Advanced Methods for Screening in Fire PSA

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ABSTRACT

Fire PSA is part of the comprehensive safety reviews to be mandatory performed in several steps since 2002 for nuclear power plants in Germany at a time interval of ten years. In the recent technical document on PSA methods supporting the German PSA Guideline an advanced screening approach is outlined. This method has meanwhile been successfully applied in the frame of a Fire PSA for a German boiling water reactor plant for full power operation states.

This paper presents the Fire PSA methodology using the German technical guidance documents. The main focus is on the boundary conditions and application criteria for the compartment selection process ("screening"). The theory of this screening approach is demonstrated by a practical example from the Fire PSA for the reference nuclear power plant designed to earlier standards.

BACKGROUND

Comprehensive safety reviews of nuclear power plants (NPP) at a time interval of ten years are mandatory in Germany since April 2002. Probabilistic safety analysis (PSA) for full power operational plant states including Fire PSA is part of such a comprehensive safety review.

Fire PSA has to be performed in several steps. First step is a selection process ("screening") providing critical fire areas, where a fully developed fire has the potential to both cause an initiating event and impair the function of at least one nuclear safety related component or system. In the recent technical guidance document on PSA methods [1] supporting the German PSA Guideline an advanced screening approach is outlined. This methodology has meanwhile been successfully applied in the frame of a Fire PSA for a German boiling water reactor (BWR) plant of the type BWR-69 designed to earlier standards [2], [3].

SCOPE AND OBJECTIVES OF ADVANCED METHODS FOR SCREENING IN FIRE PSA

Fig.1 provides a principal scheme of the methodological approach for Fire PSA. It is the main objective of this paper to explain how the number of compartments, for which a detailed analysis to calculate the fire induced core damage frequency (CDF) has to be performed, can be minimized without loosing fire-relevant compartments. In a first step, the plant buildings must be divided into compartments. It has to be ensured that the partitioning has no omissions and no overlap. For that purpose, some rules have been developed to support the analyst by this more or less subjective partitioning task and will be described in the paper.

It could be shown that most of the processes for carrying out a Fire PSA can be performed automatically, if a sound base of primary data and information is available. In its second part, the paper gives an overview, which data must be available for an automatic screening process illustrated again by using the results of the above mentioned BWR Fire PSA as an example.

PLANT PARTITIONING ANALYSIS

It is the task of a Fire PSA to determine the annual frequency of fire induced core damage states F_{CD} of a nuclear power plant.

For determining F_{CD} it is in principle necessary to identify all the permanent as well as the transient fire loads (combustibles), if, due to any ignition, a fire impairing nuclear safety is possible. For quantification of the consequences the annual frequency of fire induced plant core damage states $F_{CD,(combustible)}$ has to be determined for each combustible being present. The total annual frequency of fire induced core damage states F_{CD} for the complete nuclear power plant can be derived from the sum of the annual frequencies of fire induced core damage states $F_{CD,(combustible)}$ related to the entire fire loads.

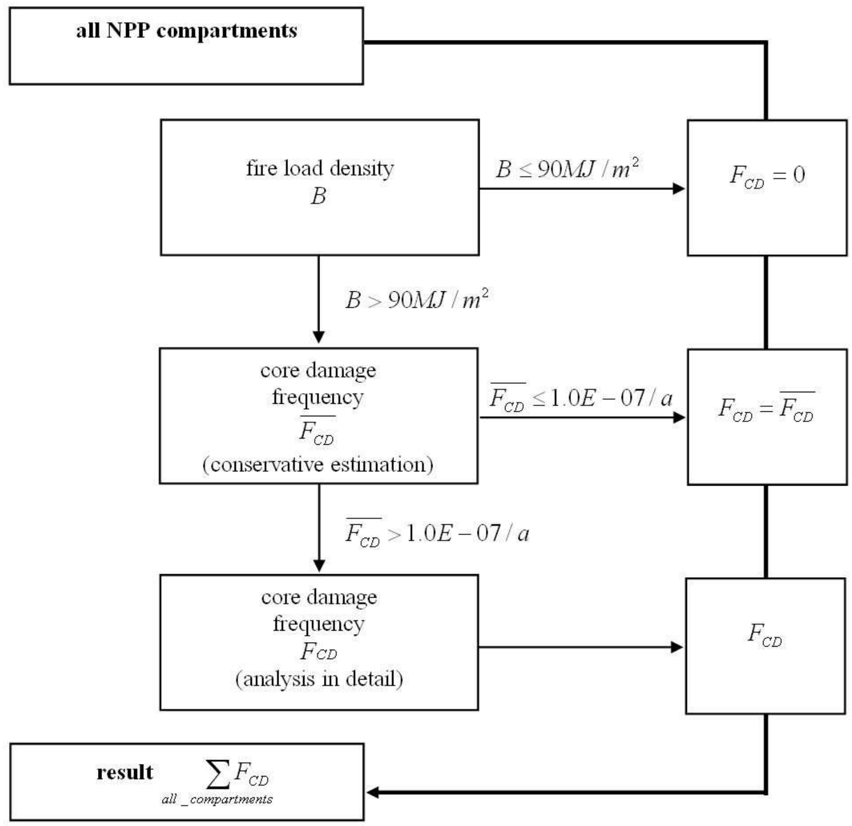

Fig. 1. Stepwise analysis of the compartments

In practice, it is impossible to determine the annual frequencies of core damage states for each combustible being present at a plant. Therefore, several combustibles are grouped in an appropriate manner, i.e. locally connected plant areas are generated. These areas are named "compartments" in the following.

In the case that the entire NPP is partitioned such that the compartments are not overlapping each other the total annual frequency of fire induced core damage states of the plant F_{CD} is derived from the sum of all compartment related annual frequencies of fire induced core damage states $F_{CD,(compartment)}$.

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 (long cable channels/ducts);
- Compartments with cable routes/raceways protected by wraps, coatings, etc. (e.g. cable channels and/or cable ducts should be understood as compartments itself);,
- Large fire compartments (reactor annulus, large halls, staircases, etc.).

Carrying out a Fire PSA has to be started with the determination of the building structures to be analyzed. This task requires some sensitivity, insofar as the effort of the analytical work can be drastically reduced selecting compartments by engineering judgment 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 found for the optimum partitioning between the highest level of detail (analysis of each individual fire load) and a plant sub-division being too little detailed. The only requirement to be met is that each fire load considered has to be correlated only to one compartment.

There are two screening steps which have to be performed:

- First, the compartments with low fire load densities have to be eliminated (screened out), and
- Second, a conservative estimation of the core damage frequency for all the remaining compartments has to be provided.

This process should be carried out as far as possible in an automatic manner. Therefore, a specific Fire PSA database has been developed and implemented in the approach.

FIRE PSA DATABASE

The database for performing a Fire PSA is developed based on a compartment partitioning of the NPP. In particular, the following questions have to be answered for all the compartments by means of the collected data:

(1) Can an incipient fire expand to a fully developed fire?
(2) What damage can be caused by a fire inside the compartment?
(3) Is fire propagation to adjacent compartments possible?
(4) How can damage of components by the fire and its effects be prevented?

Question (1) mainly concerns the type and amount of combustibles being present inside the compartment. Based on these data, the compartment specific fire load density can be determined. Only in case of ignition a fire occurs. Therefore, all the available potential ignition sources (characterized by e.g. staff attendance frequency, availability of hot surfaces, amount of mechanical and electrical equipment present) in the compartment have to be compiled.

The answer to question (2) mainly depends on the compartment inventory, which means there must be an allocation of the inventory (components and equipment including cables) to the compartments. The intended equipment functions as well as the consequences of malfunctions or failures have to be known. The inventory has to be classified. The related classifications are safety related equipment (so called PSA components) and equipment, for which the failure induces a transient or an initiating event (so called IE components).

For answering question (3) the entire building structures of the NPP must be included in the database. For each compartment, the fire compartment boundaries (fire barriers such as walls, ceilings, and floors including all the fire barrier elements, such as doors or dampers, etc.) as well as the connections between compartments (e.g. doors, hatches, ventilation ducts and their attributes) have to be known. In this context, it has to be ensured that the questions (1) and (2) can also be answered for all compartments adjacent to the initial compartment.

Question (4) – to what extent damage by fire can be prevented – can only be answered with information about the fire protection features being implemented in the fire compartment and its adjacent compartments. This concerns all the potential fire detection and alarm features as well as the fire fighting systems and equipment.

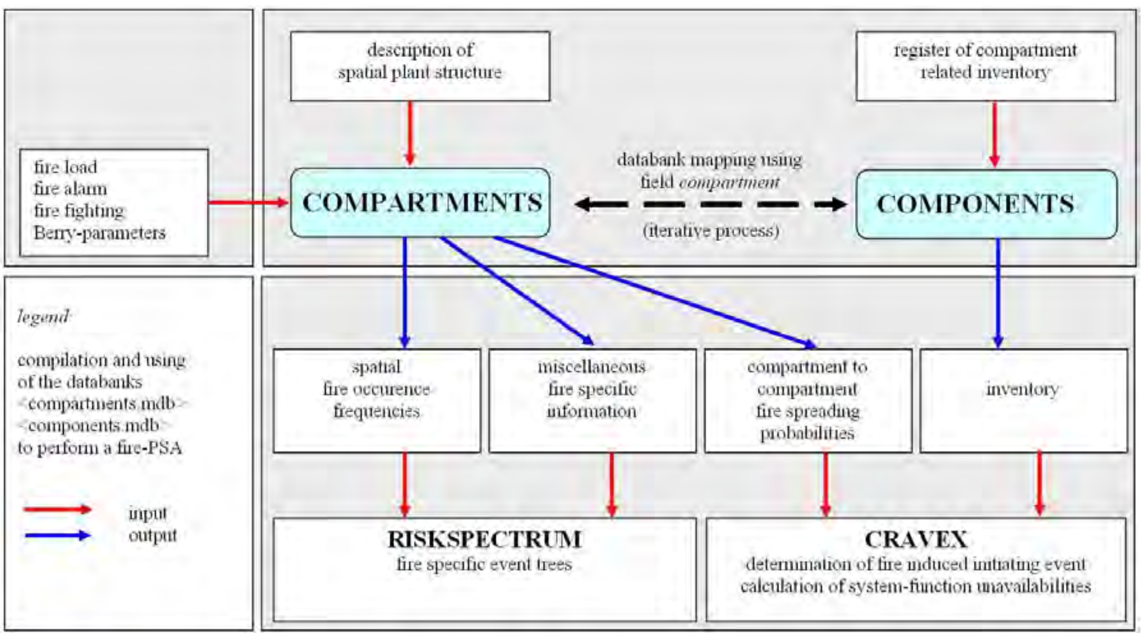

Fig. 2. Fire PSA Database

The Fire PSA database must meet the following requirements:

– Provision and compilation of compartment related primary data for all compartments of 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 as basis for calculating FCD, (comp).

Such a database enables a flexible overview and examination of the primary data available and guarantees the traceability of the Fire PSA analyses. The principle scheme of the Fire PSA database as well as some important input and output parameters are outlined in Fig. 2. Details can be found in [4].

FREQUENCY CALCULATION OF FIRE INDUCED CORE DAMAGE STATES IN THE SCREENING PROCESS

The compartment related frequency of core damage states $F_{CD,(compartment)}$ results from the product of the fire induced initiating event frequency and the unavailability of system functions needed to control the negative effects of the correspondent initiating event. The unavailability of the needed system functions is calculated by means of the internal events PSA plant model taking into consideration the failures of the components from the set of components affected by fire.

The simulation code CRAVEX has been developed for performing the analyses in an automatic manner as far as practicable. CRAVEX can be used to determine the fire induced failed components and their failure probabilities. The following input data are generated by means of the database: compartment specific fire occurrence frequencies, all probabilities of fire spreading to adjacent compartments, and the inventory list of all compartments affected by fire. The second task solved with the code CRAVEX is the determination of the compartment related frequencies of fire induced core damage states. The level 1 internal events PSA plant model and the fire induced component failure probabilities are used as input data.

A pessimistic estimation of fire induced core damage states $F_{CD,\ (compartment)}$ is needed for all compartments with a fire load density exceeding 90 MJ/m^2. If the pessimistically estimated value is less than 1.0 E-07/a, a detailed analysis of fire induced core damage states is not needed.

The following assumptions are specified for conservative estimations:

- All active functions of the components in the fire affected compartments 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 method of Berry [5]. The required fire occurrence frequencies for the buildings are derived plant specifically or, if the operating experience does not reveal sufficient data, generically from national and/or international nuclear specific databases.
- The so-called fire spreading probability is a conservative estimation of the probability of a fire propagating from a given compartment to an adjacent one. The fire spreading probabilities are automatically determined for each pair of adjacent compartments applying pessimistic assumptions for the unavailability of fire detection, fire fighting and the fire barriers separating compartments.
- For calculating $F_{CD,(compartment)}$ within the screening process, it is additionally assumed that the active component functions fail with the fire occurrence frequency of the compartment, where the fire initially started, that means that the possibilities of fire detection and fire fighting are not taken into account during screening.

EXEMPLARY ANALYSIS FOR A BWR-69 TYPE NUCLEAR POWER PLANT IN GERMANY

A complete Fire PSA has been performed for a German reference plant with BWR of the type BWR-69 designed to earlier standards, see [3]. In the following, the approach applied in the frame of this Fire PSA for full power operation is exemplarily outlined for the reactor building without the containment, which could be excluded from the analysis due to the fact that it is filled with inert gas during this operational state of the plant.

The reactor building of the reference plant (without the containment) consists in total of 351 compartments, among them 47 compartments on the level 01 (elevation - 6.5 m). In 15 of the above mentioned 47 compartments the fire load density exceeds the threshold value of 90 MJ/m^2 mentioned in [1] for being screened out. The analysis of potential compartment related fire damages reveals the result that IE-components are present in 12 of the 15 compartments, so that a fire in these compartments may cause an initiating event. The identified transients are exclusively 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 failures of PSA components are taken into account calculating the frequencies of compartment related hazard states. The frequency of damages due to fire is calculated with a fire-specific event tree. Therefore the fire occurrence frequency from the screening step is verified and all the fire fighting means available in the compartment are taken into consideration.

Table 1. Results for selected compartments of one elevation inside the reactor building of the reference BWR-69 type NPP

Compartment No.	Are there IE-components (1 = yes, 0 = no)	Are there PSA-components (1 = yes, 0 = no)	Fire load density [MJ/m^2]	Fire frequency [1/a]	$F_{HS,(compartment)}$ [1/a]
1	1	1	100	1,1 E-05	1,4 E-07
2	1	1	450	4,5 E-04	6,2 E-06
3	1	1	200	1,1 E-03	6,7 E-05
4	1	1	720	1,1 E-03	7,0 E-05
5	1	1	150	1,1 E-03	7,0 E-05
6	1	1	150	1,1 E-03	1,9 E-05
7	0	0	100	1,1 E-03	6,6 E-11
8	1	1	220	6,9 E-05	1,0 E-06
9	1	1	160	6,9 E-05	9,7 E-07
10	1	1	400	6,9 E-05	6,9 E-05
11	1	0	620	6,9 E-05	2,3 E-10
12	0	0	100	1,1 E-03	2,1 E-08
13	0	1	260	6,8 E-04	3,6 E-11
14	1	1	190	6,8 E-04	6,3 E-06
15	1	1	800	6,8 E-04	1,1 E-05

Some numerical results are given in Table 1. The results given in the table are so-called plant hazard states frequencies $F_{HS,(compartment)}$. A plant hazard state occurs if the designed safety functions fail. The core damage frequency can be derived from the plant damage frequency considering the potential failure of the intended accident management (AM) measures. In the example, there are 11 compartments with $F_{HS,(compartment)}$ exceeding a screening threshold value of 1.0 E-07/a without consideration of fire extinguishing means. For these compartments detailed analyses with in-depth investigations considering realistic fire scenarios including fire detection and extinguishing means have to be performed.

RESULTS FROM THE EXEMPLARY FIRE PSA

The screening procedure for the in total 5 buildings with in total 728 compartments of the reference plant needed to be analyzed after a first qualitative elimination of all the other buildings and plant areas results in total in only 81 compartments, for which detailed analyses with in-depth investigations including - where necessary - fire simulations have been performed. As a result of these analyzes, the sum of the calculated frequency of fire induced plant hazard states for these 81 compartments has been estimated to be 8.3 E-06/a (see [4]), the corresponding fire induced core damage frequency to be 1.5 E-06/a. The highest contribution to the overall core damage frequency results from the reactor building (without the containment qualitatively excluded) with a value of 7.8E-07/a followed by the switchgear building with a CDF value of 4.6 E-07/a.

The above mentioned results of the Fire PSA for a German BWR-69 type NPP during full power operation are based on some pessimistic assumptions, e.g. the failure of all components and cables inside a fire compartment in case of fire, pessimistic fire propagation assumptions, etc. In this context, it has to be mentioned that it has been principally assumed for the analysis that any fire will propagate from its initial fire compartment to all adjacent ones with a positive probability. Thus, the compartment-to-compartment fire spreading probabilities have been determined pessimistically on the basis of fire specific compartment features.

CONCLUDING REMARKS AND OUTLOOK

A screening analysis being conservative enough not to eliminate fire scenarios contributing to the overall fire induced core damage frequency but also limiting the analytical effort and thus also possibilities of mistakes in the analysis is essential for a Fire PSA. Qualitative and/or quantitative screening approaches are therefore required by a variety of internationally available guidance documents.

The most recently advanced screening methodology developed for nuclear power plants provides an as far as necessary conservative approach combining qualitative and quantitative criteria using as far as feasible realistic but as far as necessary pessimistic assumptions has meanwhile been successfully validated within the frame of a comprehensive Fire PSA for a nuclear power plant with boiling water reactor in Germany during full power operation. By means of this approach, it was possible to reduce the number of compartments to be investigated in further detail to a manageable amount and thus limit the time period and manpower needed for performing the Fire PSA.

The existing approach is intended to be further improved and adapted to the specific boundary conditions of low power and shutdown plant operational states in the near future. Additional efforts are ongoing to improve the existing methods for the second step of the analysis, the detailed analyses for the fire specific event tree analysis, and, in particular, to develop an advanced methodology for a complete uncertainty and sensitivity analysis being meanwhile implicitly required in the German technical guidance document on PSA methods also for Fire PSA, but not yet existing.

Finally, a more reliable and exhaustive fire event database is necessary for more realistic Fire PSA results. Thus, the possibility of using an advanced and larger database will be useful for the assessment of safety features on a national basis. For example, the data in Germany presently available do not allow establishing a useful database because only thirty reportable fire incidents out of 5715 obligatory reported incidents were identified by end of March 2007 for the German nuclear power plants. In this context, the OECD FIRE project may assist to provide further input, which can be applied in the frame of fire PSA to be performed in the future.

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