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Probabilistic safety analysis of external events in german nuclear power plants

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ABSTRACT
Procedures for performing PSAs of external hazards have been developed based on ABB's and international experience and successfully verified in complete and partial NPP applications, showing that such analyses can be performed with a reasonable effort. In general, earthquake, flooding and air plane crashes may provide non-neglectable contributions to the core damage frequency.

INTRODUCTION
The current draft of the German PSA guiding documents, which can be applied in the frame of periodic safety reviews, asks for a full scale PSA level 1+ for German NPPs including internal fires. External (natural and man induced) events will be considered in the course of future extensions of the PSA guide when methods for conducting such probabilistic analyses are available. Therefore, possible procedures for the natural hazards, such as earthquakes, flooding from rivers and the ocean and the man induced hazards, such as air plane crash and explosion pressure waves, are proposed and shortly described in the following.

EARTHQUAKE
The German NPPs are located in regions of different seismic activities. Compared with other regions, for instance, California and Japan, the seismic activity in Germany is about 2 orders of magnitude lower, but still not negligible and has therefore to be assessed in site specific safety considerations.

The proposed method for a probabilistic earthquake analysis follows corresponding analyses already performed in the USA and other countries. The analysis is based on calculations that have been performed within the deterministic earthquake analysis of the buildings and components of the plant [1] for design and licensing purposes. For all buildings and components of class I, corresponding to the German KTA rule 2201.1 [2], a fragility analysis is done, determining the relationship between the peak ground acceleration and the probability of failure (see fig. 1). These fragility curves will be derived from the median acceleration value $\breve{A}$, the logarithmic standard deviations β_R (representing the inherent randomness about the median) and β_U (representing the uncertainty in the median value). An overall safety factor F_{OS} is determined, which represents the total safety margin, taking into account not only the calculated safety margin of the original stress analysis but also all safety margins "hidden" in conservative assumptions such as neglecting the inelastic energy absorption or conservative values of material strength etc. The peak ground acceleration corresponding to the safe shutdown earthquake A_{SSE}, which has been

used in the original stress analysis, is multiplied by the overall safety factor to obtain the median ground acceleration capacity $\check{A} = A_{SSE} \bullet \check{F}_{OS}$, at which the probability of failure is 50 %.
The entire fragility curve for any component and the uncertainty of that curve can be expressed as the product of the median ground acceleration $\check{A}$ and 2 random variables ε_R and ε_U with a median of unity representing the above mentioned uncertainties: $A = \check{A} \bullet \varepsilon_R \bullet \varepsilon_U$.
Out of the family of the fragility curves, the use of the composite fragility curve $A = \check{A} \bullet \varepsilon_C$ with median $\check{\varepsilon}_C = 1$ and $\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$ is recommended for application. The construction of that curve follows the formula

$$f'(A) = \Phi \left[\frac{\ln A/\check{A}}{\beta_C}\right] \quad (1)$$

with $f'(A)$ = Conditional probability of failure at any acceleration
ϕ = Standard Gaussian cumulative distribution function
β_C = Logarithmic standard deviation describing the total variability from both inherent randomness and modelling uncertainty

The peak ground acceleration is translated into intensities according to Cancani [in 3] with reference to the safe shutdown earthquake. An increase of the intensity by 1 causes a doubling of the peak ground acceleration. For each safety relevant component of class I and each building with such equipment, a composite fragility curve is constructed.
The determination of the earthquake frequency requires a seismic hazard analysis. The historical earthquake occurrences within a radius of 200 km of the plant location are collected and evaluated together with the tectonic underground conditions. The annual exceedance frequency for earthquakes as a function of the intensity level is calculated.
Both results, i.e. the exceedance frequency and the components fragility curves, are used as input for the level 1+ PSA. The earthquake induced damage of the components/structures can lead to beyond design accidents or to accident initiating events. In the first case the core melt frequency will be taken directly from the seismic hazard curve (exceedance frequency); in the second case the core damage frequency will be calculated by means of an event tree analysis. The unavailability of the systems required to mitigate the initiated accident is determined based on the respective probabilities of component failure.
Depending on the seismicity of the respective NPP site, an analysis with different scope is recommended:

For $I \leq 6{,}5$ an analysis with minimum effort
$6{,}5 > I \leq 7{,}5$ an analysis with reduced full scope effort
$I > 7{,}5$ an analysis with full scope effort

EXTERNAL FLOODING
External flooding belongs to a class of external events, which are caused independently of human influence, but the subsequent possible damage is determined to a large extent by human factors, such as dam design, plant site selection, plant design etc.
With respect to the phenomena leading to a flooding event, the German nuclear power plants can be divided into two basic categories: "River-Site NPPs" and "Tidal-River NPPs". In the first case a high water-level situation arises from an unfavourable ratio of water inflow to outflow, in the second case the coincidence of storm, flooding and high tide is the determining factor.
In the proposed method, the frequency of reaching extremely high water levels is determined by an extrapolation of actually measured water-level data according to various established methods.

Fig. 2 demonstrates the method used in this analysis, which is basically the method of linear regression in the semilog domain. Flooding of the NPP-site is only possible if the water-level either exceeds the height of the dam, or if the dam breaks locally. Because of wave buildup on the dam, dam rupture is postulated at an average water level of 0.3 m below the dam height. The examples analysed for a "River-Site" and a "Tidal-River" NPP, the increasing water level leads first to the initiating event "Loss of off-site power", because of short circuits in the externally located electrical components. Then, at a higher water level - corresponding to the plant safety limit above which safe operation is impossible - the complete loss of the residual heat removal is possible. Fig. 3 gives a flow chart for the external flooding accident. External flooding events occur slowly enough so that there is sufficient time to prepare for counter-measures. At a specified high water level, each plant has to be shut down - according to the instructions of the operation manual - and operated in a controlled residual heat removal mode. The conditional probability for reaching a critical water level is determined by means of a flooding analysis taking into account the probability distribution of calculated spilling rates over the dam. By multiplying this probability with the frequency of reaching the dam height or the level leading to dam rupture, the initiating event frequency for "external flooding" is obtained. The frequency of the initiating event "Loss of off-site power" was estimated to be about 10^{-5}/a. The frequency of core damage for this event was calculated by means of the event tree method, using conservatively determined unavailabilities. A value of considerably less than 10^{-7}/a is expected for both categories of NPPs.

At water levels corresponding to the plant safety limit, the "Loss of residual heat removal" is assumed. In this case, no detailed event tree analysis is necessary and only the initiating event frequency - which is equivalent to the core melt frequency - needs to be calculated. For a Tidal-River NPP a value of less than $6 \cdot 10^{-7}$/a is estimated for this situation.

For practical applications it is recommended to analyse the water levels with respect to the successively initiated safety related events. If the sequence and the type of the initiating events of the plant under consideration agree with the results for the reference (see fig. 3), then only the frequency of the initiating events and the unavailability of the systems, necessary to handle the events, are compared. The amount of analysis is generally reduced to the evaluation of the frequency of reaching the plant safety limit, because the unavailability of the systems necessary to mitigate the event is set to 1.0 and the contribution of the event "Loss of off-site power" to the core melt frequency is negligible.

A more comprehensive analysis is recommended, if

- the type and sequence of the initiating events differ from the data in this analysis or if
- the initiating event frequency or
- the unavailability of the systems necessary to handle the events is remarkably worse than was assumed here.

AIR PLANE CRASH

Both, crashes of military air planes and of commercial air planes contribute to the plant risk. The location of the plant is important, both with respect to the distance from a nearby airport and to a close-by airlane and also, whether it is situated in an area of landing and take-off traffic. Because of the central position of Germany within Europe, there is a close-meshed net of civil airlanes with a high density of flights. Moreover, German and Allied Air Force units are stationed in Germany, thus there might be a non-negligible hazard due to air plane crashing on nuclear sites.

The proposed safety analysis is subdivided into different working steps: In a first step, the crash rate is determined. For that, the air traffic is divided into 3 different traffic categories:

- The landing and take-off phase,
- the airlane traffic and waiting loop traffic,
- the free air traffic.

The air planes are grouped into different weight classes (see table 1).
The annual frequency of impact for each weight class and flight phase is calculated, based on global crash rates valid for the old Federal States of Germany [4] (s. table 1), the local flight density and the impact area of the plant or the silhouette areas of the buildings.
Up to 10 km from the end of the runway, the crash rate decreases exponentially with distance R (fig. 4). For each weight class and different angular segment of flight directions, this decrease has been calculated based on data of worldwide crash vectors [4]. The number of crashes $h_{i,j}$ within definite angular segments are summed up for rings of $\Delta R = 1000$ m and approximately expressed by the following formula [5]:

$$h_{i,j} = a_{i,j} \cdot \exp(-b_{i,j} \cdot R) \tag{2}$$

Based on the number of yearly flying operations (take-offs and landings) of the airport to be considered, the number of the yearly crashes $H_{i,j}$ can be calculated for an impact area of the plant in a given annulus:

$$H_{i,j} = h_{i,j} \cdot \frac{d_i}{d_{global,i} \cdot \Delta t} \cdot \frac{F_{NPP}}{F_{\alpha j}} \tag{3}$$

with	$F_{\alpha j}$	=	$C_j \bullet \pi [R^2 - (R - \Delta R)^2]$ = annular segment
	i	=	Weight class
	j	=	Annular segment (with corresponding C_j as portion of the total sector)
	$a_{i,j}$; $b_{i,j}$	=	Constants
	F_{NPP}	=	Impact area of NPP
	Δt	=	Time span analysed
	d_i	=	Number of flying operations of the airport
	$d_{global,i}$	=	Number of global flying operations [6]

For the calculation of the crash frequency at lateral locations to air lanes, it has been assumed that the frequency distribution will be governed by a Gaussian distribution at right angles to the airlane with a standard deviation of σ (fig. 5). The fraction of the expected number of crashes onto the area of the NPP is explained in fig. 5 [5].
Outside a distance of 10 km from the airport each flight direction becomes equally probable within the free air traffic. The number of crashes H_i will be calculated by multiplying the global crash rate with the local flight density (number of take-offs and landings of the considered airport):

$$H_i = \frac{a}{2\pi R} \cdot \frac{b}{v_i} \cdot d_i \cdot h_i \tag{4}$$

with	i	=	Air plane weight class	v	=	Average flying speed
	a, b	=	Lateral length of the NPP	R	=	Distance airport - NPP

With the above formulae the contributions to the overall crash frequency are calculated. The contribution from the fast flying military air planes can be calculated only via the local crash history in the vicinity of the plant (e.g. 2 crashes within an area of 20 x 20 km^2 around the plant).
For the hazard analysis, the buildings are divided into 2 classes to reflect the degree of protection against air plane impact: one which is designed against air plane crash and another one which is not specifically designed against it. It will be distinguished between a direct hit frequency and a penetration frequency. In case the kinetic energy of the projectile is greater than the penetration energy of the outer shell damage of the building with all equipment in it is postulated. A transient or an initiating event leading to a core damage situation will be caused only, if systems in other buildings, necessary to mitigate that event, fail stochastically. For that case, the core melt frequency will be calculated in an event tree analysis. For penetrations leading directly to core melt accidents, the initiating frequency is assumed to be equal to the core melt frequency. For the buildings, not specifically designed against air plane crashes, additional hits by parts of the wrecked plane are taken into account.

EXPLOSION PRESSURE WAVE

The proposed analysis includes only the pressure waves coming from external events, caused by shipping, fabrication, storage and reloading of explosive materials in closer distances to the NPP. Pressure waves caused by detonation of liquids or solid explosives or air-gas mixtures and such pressure waves caused by deflagrations of only air-gas mixtures, are distinguished.
The initiating frequency of an explosion pressure wave H_{EPW}, which is independent of the transportation vehicle of dangerous materials, is calculated applying the following formula:

$$H_{EPW} = H_1 \cdot W_1 \cdot W_2 \cdot n \cdot l \qquad (5)$$

with
- H_1 = Number of accidents per vehicle (ship, train, truck etc.), km and year
- W_1 = Conditional probability for the participation of dangerous material per accident
- W_2 = Conditional probability for causing explosions per accident with dangerous materials
- n = Number of vehicles per year with dangerous materials passing the NPP
- l = Length along the NPP from where a hazard is possible

The application of this formula to a particular transportation system needs some adaptation of the input data.
For the quantification of the consequences of pressure waves, the buildings are classified into 2 classes to reflect the degree of protection against pressure wave loads. The induced initiating event will be identified taking into account all failures of equipment within the destroyed buildings.
It is recommended to determine the frequency of possible explosion pressure waves and to compare this value with a threshold value. A detailed analysis is recommended, if
- the building overpressure load is higher than the design load,
- the threshold value of $5 \cdot 10^{-6}$/a is violated
- the unavailability of the mitigating systems is considerably worse than 10^{-3} for one of the pressure wave-induced initiating events.

CONCLUSIONS

Methods for the probabilistic analysis of external events have been developed and described in form of procedure guides, which still have to be discussed with other PSA experts in Germany to find a consensus on how to deal with external events in PSA studies in the future. The proposed methods have proved to be efficient and to be suitable for application to German NPP. The proposed analysis for earthquakes is based on existing design calculations as performed during the erection phase of the plant. Therefore no additional earthquake design analysis is necessary and depending on the seismicity of the plant site an analysis with different scope is recommended. The probabilistic safety assessment is an additional tool to investigate, verify and improve safety practices and to complement the existing deterministic assessment in case of external events. With a reasonable effort, PSA experts, in cooperation with system engineers, are able to assess the current safety level of the plant and if necessary to set priorities with respect to envisaged improvements.

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Weight class [t]	Sum accidents / hours flown [1989 - 1995]	Average flying speed [km h^{-1}]	Accidents / km flown
> 20	1/5.762.300	833,4	2,0823 E-10
5,7 - 20	1/672.815	463,0	3,2101 E-09
- 5,7	14/772.656	333,4	5,4347 E-08
< 2	121/5.361.024	203,7	1,1080 E-07

Table 1: Global air plane crash rates outside the airports for the Federal States of Germany (1989 - 1995) [4]

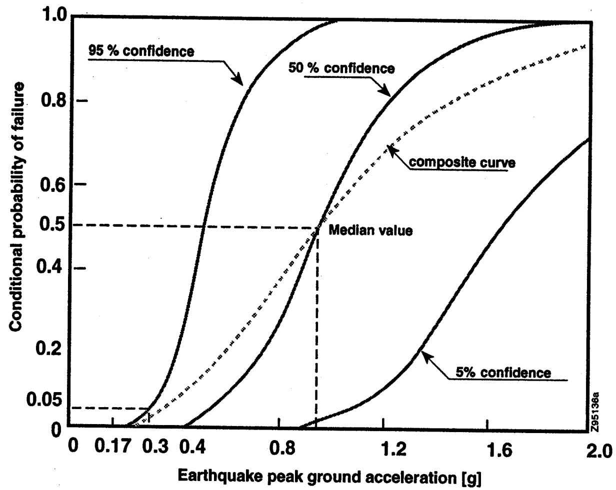


Fig. 1 Example fragility curves for a structure

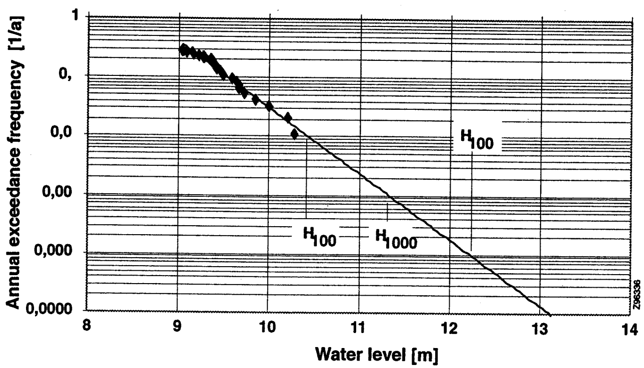


Fig. 2 Extrapolation of the annual exceedance frequencies of the annual extreme water levels

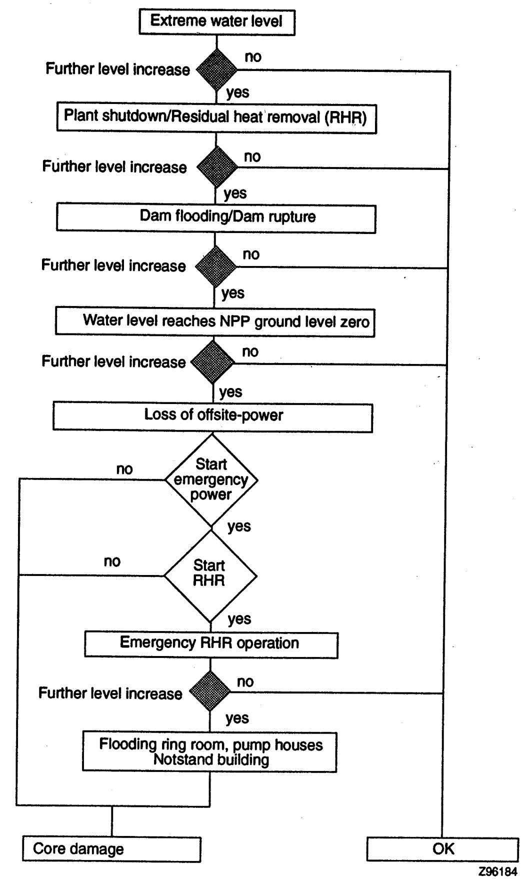


Fig. 3 Event sequence diagram „External Flooding“

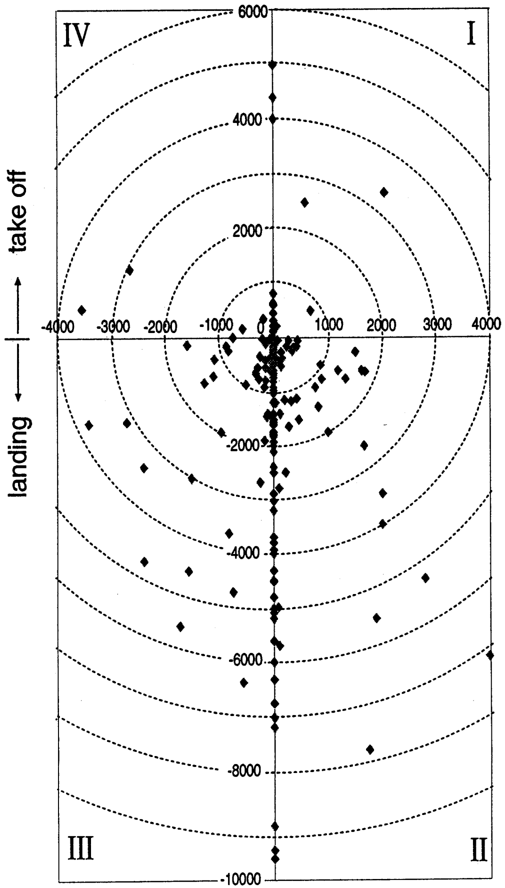
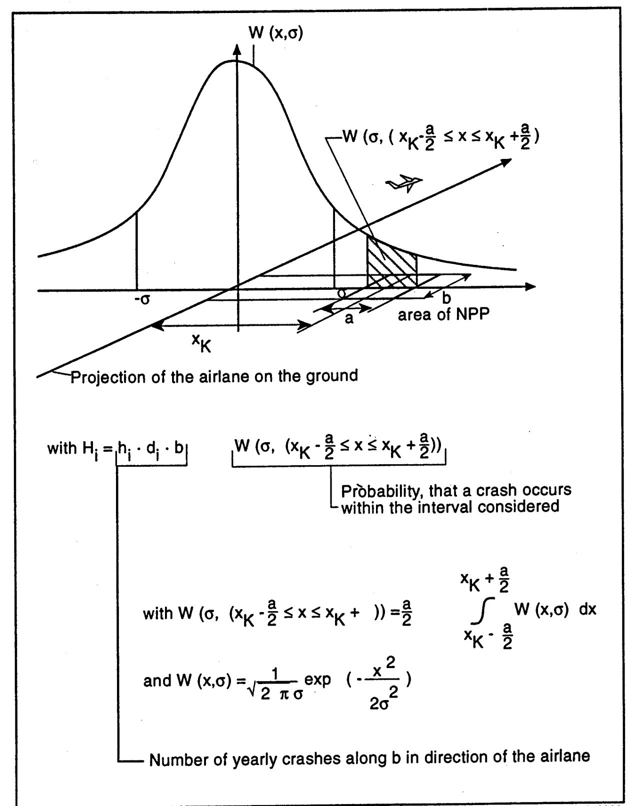


Fig. 4 World wide crash vectors during the take off and landing phase (1973-1991; weigth cat. 2)



h_i: Frequency of crashes (1/km flown)

d_i: Density of flights (1/a)

Fig. 5 Determination of the frequency of crashes from airplanes flying along commercial airlanes