surrete Nucleaire (France)

I & C: instrumentation and control

KfK: Forschungszentrum Karlsruhe (Research Center of Karlsruhe, Germany)

LOCA: loss of coolant accident

MCP: main coolant pump

MCR: main control room

NIST: National Institute for Standards and technology (USA)

NPP: nuclear power plant

NUREG: Nuclear Regulatory Commission Publication (USA)

NUPEC: Nuclear Power Engineering Corporation (Japan)

PORV: power operated relief valve

PRA: Probabilistic Risk Assessment

PSA: Probabilistic Safety Analysis

RHR: residual heat removal

SNL: Sandia National Laboratories (USA)

STUK: Säteilyturvakeskus (Radiation and Nuclear Safety Authority of Finland)

TU Braunschweig: Technical University of Braunschweig (Germany)

USNRC: United States Nuclear Regulatory Commission

VTT: Valtion teknillinen tutkimuskeskus (Technical Research Centre of Finland)

APPENDIX 1 - QUESTIONNAIRE ON CSNI/PWG5 TASK 97-3 “FIRE RISK ANALYSIS, FIRE SIMULATION, FIRE SPREADING, AND IMPACT OF SMOKE AND HEAT ON INSTRUMENTATION ELECTRONICS ”

Introduction

Fire risk analysis has become an integral part of PSA and the fires have been recognized as one of the major contributors to risk of nuclear power plants. The fire simulation methods which pose an important role in fire risk analysis are still largely questioned because of large uncertainties typically associated with the quantitative estimates of fire risks. The uncertainties embedded in fire risk analysis are of dual nature. On one hand there is shortage of basic data on fire ignition and parameters prevailing in fire spreading models, on the other hand there is a lack of knowledge and experimental data on vulnerability of equipment of different sort - electronic, electrical and mechanical. However, not only the impact of high temperature of fires but also the spreading of smoke has been well recognized in the three SESAR reports recently published.

The main objective of the task is to perform a state-of-the-art review of the most essential methods and practices vital to fire risk analysis. In order to provide a clear picture of the present practices and analysis methods, it is necessary to make a survey of the general framework of fire risk analysis. The scope of this part should however be limited and focused on few most essential analysis tools and methods. This part of the task is reflected by question 1.

Accordingly, the prime focus of the task is to concentrate on some special issues such as fire simulation, fire spreading, and impact of smoke and heat on instrumentation electronics which is reflected by questions 1 through 7 of the questionnaire.

QUESTION 1: Characterization of fire risk PSA Applications

Please list the applications on fire risk assessment in your country and describe in general terms the purpose and content of the studies and consider for instance the following items in your response.

- What is the objective of your fire risk analysis?
- How you deal with the reliability and associated data of fire protection measures in the analysis concerning
    - physical barriers
    - fire detection and suppression systems
    - operational fire fighting
- Has human reliability been analyzed differently for fire initiators? If so, how?

- How do you deal with dependencies (direct, indirect) between fire and the safety systems? What are the assumptions made and on which basis?
- As part of the description of procedures used, please describe how fire data is separated by plant operational state (e.g. full power and low power operation)

Further please answer the following more detailed questions

(a) Did you apply a special overall methodology or guideline? If yes, which one? If no, how was the actual program developed?

(b) What is the definition of the initiating event in case of fire incident?

(c) Give references to the data sources used for analyzing the fire incident frequencies in the study. (*Describe the procedure used to derive the scenario frequencies from fire incident frequencies)*

(d) Describe the applied screening method to identify the rooms/ plant areas that were analyzed in the detailed fire analysis.

(e) Give representative examples on how the analysis treats (1) fire ignition, fire loads, location, time, access of plant fire fighting force to the affected room and (2) fire growth (as per size and nature of the room), fire spreading from the affected room to other rooms and from one redundant train to another train. (*Describe the level of detail used in analyzing the respective scenario*).

(f) Depict please the basic approach (if any) used in analyzing the fire impact on safety systems.

(g) Further , how the plant fire protection measures are modeled, how the fire suppression and extinguishing systems and other available fire protection measures are modeled. How is the impact of smoke on fire fighting measures assessed?

(h) Characterize the level of conservatism / non-conservatism applied (or induced) used in different parts of analysis including the screening of rooms, allocating the fire incident frequencies etc.

(i) Other important remarks

QUESTION 2: Fire simulation codes applied or available

For each application described in question 1 identify and response (if not relevant give responses in general terms) to the following:

- which kind of fire simulation codes you have used in PSAs and/ or in other applications and for which fire objectives (and in which locations)
- which kind of fire simulation code development project are being in progress in your country
- please give examples of fire scenarios the fire simulation codes are utilized for
- What experimental validation is made for the codes
- Please reflect the conservative assumptions used in the code applications

QUESTION 3: Review and assessment of fire ignition data

Please provide relevant information on following questions:

(a) information on fire event cases
(b) fire development experiments made
(c) research on ignition of
  - cables
  - printed circuit boards
  - electronics cabinets

QUESTION 4: Modelling of fire spreading on cables or other equipment

Provide reference for the physical parameters used in your analysis to model ignition thresholds of the target material, velocity of the flame front and rate of the heat energy released on

- cables, cable trains, cable tunnels and cable spreading rooms
- electrical equipment of importance (cabinets, *control room panel* etc.)
- other equipment.

QUESTION 5: Modeling of smoke production and spreading

Describe any experimental case studies and related simulation models and codes used for analyzing the production and spreading of smoke. Provide respective references to e.g. *switch gear*, *printed circuit boards, habitability of main control room etc.*