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Aircraft crash onto a nuclear power plant - screening procedure and approach for a probabilistic analysis

Keywords

aircraft crash, crash frequency, probabilistic safety assessment, screening

Abstract

International experience has shown that external hazards (e.g. aircraft crash, flooding) can be safety significant contributors to the risk in case of nuclear power plants` operation. This is due to the fact that such hazards have the potential to reduce simultaneously the level of redundancy by damaging redundant systems or their supporting systems. In this paper, the procedure for the external hazard aircraft crash is described in more detail, starting with the screening procedure in order to determine scope and content of the assessment and the approach for those cases where a full scope analysis has to be performed. The consideration regarding this hazard does as not cover an intended aircraft crash.

1. Introduction

International experience has shown that internal (e.g. fire) and external hazards (e.g. aircraft crash, flooding) can be safety significant contributors to the risk in case of nuclear power plants` operation. This is due to the fact that such hazards have the potential to reduce simultaneously the level of redundancy by damaging redundant systems or their supporting systems.

Thus, the regulators expect that the licensees justify their arrangements for assessing the vulnerability of plant and structures, determining how the safe operation of a plant is affected, and introducing measures to prevent a hazard developing and mitigate against its effects if it should nevertheless develop.

Methods to analyse operating nuclear power plants systematically regarding the adequacy of their existing protection equipment against hazards can be deterministic as well as probabilistic. In particular in case of probabilistic analyses, the assessment can be very detailed and time consuming. Therefore, it is necessary to develop procedures to screen out, e.g., rooms or buildings of a plant where no further analysis is required or to have a graded procedure for the respective hazard taking into account plant- and site-specific conditions.

Since October 2005, a revised guideline as well as revised and extended technical documents are issued in Germany which describe the methods and data to be used in performing probabilistic safety assessment in the frame of comprehensive safety reviews. In these documents, probabilistic considerations of aircraft crash, external flooding, earthquake and explosions pressure waves are required and described in [3]. Also on international level, new recommendations are under development regarding external hazards such as the Safety Guide on Level 1 PSA [7] which is expected to be published in 2010.

In this paper, the procedure for the external hazard air craft crash is described in more detail, starting with the screening procedure in order to determine scope and content of the assessment to be performed and the approach for those cases where a full scope analysis has to be performed. The consideration regarding this hazard does as not cover an intended aircraft crash.

Both, crashes of military aircrafts and of commercial aircrafts contribute to the plant risk. The location of the nuclear power plant under consideration is important, both with respect to the distance from a nearby airport and to a close-by airlane. Moreover, it has to be taken into account whether the plant is situated in an area of landing and take-off traffic.

2. Flight situation in Germany

Because of the central position of Germany within Europe, there is a close-meshed net of civil air lanes with a high density of flights. Moreover, German and Allied Air Force units are stationed in Germany and a lot of air traffic of military units stationed outside Germany has to be considered. Thus there might be a non-negligible hazard due to aircraft crashing on nuclear sites.

German nuclear power plants can be divided in three generations with respect to air craft crash depending on the load assumptions which had been the basis for the structural design of the building structures to protect against hints of aircrafts or wracked aircraft parts. The consequences of hints in case of buildings which are not protected depend on the plant specific layout of buildings and systems. This is reflected in the safety assessment in the frame of comprehensive (periodic) safety reviews.

3. Screening

In the following guidance is given to perform a probabilistic safety analysis of nuclear power plants for the initiating event aircraft crash. A conservative approach in form of a rough analysis is described which allows the estimation of an upper limit for the frequency of plant hazard states caused by an aircraft crash. Further methods are described which are appropriate to replace the conservative considerations of the rough analysis by more detailed validation procedures. Application of these methods with a larger analysis effort lead to a more realistic validation compared to the rough analysis.

Requirements with respect to aircraft crash are laid down in a document of the German Reactor Safety Commission [12]. A load function for buildings to be protected (reactor building etc.) has been defined mainly based on theoretical calculations assuming an impact of the military aircraft "Phantom F4" (see *Figure 1*).

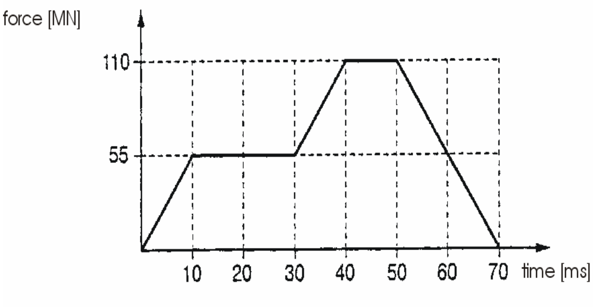


Figure 1. Load time diagram

Table 1 provides on overview of the graded process with aspect to aircraft crashes applied in Germany [1].

Table 1. The graded process of evidence regarding aircraft crash impact.

Criterion	Extent of analysis
Structures are designed according to the diagram in Fig. 1 and not located in a military zone for fly maneuver drills	Analysis is not necessary
Contribution is negligible compared to the other contributions in the PSA	A conservative rough-analysis regarding the consequences of impact on important areas A, B, C where A: e.g. primary circuit B: e.g. turbine building C: separated emergency building
Not negligible	Detailed probabilistic analysis of all plant areas, e.g. by using Monte-Carlo-methods

4. Determination of the frequency of an aircraft crash

The plant-specific determination of the frequency for the occurrence of an aircraft crash is performed on the basis of flight accident statistics valid for the respective location, taking into account the types of aircrafts and the weight classes which can be set.

The following input information is needed:

- the air traffic lanes in the near field of the plant,
- data concerning civil and military small and middle airports (in the range of about 50 km) and large airports (in the range up to 150 km) such as distance and adjustment of the starting and take-off runways.

The crash frequencies are determined separately in three 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 2*).

Table 2. Aircraft crash rates outside the airports onto the ground according to [5]

Weight class (Mg)		Accidents /km flown
1	> 20	$2.08 \cdot 10^{-10}$
	5.7 – 20	$3.21 \cdot 10^{-09}$
2	2 – 5.7	$5.44 \cdot 10^{-08}$
3	< 2	$1.11 \cdot 10^{-07}$

The annual frequency of impact for each weight class and flight phase is calculated, based on global crash rates valid for Germany as reported in [2] (see *Table 2*), the local flight density and the impact area of the plant or the silhouette areas of the buildings.

Conservatively, crash angles are assumed as 30° to the horizon. The silhouette areas result from the projection of the crash angle over the up-stations of the building onto the power plant surface (over the four directions).

As already explained, further hits can result from wracked aircraft parts, even if the aircraft crashes outside the defined arises defined silhouette areas. As a possible hazard range an area of 1000 m outside the silhouette areas is assumed, the probability of a hit by a wracked part is estimated as 20%. More than one hit per crash is not assumed. As relevant for the generation of such wracked parts aircrafts of the weight classes 1 and 2 as well as fast flying military aircrafts are considered. The wracked part is treated like an aircraft of the weight class 3.

5. Crash frequency in commercial air traffic

Up to 10 km from the end of the runway, the crash rate decreases exponentially with distance R. For each weight class and different angular segment (or sector) of flight directions, this decrease has been calculated based on data of worldwide crash vectors (see *Figure 2*).

The landing range before the touch-down and the take-off range after the start are subdivided into three different sectors:

Sector 1: ± 15° to the landing and take-off axis (30° sector angle),

Sector 2: outside of segment 1 to ± 45° to the landing and take-off axis (90° sector angle),

Sector 3: outside of sector 2 to ± 90° to the landing and take-off axis (180° sector angle).

The number of crashes $h_{i,j}$ within definite angular sectors are summed up for rings of ΔR= 1000 m and approximately expressed by the following formula [4]:

$$h_{i,j} = \frac{a_{i,j}}{c_i} \cdot \exp\left(-b_{i,j} \cdot R\right) \quad (2)$$

With

i = Weight class

j = Annular segment with corresponding C_j as portion of the total sector as provided in Table 3

$a_{i,j}$; $b_{i,j}$ = Constants to approximate the observed number of crashes in weight class i and sector j

c_i = number of landing and take-offs in the weight class i and within the observation time

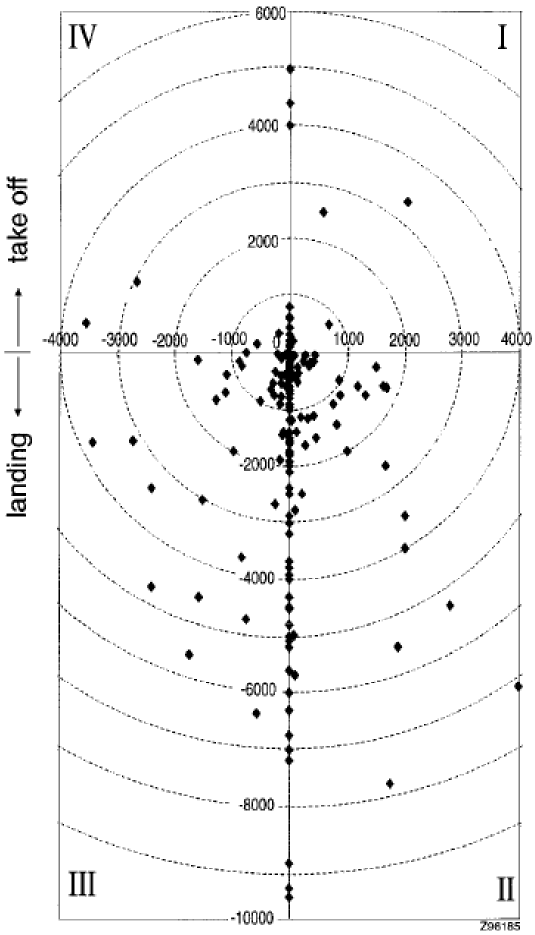


Figure 2. Worldwide crash vectors of aircraft crashes during landing and take-off phase (weight class 2)

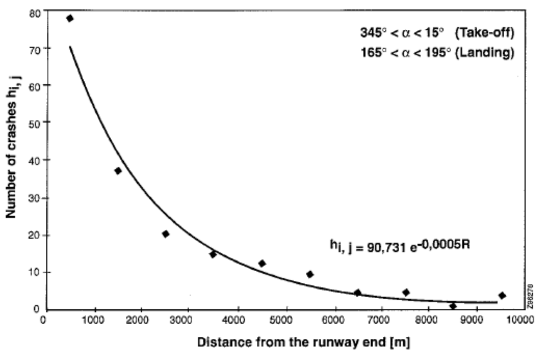
Based on the number of yearly flying operations (take-offs and landings) of the airport to be considered, the number of the yearly crashes $H_{i,j}$ can be calculated for an impact area of the plant in a given annulus:

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

One result for an observation time of 19 years and the number of global flying operations per year according to [8] is shown in *Figure 3*. For the calculation of the crash frequency at lateral locations to airlanes, 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. The fraction of the expected number of crashes onto the area of the NPP is explained in *Figure 4.*

Table 3. Correlation between sectors and aircraft weight classes

Sector	Weight class 1a > 20 Mg			Weight class 1b 14 bis 20 Mg			Weight class 1c 5,7 bis 14 Mg		
	$a_{1a,j}$	$b_{1a,j}$	c_{1a}	$a_{1b,j}$	$b_{1b,j}$	c_{1b}	$a_{1c,j}$	$b_{1c,j}$	c_{1c}
1	90.7	0.0005	$2.7{\cdot}10^{8}$	10.4	0.0004	$7.1{\cdot}10^{7}$	13.3	0.0006	$6.3{\cdot}10^{7}$
2	17.4	0.0005		3.4	0.0005		9.2	0.0006	
3	10.6	0.0006							



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

$h_{i,j}$	=	Number of crashes within definite angular segment j at distance R (ΔR = 1000 m) and weight class i (Δt = 19 years)
d_i	=	Number of flying operations per year at the airport considered
$d_{global,i}$	=	Number of global flying operations per year
F_{NPP}, $F_{\alpha i}$	=	Area of NPP, annular segment
i, j	=	Weight class, annular segment
Δt	=	Time span analysed (19 years)
$H_{i,j}$	=	Number of theoretical yearly crashes within the NPP area

Figure 3. Exponential decrease of the number of worldwide crash vectors in the annular segment with the distance from the runway

The aircraft crash rates outside the airports in correlation to the weight class has been listed in *Table 2.* Passenger aircrafts are only part of the aircrafts in weight class 1. Resulting from data of the German Federal Bureau of Aircraft Accident Investigation a lower crash frequency in the range of 10^{-12} to 10^{-11} per flight km can be assumed.

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):

$$H_{i,j} = \frac{a}{2\pi R_i} \cdot \frac{b}{v_j} \cdot d_{i,j} \cdot h_j \qquad (4)$$

With equation (4) the contributions to the overall crash frequency are calculated as shown in *Figure 5.* The average flying speed in the respective weight class as described in *Figure 5* (see [5]) is given in *Table 3*.

Table 3. Average flying speed correlated to weight classes

Weight class (Mg)		Average flying speed km/h
1	> 20	833.4
	5.7 – 20	463.0
2	– 5.7	333,4
3	< 2	203.7

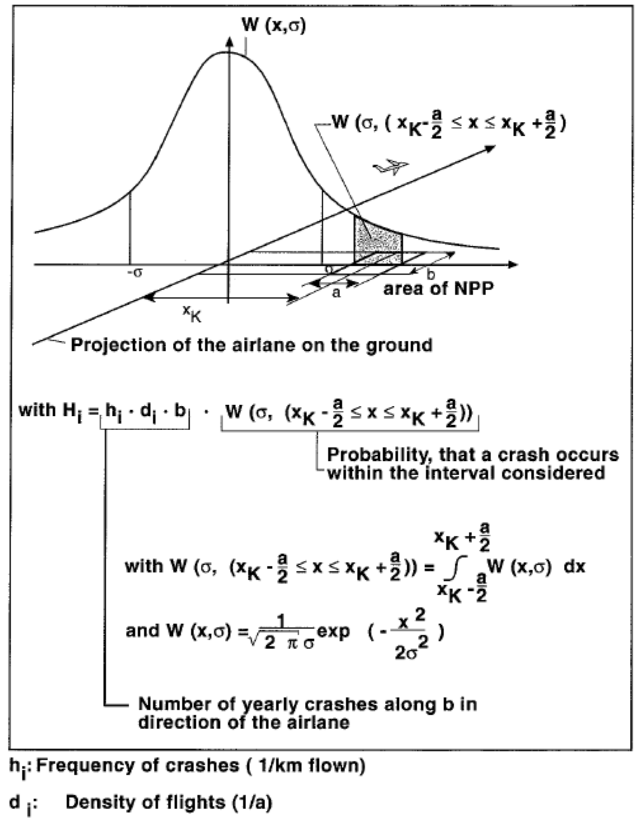


Figure 4. Determination of the crash frequency of aircrafts flying along airlanes

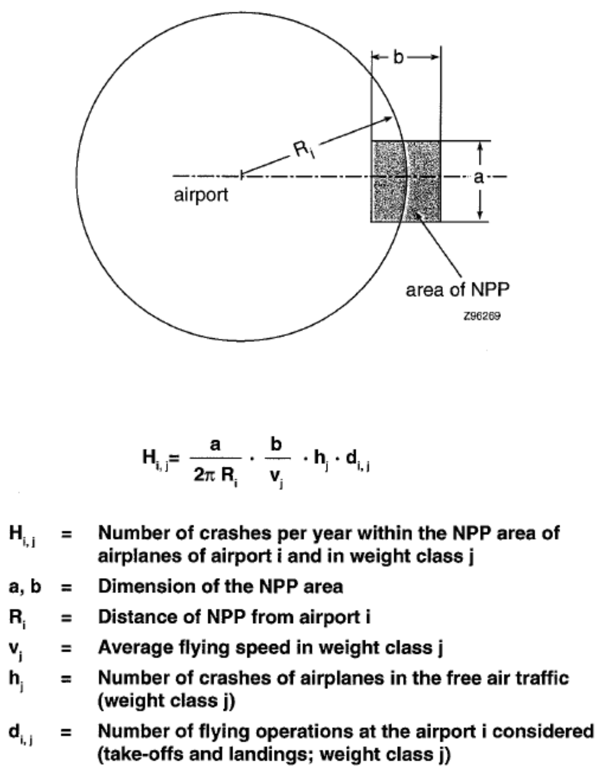


Figure 5. Determination of the crash frequency of aircrafts in the free air traffic

6. Crash frequency in military air traffic

The following considerations are not valid for large military aircrafts, which are used to transport military equipment, goods or soldiers. They use the airlanes of the commercial air traffic and have to be treated for the flying operation outside the landing and take-off phase as described earlier.

The plant-specific crash frequency of military aircrafts has to be calculated according to the procedures applied for the free air traffic taking into account the crash frequency per flying hour and the number of take-offs and landings on the neighbouring military airports.

In addition, the statistics of the local crash history which took place in the square of 30 km x 30 km around the power plant area is to be evaluated.

Figure 6a and b show the statistics of crashes of fast flying military aircrafts from Germany and abroad with more than 7.5 Mg in Germany for the time frame of 1984 to 2000 and of 2000 up to 2008. As one can see, changes in the military flying operation resulted in a significant reduction of the crash frequency. Therefore, for current calculations it has been recommended to take into account only events since 1991.

For the hazard analysis, the buildings are divided into classes to reflect the degree of protection against aircraft crash impact: one which is designed against air plane crash and another which is not specifically designed against it. It will be distinguished between a direct hit frequency and a penetration frequency.

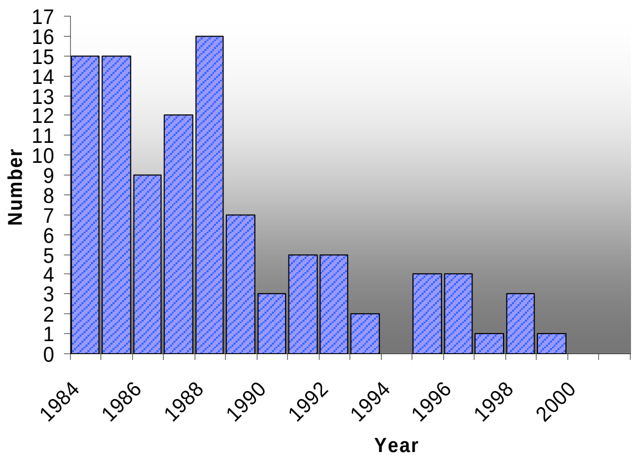


Figure 6a. Number of military aircraft crashes since 1984 up to 2000

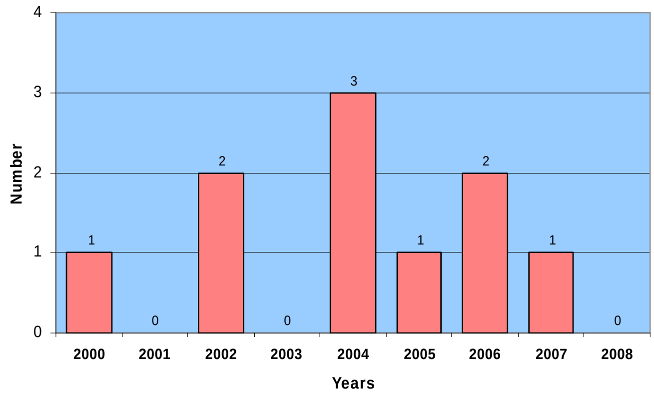


Figure 6b. Number of military aircraft crashes since 2000

In case the kinetic energy of the projectile is greater than the penetration energy of the outer shell a total damage of the building with all equipment in it is postulated.

In the detailed assessment, a plant-specific probability for the penetration can be determined, using, e.g., Monte Carlo procedures which allow calculations with a large number of possible impact points and impact angles to determine the position where design loads of the buildings are exceeded.

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 wracked aircraft are taken into account.

7. Concluding remarks

Aircraft crash onto a nuclear power plant or a chemical plant is an external hazard which has to be taken into account in a comprehensive safety assessment.

Methods to analyse plants systematically regarding the adequacy of their existing protection equipment against hazards can be deterministic as well as probabilistic.

In case of probabilistic safety assessments experience has shown that is reasonable to have procedures to screen out, e.g., rooms or buildings of the plant under consideration where no further analysis is required or to establish a safety graded procedure taking into account plant- and site-specific conditions such as design of buildings against aircraft crash impact as well as distance to smaller and larger airports including the current travel situation for commercial and military aircrafts. This information has to be site-specific and has to be collected from the respective national organizations (e.g., for commercial flights from the National Department of Civil Aviation).

Some guidance to perform frequency calculations is given in [13], describing the determination of the number of operations, aircraft crash rates and crash location probability including some (unfortunately older) data.

More recently, a guide to assess aircraft accidents and incidents with the focus on fires and explosions has been published [9].

For the free air traffic, also international data bases can be taken into account (see for example [6], [10] and [11]). However, such databases have to be used very carefully because they cover all aircraft crash statistics including those from countries which are well known for a high risk of aircraft crashes due to the age of the aircrafts used, the reduced maintenance activities and an unsufficient flight control system.

In general, the km flown are increasing from year to year, however, there is no systemetic increase of the crash rates per year.

As described aircraft crash rates are determined according to weight classes because of the different impact and resulting consequences for the plant. New and bigger aircrafts are on the market and partially already in operation. These aircrafts are constructed with new material such as fibre reinforced composite materials which leads to a reduction of the weight of the structures. On the other hand, during the take-off phase the amount of fuel is bigger compared to older aircrafts.

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