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FIRE RISK ASSESSMENT IN GERMANY

H. P. Berg
Bundesamt für Strahlenschutz (BfS), Salzgitter
Germany

Abstract

Quantitative fire risk assessment can serve as an additional tool to assess the safety level of a nuclear power plant (NPP) and to set priorities for fire protection improvement measures. The recommended approach to be applied within periodic safety reviews of NPPs in Germany starts with a screening process providing critical fire zones in which a fully developed fire has the potential to both cause an initiating event and impair the function of at least one component or system critical to safety. The second step is to perform a quantitative analysis using a standard event tree has been developed with elements for fire initiation, ventilation of the room, fire detection, fire suppression, and fire propagation. In a final step, the fire induced frequency of initiating events, the main contributors and the calculated hazard state frequency for the fire event are determined. Results of the first quantitative fire risk studies performed in Germany are reported.

1. Introduction

Experience has shown that fire can be a safety significant hazard. Thus, the regulators expect the licensees to justify their arrangements for identifying how fires can occur and spread, assessing the vulnerability of plant and structures, determining how the safe operation of a plant is affected, and introducing measures to prevent a fire hazard developing and mitigate against its effects if it should nevertheless develop.

Methods to analyse existing plants systematically regarding the adequacy of their existing fire protection equipment can be deterministic as well as probabilistic. Fire risk assessment has become an integral part of PSA and, at international level, fires have been recognised as one of the major contributors to risk of nuclear power plants, e.g. in the USA [1].

In the past, most of the engineering work in designing fire protection measures in German nuclear power plants has been performed on a deterministic basis. Moreover, the use of deterministic fire risk analysis is current practice in Germany to review the fire protection state of operating NPP. It should be underlined that these reviews have led to comprehensive backfitting and upgrading measures including structural fire protection measures (e.g. fire barriers) as well as the active fire detection, alarm and extinguishing features and administrative fire protection measures (for manual fire fighting) resulting in significant improvements in fire safety, in particular in case of a NPP built to earlier standards.

However, as it can be seen from other areas the probabilistic approach provides different insights into design and availability of systems and components and supplements the results from deterministic analyses. Thus, probabilistic considerations have been taken into account for decision making on a case-by-case basis. A more comprehensive fire risk assessment is recommended in the frame of periodic safety reviews in Germany.

For fire risk assessment in Germany, a qualitative or quantitative screening process is proposed to identify critical fire zones followed by a quantitative event tree analysis in which the fire caused hazard state frequency will be determined. The models proposed have been successfully applied in complete and partial fire risk studies for German nuclear power plants.

2. Regulatory guidance for fire risk assessment

The PSA Guide contains reference listings of initiating events for NPP with PWR and BWR respectively which have to be checked plant specifically with respect to applicability and completeness. Plant internal fires are included in these listings.

Detailed instructions are provided in the technical documents on PSA methods [2] and PSA data [3] which are shortly reported. These technical documents have been developed by a working group of technical experts chaired by the BfS (Bundesamt für Strahlenschutz - Federal Office for Radiation Protection). The German regulatory guidance as it is available now has been restricted in scope to comprise only applications where sufficient practical experience is available and a reasonable consensus between the parties involved is achieved. However, the PSA working group is still in force to further develop and amend the technical documents, also with regard to fire specific aspects.

2.1 Screening analysis

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

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 (qualitative screening) or in a quantitative process (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/m2,
(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 (Operational equipment is not consedered,
(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 those neglected contributions shall not exceed 5 %.

2.2 Quantitative analysis

For the quantitative part of the fire risk assessment a standard event tree has been developed with nodes for fire initiation, ventilation of the room, fire detection and suppression, both in the pilot fire phase and the fully developed fire phase, as well as fire propagation. This standard event tree must be adapted to each critical fire zone or room.

For the assessment of fire spread through walls, fire doors, dampers, cable penetration sealings, etc. into adjacent rooms different methods are recommended in [2]. 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 [4].

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.

If a complete plant specific PSA is available, for each initiator the fire induced frequency will be summed up and specified as input to the corresponding system event tree of the level 1+ PSA. Additionally, the damage state of the equipment has to be introduced into the fault trees. The plant hazard state frequency is calculated for each transient as the sum of the single event core melt frequencies. The total plant hazard state frequency is obtained by summarising the contributions of all transients. The requirement to use only qualified PSA codes has also to be fulfilled for the fire PSA. Moreover, validated fire simulation models and codes have to be used in case of deterministic fire hazard analysis and probabilistic fire risk assessments.

2.3 Data base

In order to perform a quantitative fire risk assessment, a basic data base must be established which should, e.g., include initiating frequencies, reliability data for all fire protection measures, fire barriers, etc. Detailed information is needed on ignition sources, detection and extinguishing systems, manual fire fighting, stationary fire suppression systems; further information on secondary effects, safety consequences, analysis of the cause of the event and corrective measures, etc. would be helpful. It should be underlined that plant specific data are to be used as far as possible.

As one contributor to fire specific PSA input data, reliability data for the active fire protection measures are required for the application in the fire specific event tree analysis. These data needed to be estimated are unavailabilities per demand or failure rates per hour of plant operation for those components or systems belonging to the active fire protection means.

Active fire protection measures to be studied include all the fire detection equipment, that means all types of fire detectors including their power supplies, the alarm panels and boards, fire doors and dampers and the stationary fire extinguishing systems including the extinguishing media supplies.

In Germany, for two different types of reactors (PWR and BWR) unavailabilities and failure rates were estimated. These reliability data given in tables 1 and 2 and are updated values of those provided in [5, 6] by processing additional information. The scattering factor k given in these tables is correlated to the failure rates.

The data on potential failures or unavailabilities per demand of the respective fire protection measures were gained from the plant specific documentation of inspection and maintenance. The assessment whether the detected findings are estimated as failures or only as deficiencies or deteriorations requires a deep insight in the plant specific operating conditions for the fire protection means and needs careful engineering judgement.

Table 3 gives an overview of the generic failure rates for active fire protection features revealed from the plant specific data estimated.

Table 1: Plant specific reliability data estimated for active fire protection features in a German BWR reference plant

Active fire protection feature	Inspection period	Scattering factor k	Failure rate λ (t) [1/h]	Unavailability per demand
Fire alarm boards:				
detection drawers	3m, 1a	3.31	$6.7 \cdot 10^{-8}$	$1.2 \cdot 10^{-4}$
detection lines	3m, 1a	3.29	$2.3 \cdot 10^{-8}$	$4.0 \cdot 10^{-5}$
Fire detectors:				
automatic	1a	1.25	$1.4 \cdot 10^{-7}$	$1.3 \cdot 10^{-3}$
press button	1a	2.55	$1.1 \cdot 10^{-7}$	$9.4 \cdot 10^{-4}$
Fire dampers	3m, 1a, 3a	1.13	$2.3 \cdot 10^{-6}$	$6.6 \cdot 10^{-3}$
Fire doors	1a	1.36	$4.9 \cdot 10^{-7}$	$4.3 \cdot 10^{-3}$
Dry sprinkler extinguishing system (total failure)	6 m, 1a, 5a	3.14	$2.2 \cdot 10^{-7}$	$9.9 \cdot 10^{-4}$
Dry sprinkler extinguishing system: automatic actuation failure only	6m, 1a, 5a	1.35	$4.1 \cdot 10^{-6}$	$1.8 \cdot 10^{-2}$
Wet sprinkler extinguishing system	6m, 1a, 5a	7.62	$6.4 \cdot 10^{-8}$	$3.2 \cdot 10^{-4}$
Gas extinguishing systems (CO_2)	6m	7.64	$1.9 \cdot 10^{-6}$	$9.2 \cdot 10^{-3}$
Stationary fire pumps	1m, 1a	7.64	$1.9 \cdot 10^{-6}$	$1.4 \cdot 10^{-3}$
Wall hydrants	6m, 1a	7,64	$3.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-4}$

Table 2: Plant specific reliability data estimated for active fire protection features in a German PWR reference plant

Active fire protection feature	Inspection period	Scattering factor k	Failure rate λ (t) [1/h]	Unavailability per demand
Fire alarm boards:				
detection drawers	3m	7.63	$3.0 \cdot 10^{-8}$	$7.4.10^{-5}$
detection lines	3m	7.63	$1.7 \cdot 10^{-8}$	$4.3 \cdot 10^{-5}$
Fire detectors:				
automatic	1a	1.75	$4.8 \cdot 10^{-8}$	$4.2 \cdot 10^{-4}$
press button	1a	7.63	$3.4 \cdot 10^{-8}$	$3.3 \cdot 10^{-4}$
Fire dampers	6m	1.39	$6.6 \cdot 10^{-7}$	$2.9 \cdot 10^{-3}$
Fire doors	1a	1.44	$7.1 \cdot 10^{-7}$	$6.3 \cdot 10^{-3}$
Dry sprinkler extinguishing system (total failure)	3m, 1a	7.63	$1.3 \cdot 10^{-7}$	$3.2 \cdot 10^{-4}$
Dry sprinkler extinguishing system: automatic actuation failure only	3m, 1a	1.26	$1.3 \cdot 10^{-5}$	$2.9 \cdot 10^{-2}$
Stationary fire pumps	1m, 1a	7.64	$1.3 \cdot 10^{-6}$	$8.5 \cdot 10^{-4}$
Wall hydrants	1a	1.75	$8.5 \cdot 10^{-7}$	$7.4 \cdot 10^{-3}$

Further detailed information on plant specific and generic estimation of unavailabilities and failure rates for active fire protection measures can be found in [6].

Most of the estimated values for the technical reliability of active fire protection measures represent realistic data for the failure rates of these systems and components in German NPP. They can be applied in the frame of PSA studies instead of conservative data from past nuclear specific reliability studies as well as instead of generic values available from data of the insurance companies for the reliability of comparable fire protection means in non-nuclear industry, both being available up to the time being. The data have been adapted in the PSA data document [3].

Table 3: Generic reliability data estimated for active fire protection features in German NPP

Active fire protection feature	Failure rate λ (t) [1/h]	Scattering factor k
Fire alarm boards:		
detection drawers	$9.1 \cdot 10^{-8}$	4.24
detection lines	$4.0 \cdot 10^{-8}$	4.34
Fire detectors:		
automatic	$1.2 \cdot 10^{-7}$	2.88
press button	$1.2 \cdot 10^{-7}$	3.60
Fire dampers	$1.9 \cdot 10^{-6}$	2.93
Fire doors	$7.5 \cdot 10^{-7}$	2.92
Dry sprinkler extinguishing systems (total failure)	$3.4 \cdot 10^{-7}$	4.32
Dry sprinkler extinguishing system: (automatic actuation failure only)	$1.1 \cdot 10^{-5}$	2.90
Wet sprinkler extinguishing systems (total failure)	$1,4 \cdot 10^{-7}$	5.67
Gas extinguishing systems (CO_2)	$4.5 \cdot 10^{-6}$	6.60
Stationary fire pumps	$3.9 \cdot 10^{-6}$	4.19

3.2 Applications

In 1995, a complete fire PSA as part of the level 1+ analysis for the German Unterweser NPP (PWR) has been performed. The procedure outlined in [2] has been applied consistently. From a total of approximately 1100 rooms, 120 essential fire rooms/compartments have been identified and, based on the most important criterion that the fire has to cause an initiating event, 70 critical fire zones were identified using the qualitative screening process. These have been condensed to 13 representative critical rooms for which a quantitative analysis has been performed [7]. The quantification of the fire induced initiating events has resulted in two classes:

- rooms in which a fire directly leads to an initiating event; in this class, 8 rooms are classified. Only 3 of these 8 rooms gave countable contributions to the hazard state frequency,
- rooms where a fire results in a plant transient and where an initiating event is caused due to the stochastic failure of the operational equipment necessary to prevent an incident; in these rooms, no countable hazard state frequencies are calculated ($< 10^{-8}$/a).

The fire induced hazard state frequency amounted to a value of about $5 \cdot 10^{-7}$/a for the whole plant [7]; thus, the fire event contributes to about 6 % of the total plant hazard state frequency (taking into account internal and external events). Main contributors are fires in the electronic rooms of the switchgear buildings.

For the German Isar I nuclear power plant (BWR) a complete fire PSA has been performed, too [8]. The quantitative screening process has been applied to approximately 500 rooms in the reactor building, turbine building, switchgear building, emergency diesel generator room and service water intake structure. 172 critical rooms have been identified and analysed. The relation of local fire frequencies was calculated according to Berry's method. The fire induced hazard state frequency of about $6.3 \cdot 10^{-7}$/a for the whole plant resulted mainly from 14 single rooms and 7 room pairs (calculation including fire spreading analysis). In order to get more information on the consequences on the safety in case of system unavailability the analysis of common cause initiators has been performed for 15 rooms with a contribution of more than 1% to the system unavailability. Main contributors are fires in switchgear buildings.

After completion of a full-power PSA for the Grafenrheinfeld 1300 MW_e PWR nuclear power plant a probabilistic fire risk assessment has also been performed on the basis of [2, 3]. In a first step, 1250 rooms were condensed into 350 fire zones. As a result of the determination of possible fire induced initiating events, 204 PSA relevant zones have been identified and pairs of fire zones have been formed. Further considerations have shown that a screening analysis should be carried out for 117 room pairs. Within the screening analysis the event sequences for the room where a fire is assumed are quantified under the boundary condition that the components of the adjacent fire zone also fail with a probability of 1 caused by the fire. Based on the results, those zone combinations are selected for further considerations where a relevant contribution (i.e. hazard state frequency of > 10 % of the sum of the frequency of the single fire zone) is to be expected. As a result, 19 pairs of fire zones have to be quantified. For the selected reference plant, a value of $3.5 \cdot 10^{-7}$/a for the plant hazard state frequency has been calculated [9] 62 % of which result from fires without fire propagation. Also this fire PSA shows that the fire risk does not provide a dominant factor (about 12 %) to the total occurrence frequency of a plant hazard state with an amount of $2.5 \cdot 10^{-6}$ for the full power operational state. The successful fire fighting in the initial phase of a fire is one of the most significant factors for the low plant hazard state frequency. A detailed consideration shows that the area of a main feed water pump oil supply where additional cable trays are located is the main contributor to the hazard state frequency.

4. Concluding remarks

Fire risk assessment, as an important part of PSA, has not yet achieved the same level of methodological maturity as being typical for some other disciplines of PSA. Major issues in the fire risk analysis are to a large extent correlated with the physical part of fire analysis and the interface between the deterministic and probabilistic analyses. Thus, more investigations are needed in the areas of determination of fire frequencies, the appropriate modelling of human actions in response to a fire event, and analysis of the dynamic fire development for a better understanding of the fire growth phenomena and the plant response to fire occurrences and recovery actions.

Apart from that, fire risk assessment meanwhile represents an important tool to get a more comprehensive picture of the safety level of a NPP regarding its fire protection arrangements.

The first fire PSA that have been performed for NPP in Germany show that the contribution of plant internal fires to the total plant hazard state frequency is low and that these events do not represent - for the investigated plants - significant contributors to the plant hazard state frequency compared to the results from, e.g., US plants. However, the results of the fire PSA can be used to analyse in detail and assess findings of the deterministic part of the periodic safety review, to determine the necessity and urgency of safety improvements and to set priorities for fire protection improvement measures.

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