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Approach to assess fire risk for nuclear power plants

Keywords

fire, risk assessment, screening, compartment configuration, databases, fire induced core damage states

Abstract

The results of the first fire risk assessments on an international level have shown that fires are one major contributor to the risk of a nuclear power plant depending on the plant specific fire protection concept. Therefore, fire risk assessment has today become an integral part of the probabilistic safety assessment of nuclear power plants in addition to deterministic analyses. Based on existing guidance documents a state-of-the-art approach for performing probabilistic fire risk assessment has also been developed in Germany. This approach has been exemplarily and completely applied to a German nuclear power plant with boiling water reactor for the full power states PSA. The general approach outlines the steps necessary for performing fire risk assessment and the prerequisites for a sound and traceable database.

1. Introduction

Depending on design and operational characteristics of a nuclear power plant (NPP), operating experience worldwide has shown that fire can be a safety significant hazard. Therefore, adequate arrangements have to be implemented to identify how fires can occur and spread, to assess the vulnerability of the existing plant structures, systems and components (SSC), to determine how the safe operation of a plant is affected, and to introduce or improve technical and operational measures to prevent a fire hazard from developing and propagating as well as to mitigate its effects. This has also to be investigated with respect to potential combinations of events and/or hazards as one of the lessons learned from the nuclear accident in Fukushima (Japan) in 2011.

Methods for analyzing existing NPP systematically regarding the adequacy of the implemented fire protection features can be deterministic as well as probabilistic ones. Probabilistic fire risk assessment (Fire PSA) has become an integral part of probabilistic safety assessment (PSA).

In particular on international level, fire events have been recognized as one major contributor to the risk of NPP depending on the plant specific fire protection concept.

In the past, most of the engineering work in designing NPP fire protection features has been performed on a deterministic basis.

In Germany, the use of deterministic fire hazard analysis is also current practice for reviewing the fire protection status of operating NPP. Probabilistic aspects have only been taken into account for decision making on a case-by-case basis. This is also valid for fire protection aspects. However, a more comprehensive fire risk assessment is recommended in the frame of periodic safety reviews (PSR) which are now a common tool in nearly all countries with commercial NPP.

2. General approach for Fire PSA

At present, it is international practice to perform Fire PSA as part and supplement of the internal events PSA (e.g., [1], [9] and [10]). However, up to the time being Fire PSA is still a methodology needing further development, in particular with respect to low power and shutdown states of the NPP.

Detailed recommendations for fire risk analysis in Germany including the calculation of fire frequencies and unavailability of fire detection and alarm features as well as data, e.g. on the reliability of active and passive fire protection means, are given in technical documents on PSA methods [11] and PSA data [12] supplementing the German safety guide on PSA.

In this context, a state-of-the-art approach for performing Fire PSA has been developed in Germany which has been exemplarily and completely applied to a German NPP with boiling water reactor (BWR) of the type BWR-69 for full power operation [24, 25].

It is the task of a Fire PSA to determine the annual frequency of fire induced core damage states (FCDF) of a NPP within the global analysis boundary defined in advance. Core damage frequencies (CDF) are the results of so-called Level 1 PSA. The CDF of all internal and external events are added up to gain the total CDF for the NPP under consideration and to compare it with prescribed or recommended safety goals.

The set of all compartments is the starting point of the fire analysis. The spatial plant partitioning should be performed in a way that all compartments characterize the global analysis boundary and that the compartments do not overlap. In this case, the annual frequency of fire induced core damage states of the plant results from the sum of all compartment related annual frequencies of fire induced core damage states.

It is assumed that compartments with a low fire load density do not impact the Fire PSA result. Such compartments are screened out before starting the detailed compartment and scenario specific analysis. The fire induced core damage frequencies of all the remaining compartments are determined in a first step using simplified and conservative assumptions. In the following, only such compartments must be analyzed in detail, for which in case of fire relevant contributions to the FCDF of the whole plant are to be expected.

A comprehensive Fire PSA has to be performed for power operation as well as low power and shutdown plant operational modes as part of Level 1 PSA.

For the analysis, it is assumed that the plant contains *n* disjoint spatial units (so-called compartments) for the plant operational states mentioned in *Table 1* according to [19].

The Level 1 Fire PSA aims on estimating the frequencies of fire induced damage states (in the most cases hazard states or core damage states) per reactor year (ry).

The total FCDF is the result of adding up the FCDF for the entire compartments and plant modes including full power as well as low power and shutdown states as given in equation (1):

$$FCDF = \sum_{i=1}^{n} \sum_{j=1}^{m} f_{ij} \qquad (1)$$

Table 1. Denominations of the fire induced core damage frequencies per compartment and plant operational state (from [19]).

Compartment i	***Plant operational state j***					
	1	…	j	…	m	$\sum j$
1	f_{11}	…	f_{1j}	…	f_{1m}	$f_{1\bar{j}}$
…	…	…	…	…	…	…
i	f_{i1}	…	f_{ij}	…	f_{im}	$f_{i\bar{j}}$
…	…	…	…	…	…	
n	f_{n1}	…	f_{nj}	…	f_{nm}	$f_{n\bar{j}}$
$\sum i$	$f_{\bar{i}1}$		$f_{\bar{i}j}$		$f_{\bar{i}m}$	*FCDF*
	f_{FP}	$f_{LP/SD} = \sum_{j=2}^{m} f_{\bar{i}j}$				

For estimating the overall plant FCDF (for the entire plant) the individual frequencies for each compartment *i* (*i* = 1, …, n) and each plant mode *j* (*j* = 1, …, m) have to be calculated.

For minimizing this effort, a stepwise approach is chosen. If a screening approach provides the result of f_{ij} exceeding a specific threshold a detailed analysis is carried out for estimating f_{ij} considering all the available information and data. A threshold value of 1.0 0E-07/ry has been used for the Fire PSA for full power modes.

First, each compartment is analyzed with respect to fire specific aspects. If this analysis gives the result that no fire impairing nuclear safety can occur under the boundary conditions of plant mode being analyzed the compartment can be excluded from further analysis for this mode.

For estimating the fire induced core damage frequency f_{ij} for a specific compartment *i* and a plant mode *j* the compartment inventory of this compartment as well as that of adjacent ones must be analyzed with respect to fire specific aspects and to the safety significance of the inventory.

The potential fire event sequence can be analyzed by several fire scenarios with {source *a*, target *z*}, where the fire source is located inside the fire compartment *i* to be analyzed, while the critical target *z* can be located in the same compartment or in an adjacent one.

The fire induced CDF f_{ij} is calculated corresponding to Figure 1. f_{ij} is the sum of the entire critical fire scenarios with {source *a*, target *z*} identified for the compartment *i* and plant operational state *j*.

In this context, a scenario is called a critical one if the target is an item, for which its failure causes an initiating event or which itself is a safety related component [19].

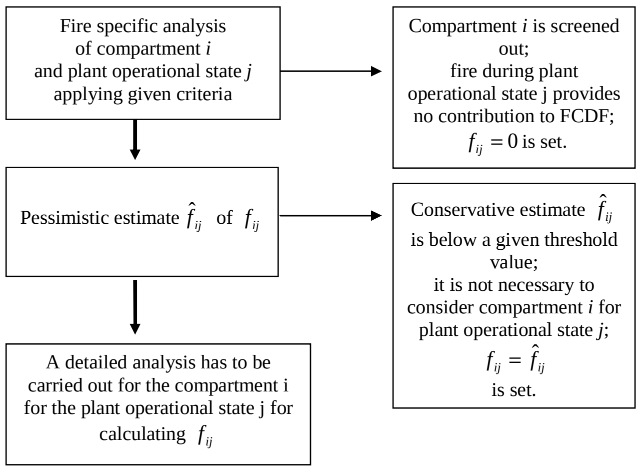

Figure 1. Scheme for estimating f_{ij} for compartment i and plant mode j.

Some simplifications are particularly applied for a conservative estimate $\hat{f}_{ij}$ of f_{ij} (see *Figure 1*).

One assumptions is that a fire inside a compartment i impairs the entire equipment in this compartment. Another one is that no fire source a is specified in the compartment i.

Table 2. Scheme and parameters for estimating fire induced damage frequency $f_{\{a,z\}}$ for a given plant state.

Characteristic Parameters		Analysis
a	fire source	Selection of a fire scenario with {source a, target z} in a compartment to be analyzed
z	fire target: A fire at the source a endangers equipment z.	
f_a	Fire occurrence frequency of fire source a	Calculation of f_a
$p_{z/a}$	Conditional failure probability for target z due to fire at source a	Estimation of $p_{z/a}$ by deriving and quantifying a fire specific event tree considering all aspects of fire suppression
$f_{z/a}$	Failure frequency of target z due to fire at source a	$f_{z/a} = f_a \cdot p_{z/a}$
IE	Initiating event (IE) due to failure or damage of target z	Estimation of IE depends on plant operational state to be analyzed; if the failure of target z does not result in an IE (z is safety related component), experts make a conservative assumption corresponding to approach given in the plant operating manual.
$p_{IE/z}$	Conditional occurrence probability of initiating event (IE) due to failure of target z	In many cases, estimation of $p_{IE/z}$ by expert judgment (simplified assumption: only one initiating event (IE) possible in case of target z failure)
$f_{IE/z}$	Occurrence frequency of an initiating event IE	$f_{IE/z} = f_{z/a} \cdot p_{IE/z} = f_a \cdot p_{z/a} \cdot p_{IE/z}$

As a result, the fire occurrence frequency of the compartment i is used for the calculation of $\hat{f}_{ij}$.

Table 2 provides the characteristic parameters needed for determining the fire induced CDF as well as the steps of the analysis for which they are needed for a given fire sequence {a,z}. This information is typically used in the frame determining f_{ij} for those scenarios not screened out before (cf. *Figure 1*, detailed analysis).

3. Steps and prerequisites to perform Fire PSA

3.1. Screening analysis as described in the full power operation PSA documents for PSR

The screening process to identify critical fire compartments is an important first step within fire risk assessment. Such a screening analysis should not be too conservative so that an unmanageable number of fire scenarios remains for the detailed quantitative analysis. However, it must be ensured that all areas relevant for nuclear safety are investigated within the quantitative analysis.

The recent German documents on PSA methods [11] and PSA data [12], elaborated for the performance of PSR, do only cover approaches for a Level 1 Fire PSA for full power operation.

According to these guidance documents, the systematic check of the entire plant compartments and/or compartment pairs can be performed in two different ways: Critical fire compartments can be identified within the frame of a qualitative (qualitative screening) or a quantitative process (screening by frequency).

The qualitative screening allows - due to the introduction of appropriate selection criteria - the determination of critical fire compartments with a limited effort.

Applying the screening by frequency, critical fire compartments are identified by means of a simplified event tree analysis.

The systematic analysis of the entire plant compartments and/or compartment pairs requires detailed knowledge of the plant specific situation.

3.2. Plant partitioning analysis

3.2.1. General approach

It is the task of Fire PSA to determine and to assess fire induced plant hazard states or plant core damage states for the NPP. A plant hazard state occurs if the required safety functions fail. A core damage state occurs, if also intended plant internal accident management measures fail.

In the following, the recently enhanced German Fire PSA methodology [20], [21] is explained for deriving fire induced core damage frequencies. An analogous approach is applied for obtaining fire induced plant hazard state frequencies.

For determining fire induced CDF it is in principle necessary to identify all those permanently as well as temporarily present combustibles (fire loads) in the plant, for which by any potential ignition a fire impairing nuclear safety might be initiated. For quantification of the consequences the annual combustible specific f_a has to be determined for each fire load a being present.

The fire induced CDF of the entire NPP is derived from the sum of f_a related to the entity of combustibles present.

In practice, it is impossible to determine f_a for each combustible being present in a plant. Therefore, several combustibles are grouped in an appropriate manner, i.e. locally interconnected plant areas, so-called compartments, are generated inside the buildings. In case of a partitioning of the entire plant into disjoint compartments not overlapping each other the annual FCDF is derived from the sum of all compartment related f_{i1}.

Practical considerations suggest analyzing compartments according to the plant specific identification system.

Depending on the compartment specific characteristics; a different partitioning of compartments may be necessary in exceptional cases, e.g.:

- Compartments with internally implemented fire barriers (e.g. long cable channels, cable ducts, etc.);
- Compartments with cable routes/raceways protected by wraps, coatings, etc. (such a cable duct or channel should be understood as a compartment itself);
- Extremely large fire compartments (reactor annulus, big halls such as the. turbine hall, staircases, etc.).

Performing Fire PSA starts by determining the building structures to be analyzed [20], [22]. This task requires some sensitivity, insofar as the effort of the analytical work can be drastically reduced selecting compartments by engineering judgement for the detailed analyses based on the knowledge of the plant in general, of the plant's fire protection in particular and, in addition, of the calculation methods used in the Fire PSA.

A compromise has to be made for the optimum partitioning between the greatest level of detail (analysis of each individual fire load) and too little details in the plant partitioning. The only requirement to be met is that each fire load considered has to be correlated only to one compartment.

3.2.2. Exemplary analysis for a BWR-69 type nuclear power plant in Germany

Five buildings of the entire NPP have been found to be representative for being analyzed within the Level 1 Fire PSA for full power plant states (for more details see [3], [16] and [18]) exemplarily performed for a German BWR-69 type NPP and given in *Table 3*.

The spatial plant partitioning for the plant analyzed is principally based on the given plant specific identification system. In a few exceptional cases deviations from this procedure have to mentioned, e.g. the subdivision of the very large reactor annulus into quadrants, or that of extremely long cable rooms and stairways. Some fire protected (sealed) cable ducts (raceways) without compartment numbers have been reassigned.

The analytical step of the spatial partitioning into compartments and the complexity of the following analyses can be simplified if the tasks are carried out building by building. It is possible to exclude those buildings from Fire PSA, for which it can be demonstrated that no components are present whose fire induced functional failure might impair nuclear safety (so-called safety related components). It should be simultaneously checked, if a fire in a compartment of such a building has the potential of spreading to any other building with safety related components.

Table 3. Spatial partitioning of the buildings relevant for Fire PSA in a BWR type reference plant analysed (from [6]).

Building	**Number of Compartments**	
	Using identification system	**To be analyzed**
Reactor Building	306	351
Switchgear Building	165	203
Turbine Building	82	106
Diesel Building	25	26

Partitioning of the NPP into compartments is an important step in performing Fire PSA. In the frame of this step of the analysis it is the major task to make available all the data and information necessary to calculate the compartment related f_{ij}.

3.3. Fire PSA database

For performing a quantitative fire risk assessment, a comprehensive database must be established which should, e.g., include initiating fire frequencies, reliability data for all active fire protection features, details on fire barriers and their elements, etc.

Detailed information is needed on potential ignition sources, fire detection and extinguishing systems, and manual fire fighting capabilities. Further information on secondary fire effects, safety consequences, analysis of the fire event's root causes, and corrective measures, etc. would be valuable. It should be pointed out that plant specific data are to be applied as far as feasible. However, generic reliability data have been provided as an additional input [5].

The database for performing a Fire PSA is developed based on the partitioning of all the buildings to be analyzed. Basis for the building selection is the entire nuclear power plant.

In particular, the following questions have to be answered by means of the collected data:

(1) Can an initial incipient fire ("pilot fire") develop to a fully developed fire spreading all over the compartment?
(2) Which damage can be caused by a fire inside the compartment?
(3) Is fire spreading to adjacent compartments possible?
(4) How can damage of components by the fire and its effects be prevented?

Question (1) mainly concerns type and amount of combustibles present inside the compartment and their protection (e.g. protective coatings and wraps for cables, enclosures of combustible lubricants, fuels, charcoal, etc.). Based on these data, the compartment specific fire load density (fire load per compartment floor size) can be estimated. A fire occurs only in case of ignition. Therefore, the entity of the permanently or temporarily available potential ignition sources (e.g. characterized by staff attendance frequency, availability of hot surfaces, amount of mechanical and electrical equipment being present) in the compartment have to be compiled for answering question (1).

The answer to question (2) mainly depends on the inventory of the compartment. This requires an allocation of the entire compartment inventory (components and equipment including cables) to the corresponding compartments. The required equipment functions as well as the potential consequences of their failure or malfunction have to be known. The inventory has to be classified. Distinguishing between important safety-related equipment (so-called PSA components) and equipment, for which their failure results in a transient or an initiating event (so-called IE components) is necessary.

For answering question (3) the entire NPP building structures must be included in the database. For each compartment, the fire compartment boundaries (fire barriers such as walls, ceilings, floors including all the fire barrier elements such as fire doors and dampers) as well as the connections between compartments (e.g., doors, hatches, ventilation ducts, cable raceways and their attributes) have to be known and documented. In this context, it has to be ensured that the questions (1) and (2) cannot only be answered for the compartment being analyzed but also for the entity of compartments adjacent to it.

Question (4) – to what extent damage by fire can be prevented – can only be answered based on information about those fire protection features being implemented in the initial fire compartment itself the compartments adjacent to it. This concerns all the potential means for fire detection and alarm a well as for fire suppression.

The Fire PSA database must meet the following requirements:

- Provision and compilation of compartment related primary data for all compartments in the entire NPP necessary to answer the questions (1) to (4);
- Compilation of data and information such as list of inventory or generation of sets of compartments applying different criteria (e.g. accumulation of compartments being openly connected to each other);

Derivation of compartment specific characteristics such as fire load density, fire occurrence frequency or fire spreading probability from one compartment to another based on the primary data for calculating $f_{i\,j}$ (see section 3.5 below).

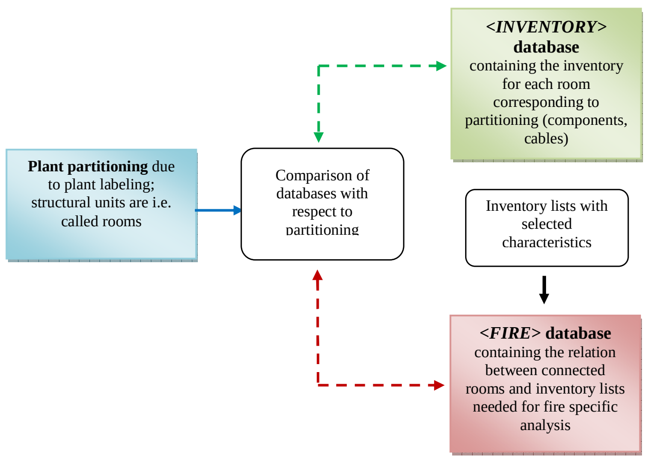

Figure 2. Fire PSA database (from [20]).

Such a database enables a flexible overview and examination of the primary data available and guarantees the traceability of the Fire PSA analyses.

The basic structure of the Fire PSA database as well as some important input and output parameters are depicted in *Figure 2*.

The information and database of a comprehensive Fire PSA consists of two databases [14], [17]:

- The database <INVENTORY> contains the compartment inventory;
- The database <FIRE> contains the compartment specific information needed for Fire PSA.

The <INVENTORY> database allocates the inventory to the before mentioned plant partitioning. There are only few prerequisites with respect to the database structure. Amount and quality of the inventory data depend on the plant labelling and the plant specific cable management system.

The <FIRE> database constitutes the ultimate information base for performing a comprehensive Fire PSA. This database with its functional features supports the performing Fire PSA but also utilization and assessment in the frame of a regulatory review of Fire PSA submitted by the licensee. In this context, it is irrelevant if the Fire PSA is performed for full power operational states or for low power and shutdown states.

More details on the use of these databases are illustrated in [20].

3.4. Simplified fire effects analysis within the screening by standardized fire simulations

Actual Fire PSA enhancements also aim on developing an approach for applying standardized fire simulations by means of relatively simple, publicly available zone models such as CFAST.

In this approach, which still has to be validated in the frame of a screening for an entire plant, generalized basic scenarios, so-called cases and sub-cases, have been defined in a first step for representative compartments and their characteristics with the corresponding dependencies of those parameters affecting the fire event sequence and the fire consequences significantly.

In a second analytical step, each fire event sequence has been characterized by means of so-called design fires carrying different input parameters including standardized time sequences and heat release rates taking into account those combustibles typically being present.

In this context, the significant parameters for binning of standard compartments into groups are floor size, room height, fire load and/or fire load density, - ventilation conditions (natural and forced ventilation), as well as the type of fire.

Examples of different standard cases are given in [14] and [17] and shortly described below.

For a set of typical fire compartments standardized fire simulations with CFAST have been successfully carried out.

For automating these simulations, specific program modules and interfaces for handling the input and output data as well as information retrievals are needed.

The main components for the automation are presented in *Figure 3* and *Table 4*.

Table 4. Modules for automated standardized CFAST fire simulations.

Module	Meaning / Task
GRS DB	Containing the geometric and fire related information on compartments in a MS ACCESS® database
allpar.xml	Alternative to the database containing all input data (XML format) needed für CFAST simulations
DBInterface	Interface for using data from alternative data sources
XMLInterface	Converting XML structure and the data included in the *allpar.xml* file to a C++-class; alternative to the direct data transfer by the *DBInterface*
GetData	Method oriented interface for sampling data stored in *ReadXML* and mapping them in a class structure
MakeFire	Estimating the parameters of a standardized HRR course using information from *allpar.xml* and storing them in a class / object
CreateFireFile	Creating the CFAST for the fire target *Fire.o*
CreateCFastInputFile	Writing the CFAST input file *CFast.in* by means of the *GetData* data structure
Fire.o	Fire object imported by the CFAST application
CFast.in	Containing all data on fire compartment, fire barriers, ventilations and systems engineering
CFast	Program logic starting the CFAST simulation
ReadData	Reading out time dependent output (e.g. hot gas temperatures)from the CFAST-output file *cfast.n.csv* storing them in an adequate class
ProcessData	Assessing the output data imported by *ReadData* depending on the program logic by means of criteria (e.g. effects on safety significant targets)
Simple.erg	Output text file E for process control in case of performing a Monte Carlo simulation; solving problem oriented equations for limiting states for being able to assess the effects of different parameters on safety significant targets
Complex.txt	Output text file for all simulation results for further processing and use of time dependent sequences of the individual simulations
MCSim (iBMB)	Generating user defined discrete random variables for Monte Carlo simulations and evaluating the distribution function of the output values providing mean values and standard deviations and the resulting safety margin β
Varpar.txt	Data file created by *MCSim* containing random values for those parameters, defined as ’stochastic’ ones in the input file *allpar.xml*
GUI	Grafic User Interface for calculations´ control

In this context, it has to be mentioned that a probabilistic calculation for individual compartments is possible, if distributions for single parameters can be provided.

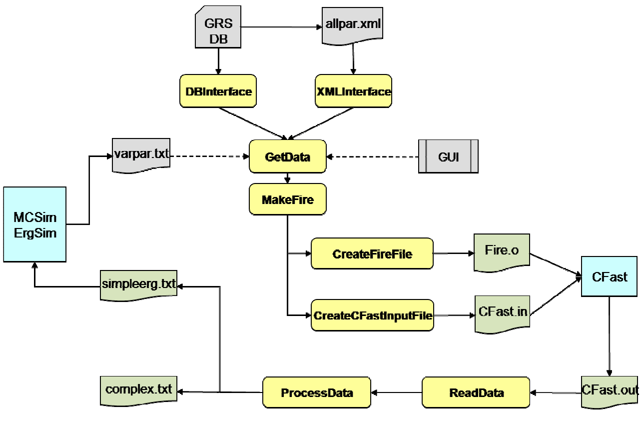

Figure 3. Approach for automated standard fire simulations with CFAST (from [14]).

3.5. Stepwise compartment fire analysis

Based on the data and information contained in the database described above, the fire induced core damage frequency f_{ij} has to be determined for each compartment i and each plant mode j as shown in Figure 1.

In the frame of the Fire PSA exemplary performed for a German NPP (boiling water reactor of the BWR-69 type), in total 351 compartments have been analyzed within the reactor building. For 287 compartments the fire load density has been found to be negligible. For all of the remaining compartments the frequencies of fire induced plant hazard states are pessimistically estimated. The sum of the estimated frequencies for 64 compartments equals 2.3 E-03/a. For 28 compartments, this frequency exceeds 1.0 E-07/a.

The sum of the frequencies for the entire compartments with a very small frequency value is equal 2.5 E-07/a so that the frequency value for the 28 compartments covers more than 99 % of the sum of all pessimistically estimated frequency values. Finally, the frequency of fire induced plant hazard states of the reactor building is estimated to be 3.8 E-06/a. This is the result of summarizing the plant hazard state by fire for all the 28 compartments. Considering the intended plant internal accident management measures fire induced core damage frequency for the reactor building is estimated to 7.8 E-07/a for the reference plant.

3.6. Frequency calculation for fire induced core damage states

The earlier mentioned necessary classification of the entity components of the NPP is extremely time-consuming in the run-up of estimating the fire induced CDF. As mentioned before, in particular, two classes of components have to be distinguished being significant:

- A component is called IE component, if its failure alone or together with additional failures of other components has got the potential to be an initiating event (IE).
- A component is called a PSA component, if its failure is regarded as a basic event in the fault trees of the corresponding Level 1 internal events PSA.

Depending on the fire growth a fire event may cause damage. The extent of the damage is characterised by the set of components affected/impaired. By means of assessing the extent of damage, in particular affecting IE components, it can be found, in how far the fire induced core damage may induce an initiating event (IE) modelled in the Level 1 internal events PSA.

The compartment related fire induced frequency of core damage states f_{ij} results from the product of the

- fire induced IE frequency and
- unavailability of system functions required to control the adverse effects of the corresponding IE.

The unavailability of the required system functions is calculated by means of the Level 1 internal events PSA plant model taking into consideration the failures of the components from the set of components affected by fire.

The GRS code CRAVEX is applied for determining those components failed by the fire and its effects and their failure probabilities, in order to perform these analyses in an as far as practicable automated manner.

CRAVEX combines fire specific and compartment specific data for determining the fire induced component failures and the PSA models for estimating core damage frequencies. It supplements the screening process as well as the detailed analyses, because the event and fault trees contained in these models describe in detail the interconnection between component failures and the occurrence of damage states.

The following input data are generated by means of the database (see *Figure 1*):

- Compartment specific fire occurrence frequencies,
- All probabilities of fire propagation to adjacent compartments,
- Inventory list of all compartments affected by fire.

Furthermore, compartment related f_{ij} can be estimated by CRAVEX (see *Figure 4*). The Level 1 internal events PSA plant model and the fire induced component failure probabilities are used as input data for the calculations.

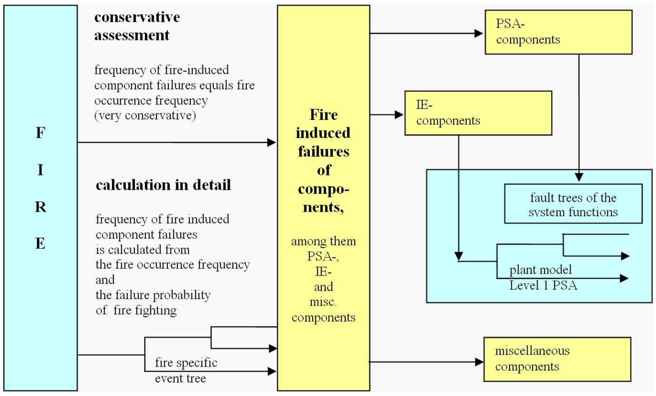

Figure 4. Estimation und calculation of f_{ij} (from [6]).

The approach of these calculations by CRAVEX is in principle depicted in *Figure 5* for an individual fire scenario. The fire occurrence is assumed inside a compartment C_i with $i = 1, \ldots, N$.

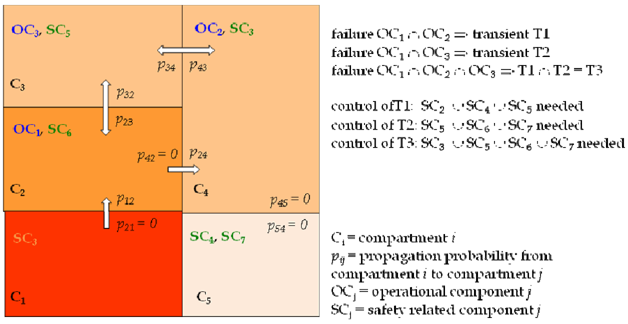

Figure 5. Compartment configuration with fire source, components, and propagation paths (from [6]).

The Level 1 internal events PSA plant model and the fire induced component failure probabilities are used as input data for the calculations.

3.6.1. Frequency estimation (pessimistic estimate)

The following assumptions are made for pessimistic estimations:

- All active functions of the components in the compartments affected by fire are failed. This is considered for the initial fire compartment as well as for all the compartments, to where the fire may propagate.
- The fire occurrence frequencies are known for each compartment. The compartment specific fire occurrence frequencies are determined by means of the Berry method [8]. The building fire frequencies needed as input for calculating compartments specific frequencies are estimated plant specifically.
- The so-called fire propagation probability is a pessimistic estimate of the probability of a fire propagating from a given compartment to an adjacent one. The fire propagation probabilities are automatically calculated for each pair of adjacent compartments. For that purpose pessimistic assumptions are made for the unavailability of fire detection and suppression as well as for the fire barriers separating compartments.

For estimating the compartment specific fire induced CDF it is additionally assumed that the active component functions fail corresponding to the fire occurrence frequency of the initial fire compartment, where the fire started, that means that the possibilities of fire detection and suppression are neglected.

3.6.2. Frequency calculation in detail

For a detailed quantification, the pessimistic assumptions used by the estimation have to be verified and possibly corrected taking into consideration detailed plant specific information as explained earlier. The realistic assessment of the fire induced damage frequencies is very important. For this assessment, fire specific event trees are developed and quantified. The development of fire specific event trees for compartments requires knowledge on the plant specific fire protection such as:

- Equipment including fire protection features (e.g. fire detection and alarm features, fire extinguishing systems and equipment, fire barriers and their elements), arrangement of combustibles, presence and type of potential ignition sources inside the initial fire compartment and adjacent compartments;
- Verification of potential ignition sources in the compartments;
- Examination of the fire occurrence frequency roughly estimated by means of the method of Berry based on the information concerning compartment inventory and the compartment characteristics (replacing the application of the more generic top-down-method within the screening by a bottom-up approach for estimating as far as possible realistic compartment specific frequencies);
- Plant specific unavailability of fire protection equipment in the compartments;
- Analysis of human behaviour and performance in case of fire;
- Using results of existing fire simulations or – in difficult cases - performing additional calculations for the compartment under consideration.

The reactor building of the reference plant having been analyzed (see [24]) consists of 351 compartments, among them 47 compartments on the building level 01. In 15 of the above mentioned 47 compartments the fire load density exceeds a prescribed threshold value during full power operational plant states. The analysis of possible compartment related fire damages gives the result that important PSA related components are present in 12 of the 15 compartments so that a fire in these compartments will cause an IE. The identified transients are exclusively transients induced by cable failures (e.g. by erroneous signals or failures of the power supply of solenoid valves of the main steam isolation valves).

The fire related PSA component failures are taken into account when calculating compartment specific fire induced CDF. The fire induced core damage frequency is revealed from a possibly modified fire occurrence frequency taking into consideration fire extinguishing means.

4. Conclusions

A state-of-the-art methodology for Fire PSA has been developed and successfully applied for a German NPP. This methodology is based on a combined multi-step qualitative and quantitative screening approach applying a comprehensive database specifically developed for the application within the frame of Fire PSA.

The approach being applied enables to automatically perform several analytical steps of Fire PSA. Some of the automatisms, e.g. the calculation of compartment specific fire occurrence frequencies or the probabilities of fire propagation to adjacent and further compartments, have been successfully implemented in the database.

Standardized input data files have been provided for other applications of the Fire PSA database, e.g. for determining fire induced core damage frequencies by means of the simulation code CRAVEX.

The Fire PSA database has meanwhile been adapted from full power plant operational plant states to low power and shutdown states. However, a complete application for a reference plant is still needed. In parallel activities to supplement the guidance given regarding fire PSA also for low power and shutdown modes are still ongoing. It should be noted that also on international level first more detailed guidance documents are still available only as a draft [23].

Another recent development focuses on fire induced cable failures and circuit faults, which are broadly discussed on an international level [9, 10]. In this context, a cable failure mode and effect analysis (FMEA) for all the PSA related cables has been developed [15] and tested for a fire compartment, which had been identified as significant in the frame of Fire PSA [7]. This leads to the requirement to enlarge the Fire PSA database considering additional data needed for cable FMEA and/or combining the compartment inventory matrix with the cable database of the FMEA. The activities for - implementing the cable FMEA approach in Fire PSA methodology are ongoing.

A further enhancement will cover the characteristics of compartments and components for supplementing the automatic data supply, such as data on the room heights for fire simulations with the zone model CFAST or the description of the ventilation systems for assessing smoke propagation.

In addition, an uncertainty and sensitivity analysis has been performed for the reference plant Fire PSA providing not only mean values for fire induced CDF but also for quantifying major uncertainties. This will increase the level of confidence of the Fire PSA results.

With respect to the statistical data applied in the frame of an as far as possible realistic Fire PSA it has to be pointed out that the existing national database, in particular data on compartment specific as well as component specific fire occurrence frequencies and on the reliability of fire protection features, has to be further improved and expanded. Moreover, the human influence has to be considered carefully.

The use of internationally available generic data (e.g. for fire occurrence frequencies), mainly from the U.S. and France, is not always appropriate for application within Fire PSA for German plants due to differences in design, inspection and maintenance. However, the German data being presently available do not always allow providing a verified database because only a very small amount of less than 40 fire events had to be obligatory reported to the national supervisory authorities.

Therefore, the OECD FIRE Database Project, which was started by OECD/NEA in 2003 to collect fire event data, comprising more than 400 fire events from twelve NEA member countries up to the time being may supplement performing Fire PSA for German NPP by further input data. First test applications of this database have been successfully performed in the last years (see, e.g., [2] and [4]).

Another important aspect is the continuous need for a variety of different data to generate and quantify fire specific event trees and to calculate the corresponding branch point probabilities and end states for core damage states. These typically include fire occurrence frequencies, fire spreading parameters, unavailability of active and passive fire protection features, and failure rates for actions by the personnel in case of fire.

In order to model the plant specific fire event trees in an as far as possible realistic manner, reliability data for those fire protection features needed for each sequence have to be estimated covering in particular technical reliability data such as unavailability per demand or failure rate per hours of plant operation for all active features, such as fire detection and extinguishing equipment as well as active fire barrier elements.

In the frame of the first Fire PSA performed for NPP in Germany in the eighties, statistical data prepared by the association of German insurance companies, from manufacturers and from the American nuclear insurance companies with respect to the unavailability of fire protection features were used. This unsatisfactory situation resulted in a first attempt in the late nineties to collect technical reliability data by analyzing the operational behavior of active fire protection systems and components in different German NPP which have been provided in [12].

Currently the database is being further updated. It is expected that the updated and extended data may provide further insights, e.g. regarding ageing effects or potential common cause failures of active fire protection features.

5. Outlook

In the light of the accidents at the nuclear power plants in Fukushima Daiichi on 11 March 2011, the German Federal Government decided to re-evaluate the risk of the use of nuclear power.

On 15 March 2011, the competent authorities of the Federal States in consent with the Federal Government ordered the license holders to take the seven oldest reactors whose start of commercial operation was before 1981 off the grid for a period of three months. A further NPP had already been shut down at that time.

The German Reactor Safety Commission, an advisory body to the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, reviewed the safety of all NPP, especially regarding their robustness against beyond design events.

As a result the German Atomic Energy Act was amended in August 2011. It states that the eight NPPs shut down in March 2011 will not resume operation. Moreover, the final shutdown dates of the remaining nine NPPs still in operation are explicitly fixed. The first of these remaining NPP has to be shutdown on 31 December 2015, the last three (all NPP of the Konvoi type) on 31 December 2022.

The improvement and further development of the fire risk assessment have been performed and will be continued in the future and are not influenced by the decisions described above because safety remains an important cornerstone.

This is due to the fact that on the one hand, due to the German decision in 2011 to finally shut down in total 8 of the 17 NPP in Germany, the issue of this unplanned long-term final shutdown states which may last over five or more years requires continued and new types of assessments and oversight decisions. On the other hand fire risk also remains as one of the main events of NPP in the decommissioning phase.

Therefore, an updated or supplementary document of [11] is intended to be issued at the end of 2013. This document should also contain the necessary guidance with respect to Fire PSA for low power and shutdown states.

At the time being, the update of technical reliability data has been completed for only one NPP [13]. The entire updated and expanded data will be available in summer 2013.

Moreover, the three German nuclear safety standards regarding fire protection are currently under revision and are planned to be issued in 2015.

All these documents will then be the basis for the fire risk assessment in the frame of the remaining periodic safety reviews and for case-by-case decisions.

Further investigations are needed to cope with potential combinations of fires with other plant internal and/or external hazards, in particular internal flooding, explosions, seismic hazards and aircraft crashes. While internal flooding may be a consequential event resulting from fire, aircraft crash and seismic events may either cause fires or the fire may occur independently. Explosions can initiate a fire, occur independently or result from the fire event.

Up to the time being validated approaches for considering such combinations of fires with other events or hazards in the Fire PSA model do not exist. However, more recent operating experience from NPP worldwide has indicated a need for enhancing the PSA models in this direction.

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