Class I Guidances

Guideline on the categorization and assessment of accidental aircraft crashes in the design of new class I nuclear installations

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February 2015

FANC

federal agency for nuclear control

Table of contents

1. Introduction

1.1. Background

External events induced by human activities or by natural events may affect the safety of nuclear installations and such external hazards are considered during the various stages of the installation´s lifetime. This guideline is concerned with one specific type of external events: the accidental (or unintentional) crash of an aircraft; it provides guidance for addressing and analyzing the event during the design stage.

Historically the requirements with respect to the extent to which a nuclear installation resists the potential impact of an aircraft, have changed strongly. For the design of the first generation of nuclear power plants, this event was considered within the residual risk, i.e. no provisions were considered for its management. In the late 70´s, following a series of military aircraft crashes, military and commercial aircraft crashes were included in the design of NPPs. Assessing the consequences of aircraft crashes onto units existing at that time was done as part of the periodic safety reviews.

After the 2001 terrorist attacks in the USA, the crash of large(r) commercial aircraft was assessed, usually, as a beyond design basis event for the plant layout and the containment sizing. The accident in Fukushima Daiichi NPP in 2011, although not related to an aircraft crash, led to an increased focus on low-probability yet conceivable events which can potentially result in large source term mobilization. The general consensus of relevance for this guideline that emerged from that accident is that for new nuclear installations such events should not lead to early or large radioactive releases [2].

No reports of accidental aircraft crashes onto nuclear installations are available up to now and such events can be considered very unlikely. Nevertheless such an event may be severe and could cause extensive damage to several safety provisions simultaneously; it could also seriously hinder (severe) accident management efforts. Despite its low probability, such an event is conceivable and provisions need to be in place to prevent intolerable consequences.

During the siting of a nuclear installation, consideration is given to external events. Such consideration will reduce the number of external events to be considered for the design, but might not completely eliminate their hazard altogether. The accidental crash of an aircraft can usually not be ruled out only on the basis of siting alone. Consequentially the impact of an accidental crash of an aircraft on the safety of a nuclear installation needs to be assessed during the design phase in order to make sure that adequate design characteristics are available to minimize the consequences of such an event.

1.2. Scope

This document provides guidance and expectations for addressing the accidental crash of an aircraft in the design of new class I nuclear installations and its associated installations; intentional aircraft crashes are not within the scope of this guideline.

This guideline applies (i.e. it should be used as an *applicable document*[1]) to new class I nuclear installations except disposal installations. A new class I nuclear installation means a nuclear installation that is the subject of a new license application and for which

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[1] This means that for new class I nuclear installations, it is expected by the regulatory authority that all applicable recommendations of this guideline are implemented in the design and/or the design evaluation. If this is not the case, the regulatory authority will likely ask the applicant to provide justifications for the recommendations that are not implemented.

the license application is introduced to the regulatory authority after the date of approval of this document.

The applicant is free to propose an approach that differs from this guideline provided it is fulfilling the regulatory requirements. The quantitative data related to the hazard levels (i.e. the probabilistic criteria defined in §3.1.8) should however always be respected. The nuclear regulator will evaluate the proposed approach and its justification against the background of this guideline.

1.3. Contents and approach

Starting with a survey of relevant background information such as the national regulatory framework and guidance by international organizations, this document continues by providing a high level discussion of the main expectations of the Belgian regulatory authority.

The expectations themselves are structured according to the assessment process to be followed.

The first step defines the necessity and extent of the analysis. Potential aircrafts are categorized in a limited number of aircraft categories according to the hazard they pose. For the military and large-commercial aircraft categories, the probability of a crash onto the installation is determined based on the installation´s layout and other site specific data. This probability will determine the type of analysis that is needed and, in relation with the third step below, the corresponding acceptance criteria.

The second step addresses the analyses of the crash of a representative aircraft for each aircraft category. The scope and general assumptions are provided as well the level of detail expected for the analysis.

Finally the safety objectives (acceptance criteria) for the analyses are given; they will allow verifying the adequacy of the design and its implemented architecture.

In general, this document does not aim to prescribe specific models, methods and data. However, methods and data have been explicitly prescribed as part of the main guidance, for the determination of the effective area of an installation (the area considered for the evaluation of the crash probability), for the aviation fuel load and for the critical impact parameters. The reason to be more specific in these cases is that these parameters strongly affect the outcome of an analysis. This ensures a uniform approach that adequately addresses the hazard posed by an aircraft crash.

Appendix A provides an overview of good practices, examples and references that may assist in carrying out the analysis. Appendix B provides an overview of the correspondence with international requirements and guidance from the IAEA.

2. Background

This section provides the general background for the remainder of the document. It starts with the national regulatory framework and international guidance.

2.1. Belgian regulatory framework

Article 7.4 of the Royal Decree of 30 November 2011 [1] which applies to all Belgian class I nuclear installations sets forth that "*the list of design basis accidents (internal and external) shall be subject to approval by the regulatory body"*.

For NPPs article 20.3 of the Royal Decree of 30 November 2011 [1] provides additional details on such list for external events:

" *Among those events of an external origin that need to be taken into account are at least (...)*
As well as those that emerge from human activities such as:
the crash of an aircraft,
(...)."

2.2. European directives

The council of the European Union published a Council Directive amending Directive 2009/71/EURATOM establishing a Community framework for the nuclear safety of nuclear installations [2]. The amendment of 2014 was published in response to lessons-learned from the accident in Fukushima Daiichi NPP in 2011 and aims at enhancing the regulatory framework for nuclear safety in the EU.

Of particular interest is section 2 with specific obligations for the nuclear safety objective for nuclear installations (article 8a, see [6]) and the implementation of the nuclear safety objective for nuclear installations (article 8b):

Article 8b indicates that in order to achieve the nuclear safety objective set out in Article 8a, Member States shall "ensure that the national framework requires that where defence-in-depth applies, it shall be applied to ensure that:

- the impact of extreme external natural and unintended man-made hazards is minimised;..."

2.3. International Atomic Energy Agency

The International Atomic Energy Agency, IAEA, issued several guides and requirements related to aircraft crashes that are discussed below. Appendix B provides an overview of the correspondence with international requirements and guidance from the IAEA. Of specific interest are IAEA NS-R-3 [3] that contains requirements regarding the site evaluation for nuclear installations, GSR Part 4 [4] on the safety assessment for installations and activities and NS-G-1.5 [5] on external events (excluding earthquakes) in the design of Nuclear Power Plants which provides in section 4 specific guidance on the assessment of aircraft crashes.

3. Guidance and expectations

The guideline on the safety demonstration of new class I nuclear installations [6] provides general guidance on the safety assessment, defence in depth, quantified safety objectives and the application of the graded approach for external hazards.

For this guideline on accidental aircraft crashes the following considerations are of specific relevance:

- The safety assessment for new class I nuclear installations should demonstrate that threats from accidental aircraft crashes are either removed or minimized so far as reasonably practicable;
- An accidental aircraft crash considered in the design basis of the plant should not lead to severe accident (objective SO2);
- Severe accidents resulting from accidental aircraft crash which would lead to early or large releases should be practically eliminated (objective SO3). For that reason, rare and severe forms of accidental aircraft crashes need to be addressed in the overall analysis.

In line with the above considerations, this guideline will define two levels for the analysis of an accidental aircraft crash:

- ACL-1: level 1 accidental aircraft crashes;
- ACL-2: level 2 accidental aircraft crashes considered as rare and severe.

3.1. Determination of the aircraft crash probability and categorization

A wide variety of aircrafts exists and the hazard they pose to an installation can strongly differ. Analyzing every potential type of aircraft and type of crash would however require excessive resources and is unlikely to significantly contribute to the overall safety. This document will therefore distinguish between three aircraft categories that are defined in a way that adequately represents the hazard of the underlying aircrafts.

Historically the approach for selecting aircraft crash events and their assessment in the design basis was solely driven by the probability. Ever since, it has become more and more common internationally to also base the selection on deterministic arguments.

In this guideline probabilistic considerations will only be used to associate each aircraft category with a specific hazard level (ACL-1 or ACL-2). The probability is not used to exclude any aircraft category from the analysis.

This approach is justified on the basis of the following arguments:

- the inherent nature of an aircraft crash is such that it, if unmitigated, may result in extensive and simultaneous damage to control, protection and mitigation provisions implemented (i.e. following the defence in depth principles), to assure the safety functions; i.e. several levels of the DiD may fail simultaneously. In addition, extensive damage to safety provisions could also seriously hinder (severe) accident management;
- the probability of the event is subject to potential future changes. Such changes are for instance the development of smaller airports, changes in air-traffic corridors and changes in maintenance practices or aircraft operators. Other uncertainties are related to the structural characteristics of aircraft such as size, shape, materials, etc. These aspects are difficult to foresee over longer time periods such as the lifetime of an installation. This uncertainty impedes the high level of confidence that would be required to consider a crash associated to a certain aircraft category as residual risk.

For each of the aircraft categories the probability that one of the underlying aircrafts crashes onto the installation, is calculated on the basis of the installation lay-out, site specific data and data from reliable expert aviation sources. Methods will be defined that guarantee a conservative, uniform and standardized approach to determine the crash probability associated with each aircraft category. Appendix A.1 contains a process diagram that assists in connecting the several steps in this section.

A priori note that a calculation of aircraft crash probabilities for the general aircraft category is not necessary for the application of this guideline as this aircraft category should always be considered as ACL-1 (or it is enveloped by other categories).

3.1.1. Categories of aircraft

Aircrafts should be categorized in one of the following three categories:

- General aircraft: local air traffic with masses up to 5.7 tons[2] (maximum take-off weight) such as aircraft for leisure, helicopters and small civil aircrafts;
- Large-commercial aircraft: other civil aircraft notably medium and large civil aircraft for national and international commercial flights;
- Military aircraft: all military aircrafts.

The categorization is based on the differences in hazards (mostly determined by the loadings and the areas on which these loads occur) associated to different aircraft and the likelihood that such hazard occurs: an impact of an aircraft of the general category is less severe, but likely more probable than an impact of an aircraft considered in the other two categories. The significantly different characteristics of aircrafts of the military and large-commercial categories, notably speed, mass, impact area, but also their crash probability and flight zones, justify a differentiation between those two types.

Although the proposed categories are considered sufficient, a sub-category may be introduced if the different types of aircraft within one of the above three aircraft categories differ strongly in the risk associated with their crash. This could be the case when new aircraft types are introduced or when existing types are reintroduced (e.g. supersonic aircraft). The introduction of such an additional aircraft sub-category should be discussed with the regulatory authority and has to be justified by risk characteristics and by a clear criterion based on which aircrafts can be assigned to the sub-category.

The intention of this categorization is to avoid the need to assess all air-borne vehicles existing world-wide, but rather focus on the characteristic hazards posed by aircraft. Since a categorization is adopted that is consistent with standard practices and data specific to each category a detailed list of aircraft per category is not considered necessary.

3.1.2. Types of crashes

Aircraft crash events should be categorized in one of the following types:

- crashes resulting from airport activities: take-off, climbing, approach and landing;
- crashes resulting from non-airport activities: in-flight or holding pattern.

3.1.3. Aviation traffic data

National and international expert aviation sources[3] should be consulted for the following data related to aviation traffic data for each of the aircraft categories:

- Annual number of operations at the airports for which aircraft perform take-off and landing operations within such a distance of the site that a crash resulting from such operations may occur on the site;
- Aviation density for non-airport activities representative for the site;

[2] A mass of 5.7 tons is generally (e.g. IAEA TECDOC 1347) used as a defining characteristic for this class. This is a historic choice that is retained in this guide.

[3] Data for the general aircraft category may need to be obtained from alternative sources such as local operators of such air traffic.

- Historic changes and foreseeable future evolution of both aspects listed above.

These data are necessary to be able to determine the event probability and its related uncertainty. Several different expert sources could and probably should be consulted depending on the type of information necessary. Such sources could be: military sources, nearby airports, local operators and national or international aviation bodies. Note that the data listed are connected to the crash statistics data (see section 3.1.4 and 3.1.6). It is advisable to use the same expert sources for aviation traffic data and crash statistics data (see next subsection) to avoid misinterpretation of the data provided.

3.1.4. Crash statistics data

Expert aviation sources, national and international, should be consulted for crash statistics data including the effects of skidding for each of the aircraft categories (i.e. if possible without explicitly considering specific types of aircraft) and specific to the type of operation (i.e. airport or non-airport).

This data should be representative for Belgium and nearby countries and may, if necessary for reducing uncertainties, be based in addition on other countries with similar air traffic conditions, regulations and practices. For contributions by airport operations, the distance and orientation of the site with respect to the airport runways are taken into account for airports located either in Belgium or sufficiently near in a neighboring country. For contributions by non-airport activities in general no specifics of the region or the site need to be taken into account; they may reflect the risk anywhere in Belgium. However, military flight training zones and corridors may introduce a strong inhomogeneity in the crash probability that should be taken into account when relevant. Another inhomogeneity that may need to be addressed concerns the surroundings of airshows.

For the crash statistics a difference is made between airport and non-airport contributions. Airport activities should take into account take-off, climbing, approach and landing. The risk posed by these activities strongly depends on the distance and orientation of the site in relation to the airport and this dependency needs to be taken into account. At a minimum all airports located within a 37 km[4] [7] radius around the site should be taken into account.

Aircraft crashes are rare and reliable statistics may require using a sufficiently long period. A period of 20 years is deemed sufficiently representative. However it is also realized that the air traffic industry performs extensive root cause analysis following an incident or accident, shares lessons learned and takes industry-wide measures when necessary. Hence, a crash statistic based on a very long period may be overly conservative; in such a case the period can be reduced.

For more modern aircraft a period of 20 years likely exceeds the timeframe for which data is available. This may necessitate basing the statistics on a shorter timeframe. When this period would become very small, for instance a couple of years for a new type of aircraft, then the statistics should be generated by including additional conservatisms and using data available for similar aircraft.

Another limitation of the timeframe could be justified when the data shows a significant change in crash statistics that can be attributed to a specific measure or practice. Also in such a case it could be justified to limit the period to a shorter timeframe in order to avoid overly conservative crash statistics.

3.1.5. Effective area

The definition of the total effective area is necessary to calculate the probability that a crash will impact on the installation or the relevant supporting buildings since these crash probabilities are normalized per unit of area. It should be calculated by accumulating the effective areas of all relevant buildings and areas (i.e., all buildings hosting nuclear fuel or

[4] Do note that the assumed probability for an airport-related crash may equal zero at distances shorter than 37 km depending on characteristics such as the angle between the installation and a runway as well as the type of aircraft.

large radioactive sources as well as all other buildings and areas of the terrain that host safety provisions - see also section 3.2.1 for the general scope of the analysis). The calculation of each contribution to the effective area may be done using the methodology and data provided in [7][5].

The method proceeds as follows: the installation is represented by a bounding rectangle. The cross-sectional area corresponding to the largest diagonal of this bounding rectangle and the roof area are projected onto the surface using a predefined crash angle specific to the type of aircraft or aircraft category. This area, together with an area over which the aircraft skids if it crashes just in front of the building, then form the effective area of the building. The determination of the largest diagonal may consider the limitation of possible flight paths by adjacent structures, buildings and terrain features (also see section 3.2.3).

Appendix A.1 provides additional guidance for the determination of the effective area. For the impact angle, a single average value (e.g. from [7]) or a probability distribution can be selected, depending on the aircraft category and the crash type, and should always be justified. A distribution is most often used for military aircrafts; for other aircraft types, a distribution is often not available, and hence an average value is most typically used which can be different for non-airport activities and airport activities.

3.1.6. Annual crash probabilities

For each aircraft category the overall annual crash event probability, P_{cat}, should be calculated by summing the contributions from airport activities and non-airport activities.

The contributions by non-airport activities are found by multiplying the aviation density representative for the site and its immediate vicinity and, if relevant, specific to the type of operation, the probability of a crash during non-airport activities (in-flight or in a holding pattern) and the effective area.

The contributions by airport activities are found by multiplying the number of operations at the relevant airport, the probability of crash given the activity (take-off plus landing and depending on distance to site and orientation), the impact chance on the site resulting from the crash and the effective area.

Appendix A.1 provides additional guidance for the calculation of the annual crash probability.

3.1.7. Uncertainties

Major sources of uncertainty in the event probabilities should be identified, categorized (e.g. aleatory/random or epistemic), quantified and reduced to the extent reasonably practical. Amongst others, a review of data and/or publications for other nearby countries is highly recommended. A justification of the reliability of the event probability should be provided notably when this could influence the categorization (see section 3.1.8).

Note that sufficient conservatisms have been included to allow addressing only the major sources of uncertainty. In addition and as pointed out in section 3.1, some uncertainties or future changes cannot be predicted with any accuracy and so addressing minor sources of uncertainties may not be worth the effort.

3.1.8. Categorization as ACL-1 and ACL-2

As a general rule, a crash associated with a certain aircraft category is categorized as ACL-1 if the overall annual crash probability for that category, P_{cat}, exceeds 10^{-6} per year. If the overall annual crash probability is lower, it should be categorized as ACL-2.

[5] Note that the dimensions/units of the data provided should be checked and converted if necessary.

ACL-1 must always contain the general aircraft category. An assessment may not be needed if one of the other two categories is also categorized under ACL-1 as these categories envelope the general category.

The above two rules to define ACL-1 and ACL-2 are presented in the table below for the three standard aircraft categories:

Hazard level	**Aircraft category**		
	General	Military	Commercial
ACL-1	Always, unless enveloped by other categories	Yes, if $P_{mil} > 10^{-6}$	Yes, if $P_{com} > 10^{-6}$
ACL-2	No: should be enveloped by other categories	Yes, if $P_{mil} < 10^{-6}$	Yes, if $P_{com} < 10^{-6}$

For the definition of the representative aircraft crash associated to ACL-1/ACL-2 and the three aircraft categories, see section 3.2.2; for the safety objectives associated to ACL-1/ACL-2, see section 3.3.1.

3.1.9. Application of the graded approach

The hazard-specific worst-case consequences (see [6] for details and definitions) will allow categorizing the installation into one of four graded approach (GA) categories. Depending on this categorization, the scope of the safety assessment for accidental aircraft crashes can be determined:

	Include in safety assessment?		
GA category	ACL-1	margin assessment[6]	ACL-2
4	yes	yes	yes
3	yes	yes	no
2	yes	no	no
1	yes, but adapted	no	no

For graded approach category 1 the ACL-1 hazard is set to correspond to the crash of an aircraft from the general aircraft category without further consideration of other aircraft categories. The adaptation for ACL-1 for the GA category 1 is given in section 3.2.2.

[6] In section 3.2.6 further details are provided on the margin assessment, which, in the case of aircraft crashes, can be performed as a sensitivity analysis by varying the impact speed or the amplitude of the load function.

3.2. Analysis of an aircraft crash event

This section defines the scope of the analysis, the event to be analyzed and the effects to be studied for each of the aircraft categories categorized as either ACL-1 or ACL-2. The aim is to ensure that each type of aircraft crash event is adequately studied in a manner that considers all relevant aspects and effects. The related safety objectives are provided in section 3.3.

Note that, consistent with the table presented in section 3.1.9, for installations categorized as graded approach category 1, 2, or 3 the rare and severe aircraft crash ACL-2 does not need to be further defined and assessed.

3.2.1. General scope

The analysis should consider all safety provisions related to the three safety functions in so far they are relevant for the installation considered [8]:

- control of reactivity (either active or through a designed level of subcriticality);
- removal of heat from the reactor and from the fuel storage;
- confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases.

The analysis should cover safety functions and safety provisions related to the whole installation: reactor (if applicable), the storage of nuclear fuel (if applicable) and other large sources of radioactivity, all buildings and structures, in so far they are part of the license of the installation and host safety provisions, and safety provisions that are not inside a building such as e.g. dikes, dams, water intake, etc..

3.2.2. Representative aircraft crash

For each aircraft category a representative aircraft as well as a representative type of crash (see also section 3.1), should be defined and justified for further analysis as ACL-1 and ACL-2. Such representative aircraft crash should be representative for the site specific hazard posed by each aircraft category. The definition of a representative aircraft crash for each category is subject to approval and should be justified.

It is not practical to analyze in detail the impact of every type of aircraft or to verify each of such analysis. Therefore a representative aircraft needs to be selected for the analysis in a manner that represents the site specific hazard of its category. Some aircraft or crash types may not be enveloped by the representative aircraft crash and would therefore not be covered by the analysis.

For ACL-1 it is generally expected that the representative aircraft is defined conservatively and envelopes the entire category with very few exceptions. For the ACL-1/general aircraft category the regulatory authority considers it acceptable to consider a two-engine airplane with mass close to 5.7 tons for installations in the GA category 2, 3 and 4. For installations in the GA category 1 a single engine airplane with a mass close to 1.5 tons (e.g. a Cessna) is acceptable for the ACL-1/general aircraft category.

For ACL-2 the representative aircraft may be defined less conservatively so that it envelopes a significant fraction of the aircraft in the specific aircraft category. The applicant is asked to propose and justify the selected representative aircraft.

Each representative aircraft crash should at least be characterized by:

- One or more (unified) load-time functions[7] accompanied by aircraft mass, impact areas and the impact speed, which should at least be:
  - o 100 m/s for general aircraft category,
  - o 215 m/s for a military aircraft,
  - o 120 m/s for a large-commercial aircraft;
- One or more additional missiles (such as engines) accompanied by their masses, velocities and impact areas. The overall impact effects of such missiles should be taken into account as part of the load-time functions; nevertheless, their separate specification is necessary for the analysis, notably in relation to penetration. For a military aircraft no loaded missiles or explosives have to be assumed;
- Full take-off weight and a full load of aircraft fuel (MTOW). For military aircraft the full take-off weight may be reduced to account for the absence of loaded missiles and explosives.

The characteristics listed here concern parameters of an aircraft and missiles that dominantly determine the extent of damage following a crash. A full take-off weight and full load of aviation fuel load are conservative upper limits. The limits for the impact speeds are judged to be conservative for the large majority of crashes; nevertheless crashes may occur at an impact speed that exceeds these values.

3.2.3. Flight paths and impact locations

The flight paths and impact locations that are analyzed should represent the worst cases and this depends on the purpose of the application. Flight paths may be screened out if the presence of permanent terrain features or nearby buildings makes such approaches physically impossible. For the study of the consequences of a penetration, several flight paths should be assessed in relation to the damage they could cause to safety provisions.

During the assessment several *different* flight paths are considered for various purposes, namely

- for the effective area: the worst case can be based on the lowest potential impact angle.
- for determining if a barrier can be penetrated:
  - o the worst case is usually given by a perpendicular impact in the center of panels.
  - o For the impact on flat roofs, a non-perpendicular impact may be considered, however, for the sensitivity analysis related to ACL-1 this angle should be taken as perpendicular (see §3.2.6).
- for the detailed assessment of the consequences of a penetration, several different flight paths need to be studied based on the layout of safety provisions inside the building; these flight paths may not necessarily impact on the center of panels and can thus be different from the flight paths for determining if a barrier can be penetrated. For the impact on flat roofs, a non-perpendicular impact may be considered, however, for the sensitivity analysis related to ACL-1 this angle should be taken as perpendicular (see §3.2.6).

Flight paths that are not physically possible do not need to be studied. However, consideration should be given not to provide credit to buildings and structures that are not under the control of the license holder. Known changes to the site and its buildings, including those that can reasonably be expected, should be included in the determination of which buildings and structures could limit the potential flight paths. The reason is that the presence of any structure used for screening flight paths represents a formal input data for the assessment and will affect the results of the safety assessment and its validity. The pertinence of crediting nearby buildings, structures or topographical features

[7] See e.g. the load-functions provided as example in appendix A.3

should be validated regularly and in any case as part of the design and the periodic safety review.

In appendix A.2 further guidance is provided on flight paths and their determination.

3.2.4. Analysis of ACL-1

The analysis carried out for the representative event should consist of identifying and assessing:

- The effects due to direct impact (see also appendix A.3):
  - global failure of a building (e.g. collapse or its overall translation or rotation),
  - local failure resulting in deformation of barriers or penetration of aircraft remnants,
  - generation of additional missiles due to the disintegration of the aircraft (notably the engines and undercarriage), scabbing or spalling or other forms of momentum transfer;
- The indirect damage to safety related provisions due to (see also appendix A.3):
  - collapse of outer barrier, roof or internal structures,
  - penetrating missiles and debris,
  - falling of heavy internal objects (e.g. fall of crane due to local deformation of outer barrier),
  - vibrations and shock waves due to impact;
- The effects of fuel ignition/explosion and fire due to:
  - overpressure and shock wave,
  - heat and spreading of fire or kerosene,
  - smoke and dust (e.g. blockage of intake filters);
- The effects on human intervention and mitigating actions[8] due to:
  - Heat, smoke and kerosene fire (e.g. impaired habitability of control room),
  - debris and missiles,
  - asphyxiant and toxic substances.

The analysis should include the determination of margins and the demonstration of conservatisms.

The list of effects to be analyzed is extensive, however, potential effects of an aircraft crash are complex and diverse, and this list covers all relevant hazards.

3.2.5. Analysis of ACL-2

The analysis carried out for the representative event may be based on realistic assumptions and methods, and should consist of:

- An assessment, to the extent applicable, of the effects on the safety functions ´reactivity control` and ´heat removal`. Such assessment may consist of a qualitative argumentation based, for instance, on sufficiency of physical separation;
- An assessment of the impact on the containment function of buildings that host nuclear fuel or large radioactive sources and their confinement barriers, which should at least provide quantitative insight in the global stability of the building, the potential for penetration of the barriers and the effects induced by vibrations;
- A qualitative analysis of the potential effects listed in section 3.2.4 with a focus on potential effects that might cause releases or that may have an impact on accident management provisions. Effects that cannot be excluded and could lead to a significant release or other adverse effects should be studied and quantified.

[8] Besides the benefits from such measures, also the potential negative effects should be identified.

3.2.6. Sensitivity analysis and margin assessment

For aircraft crashes it is not possible to establish a meaningful severity-frequency curve and hence the margin assessment (for ACL-1, for graded approach categories 3 and 4) as requested in [6] in terms of the gap in exceedance frequency cannot be performed.

The margin assessment [6] can be performed in terms of a gap in severity by performing an analysis for aircraft types different from the representative aircraft and progressively selecting more penalizing characteristics of such aircrafts. However, given the variety of characteristics that can be penalized (speed, mass, wingspan, number of engines, amount of fuel, …), the number of different aircrafts that can be considered, as well as the complexity of the ensuing analysis, this path may be too complex and too demanding for its purpose. The regulatory authority therefor accepts that a margin assessment is carried out by varying the impact speed (or alternatively the amplitude of the load function) of the representative aircraft crash. This analysis is referred to in this document as the **sensitivity analysis** and may replace the margin assessment.

The sensitivity analysis should be carried out by varying the impact velocity (or alternatively the amplitude of the load function), up to 150% of the initial value. In addition it is expected that for an impact on the roof, the impact angle is assumed to be perpendicular.

The sensitivity analysis may be limited to relevant buildings that host radiological sources whose amount can lead to consequences beyond the applicable safety objectives and related buildings that host provisions that are essential for sustaining a safety function. The margin in impact velocities or load should be determined in relation to each of the following effects:

- Penetration of containment or outer confinement barrier;
- Global failure of containment or outer confinement barrier;
- Penetration by missiles of any radiological barrier of large radiological sources
- To the extent applicable, penetration by missiles of coolant boundaries essential for the removal of residual heat;
- To the extent applicable, penetration by missiles of barriers hosting equipment/systems essential for the control of reactivity.

3.3. Safety objectives

In this section the safety objectives (acceptance criteria) are provided for the different analyses carried out to assess the consequences of an aircraft crash.

3.3.1. Objectives for the assessment of ACL-1 and ACL-2

The analyses for ACL-1 and ACL-2 should show that the releases of radioactive material from any source are minimized to the extent reasonably practical and in any case below the applicable safety objective SO2 or SO3.

In addition, the regulatory authority is of the opinion that for reactors and any associated spent fuel storage facilities an aircraft crash should not lead to severe core/fuel damage and therefore should not cause more than a minor radiological impact consistent with safety objective SO2. The reason for this expectation is twofold:

- If severe core/fuel damage would result from an accidental aircraft crash, then in all likelihood the impact has caused inner containment/confinement barriers to be breached in such a way that a direct release pathway exists and a large and early release cannot be prevented or mitigated. This would be inconsistent with safety objective SO3.
- If severe core/fuel damage would result from another reason than a catastrophic aircraft impact that breaches the containment and confinement barriers, e.g. by a crash that impedes heat removal paths, then by means of diversity and separation core melt could have been prevented. Such measures

are judged as reasonably practicable for an NPP and any associated spent fuel storage facility and should therefore be implemented.

For a research reactor the reasonability of measures to reduce the consequences to SO2 should be discussed with the regulatory authority.

4. Summary

This document provides guidance and expectations for the categorization and assessment of accidental aircraft crashes in the design of new class 1 nuclear installations.

This document builds on national regulations and international practices and aims to ensure that the potentially severe consequences of aircraft crashes are adequately prevented by design. In addition applying the guideline will ensure completeness and uniformity in the assessment of aircraft crashes.

To further assist in assessing and analyzing the potentially complex and diverse nature of aircraft crash events this document provides an overview of good and recommended practices and examples.

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A. APPENDIX: examples and good practices

This appendix provides an overview of good practices with regards to methodologies that may be applied in the safety assessment or the additional assessment as well as some additional guidance in the form of process diagrams and examples. In addition this appendix presents process flow diagrams that can be used as part of the assessment.

A.1. Evaluation of aircraft crash probability

For airport operations, the crash probability is found by summing contributions, p, calculated using the following formula:

$$p = N_{\text{ops}}\, p_{\text{crash}}\, C_{\text{site}}\, A_{\text{eff}}$$

with:

- N_{ops} [y^{-1}] number of operations per year
- P_{crash} [km^{-2}] chance that given an operation the aircraft crashes per measure of area
- C_{site} [ ] correction factor for airport contributions taking distance and orientation of site to airport and runway into account ; equal to 1 for non-airport contributions (see [7] for details).
- A_{eff} [km^2] effective area

Alternatively, for non-airport contributions N may be taken as the total length of flights over the territory per year (i.e. [km y^{-1}]) with P then being the probability of a crash per measure of area per length of flight ([km^{-2} km^{-1}]). The change of units in this alternative can lead to misinterpretations and underlies the advice in section 3.1.3 that the same (or similar) expert sources should be used to the extent possible. Note that the product Np [y^{-1} km^{-2}] may be obtained directly for non-airport contributions.

When necessary the product Np [y^{-1} km^{-2}] should depend on the location of the site.

A process flow diagram based on the steps described in the main contents of this document (section 3.1) is given in Figure 1.

Figure 2 provides a schematic overview of the calculation of the effective area and the concepts involved in it. Note that the wing span, skid area and impact angle may depend on the aircraft type and need to be taken into account for the calculation of the effective area (see [7] for details).

If the installation consists of more than one building, then the overall aircraft crash probability is the sum of the probabilities for every relevant building and areas (see § 3.1.5). Alternatively, the largest diagonal can be applied to the footprint of all relevant buildings and areas together.

If the installation comprises only a part of a building, then either the entire building or all relevant parts of that building (see § 3.1.5) should be taken into account.

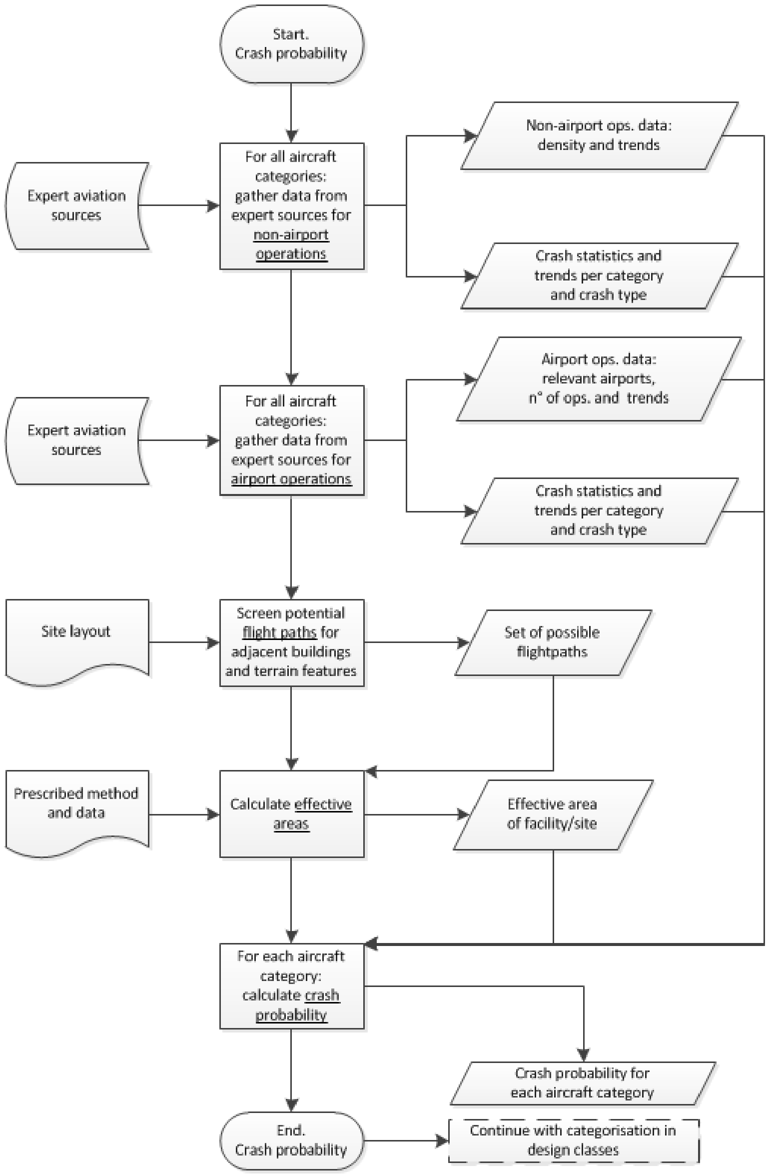

Figure 1. Overview of steps, necessary information and output data for the determination of the crash probability of each aircraft category.

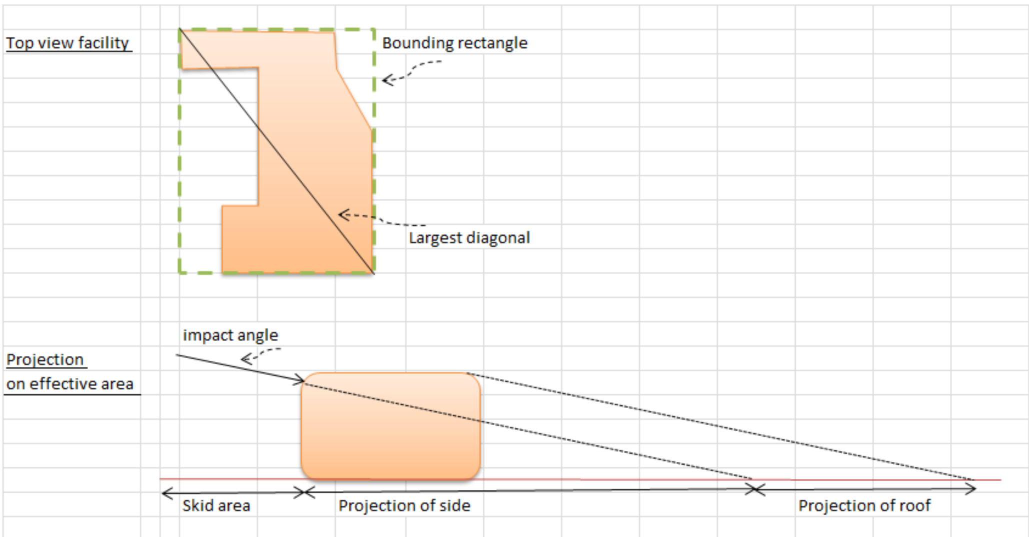

Figure 2. Schematic overview of calculation of effective area of a installation and concepts involved.

A.2. Assessment of flight paths and impact location

Under specific circumstances flight paths may be screened for the presence of nearby building and structures. This screening can be applied to flight directions as well as impact angles associated with those directions.

For the determination of the flight path the worst case should be taken and this depends on the actual use of the flight path. Two different usages are discussed here: the potential for penetration and the consequences of penetration.

To determine the potential for penetration it is recommended to determine barrier zones with equal or similar characteristics when it comes to penetration. Figure 3 shows a installation consistent of three different areas separated by an internal barrier and three different outer barrier zones that are assumed to resist differently to an impact. In this case each area can be surrounded by more than one barrier zone.

The worst case flight path should be determined for each of these barrier zones and usually constitutes an impact perpendicular to the barrier in the center of panels, if any. In some cases a perpendicular impact is not possible due to the presence of nearby buildings etc., and credit may be taken for this. In Figure 3 the nearby structure may limit the possible impact angles for barrier zone 2; it does not limit the flight paths for the other two barrier zones.

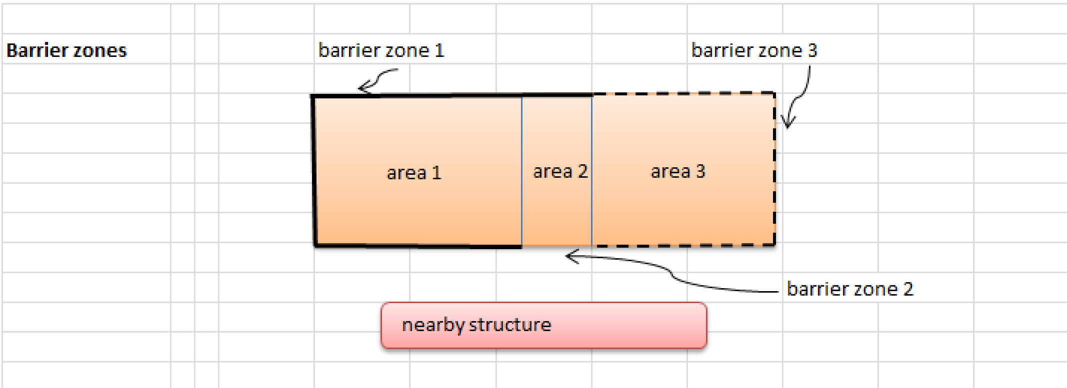

Figure 3. Schematic overview of barrier zones and screening of flight paths for the determination of the potential for penetration.

The final step in this part of the assessment would be to determine the potential for penetration. Assume that barrier zone 2 cannot be impacted at all due to the presence of the nearby structure and what remains is the determination of impact loads or speeds that would breach barrier zone 1 and 3.

For the remainder of the example it is assumed that barrier zone 1 is so strong that it would resist against the penetration of all impacts at all relevant impact speeds and angles whereas barrier zone 3 may be breached.

The information of barrier zones and their potential for penetration is used as a starting point to determine the consequences of penetration. Other information required for this is the layout of the installation and the relevant provisions and sources (see Figure 4).

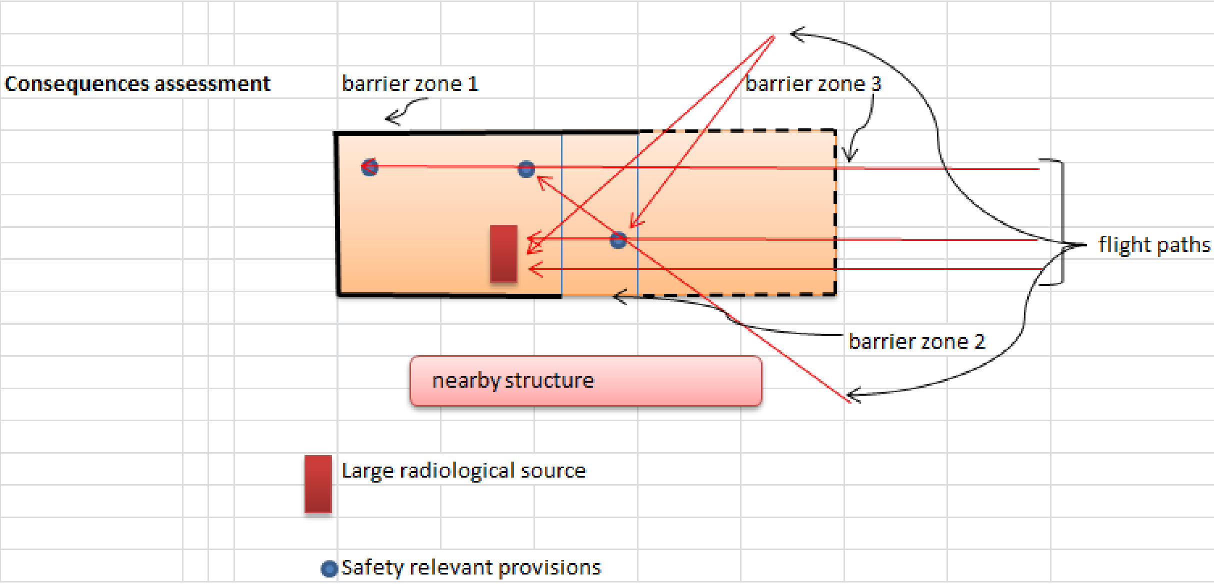

Figure 4. Layout of the installation, location of sources and provisions and relevant flight paths breaching barrier zone 3.

The process for determining the flight paths relevant for the determination of the consequences of penetration is more complex and time consuming than the determination of the other types of flight paths. As can be seen from Figure 4, several flight paths through barrier zone 3 may exist that impact on one or more sources and/or provisions even though these are present in areas not surrounded by this outer barrier. All these flight paths should be subject to further screening for their relevancy and the worst cases should be selected for detailed assessment. In the example provided one could probably argue that the three flight paths impacting perpendicular on the right side of the building are the worst-cases for the subsequent damage; an investigation of the strength of the internal barriers, probably necessary in any case for the sensitivity study, could reduce the number of flight paths further.

A.3. Assessment of impact: local failure, global failure and missiles

For the assessment of the extent of the damage resulting from the local, global, missiles and vibrations, use can be made of several methods of which the load-time function often forms the basis. In addition, other models may be used to assess the potential for penetration by hard missiles such as the engine. Finally it is becoming more common to use detailed finite element methods[9] modeling both aircraft and installation to assess the impact; such studies can also be used to confirm results of studies based on less detailed models. A recent overview of structural analysis methods in relation to aircraft crashes can be found in [11]; for supporting empirical formulas, material data and mathematical models see [14].

The most commonly used and recognized methods to assess the direct effect of an aircraft impact are based on the application of a load-time function, a method which was originally developed by Riera [12] and which estimates the force caused by an aircraft impact into a rigid structure using the equation for momentum conservation and the aircraft's mass and strength distribution modeled as spring-mass system.

The approach by Riera for a military aircraft was validated by a test in 1988 that was performed by US Sandia National Laboratories in cooperation with the Muto Institute of Structural Mechanics of Tokyo. The purpose of the test was to determine the impact force versus time due to the impact onto a reinforced concrete target of a Phantom F-4 military aircraft at 215 m/s, including both engines and water simulating the aircraft fuel. The subsequent analysis of test data gave an accurate impact force-time curve and confirmed

[9] Do note that such FEM analysis may be very time consuming (both in setting up the model and calculating the solution) and may require material data and details of the aircraft that are not readily available.

the practical use of the analytical method [13].

Several load-time functions are available in literature (e.g. [3]) which represent actual aircraft or models thereof and ´unified` load-functions that do not represent a specific aircraft but rather envelope several types. As an example some of these load-time functions are reproduced in Figure 5 and Figure 6. Note that the applicant himself is expected to propose and justify the load functions for the representative aircraft crashes used.

Do note that in addition to the load-function also the impact area is an important parameter for the structural analysis.

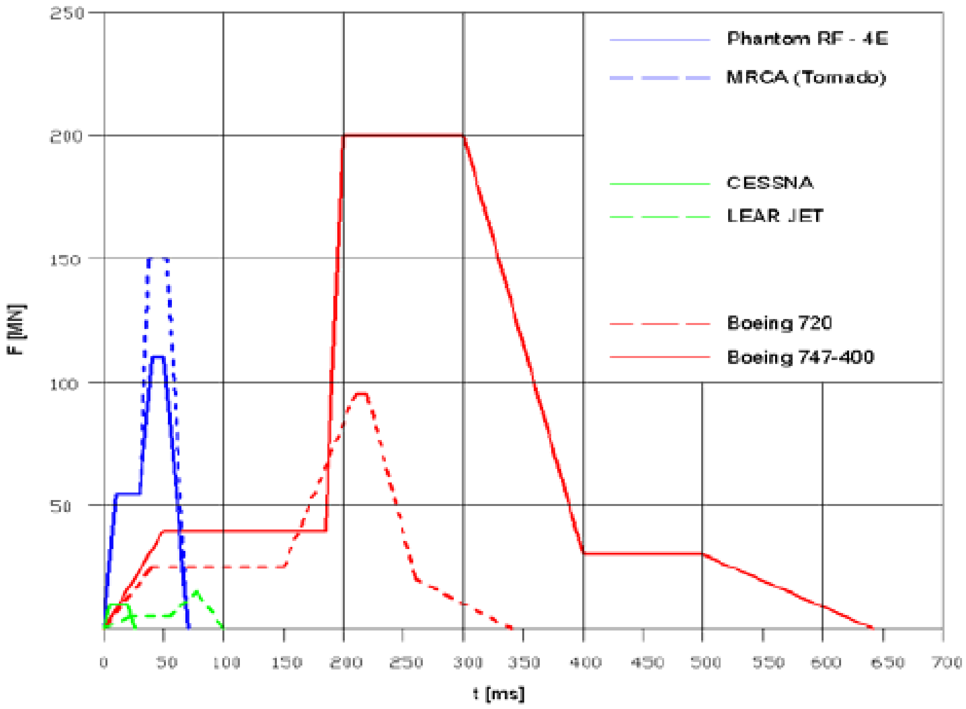

Figure 5. **Example of aircraft specific load-time functions (taken from [11]).**

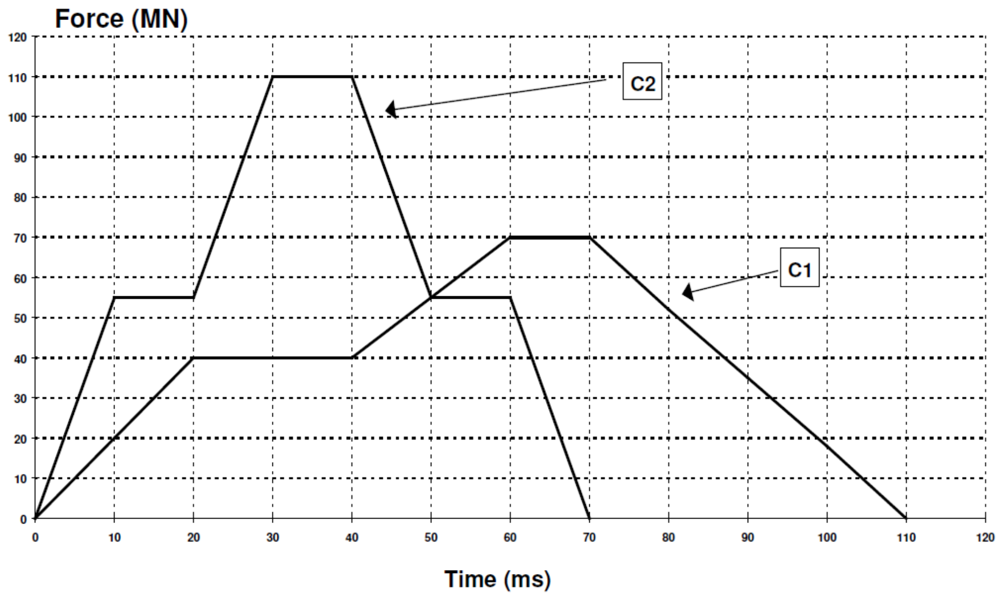

Figure 6. Example of unified load functions from [9] and [3].

B. Correspondence with international documentation

This appendix presents the correspondence between the sections in this guideline and relevant documentation issued by the IAEA. Note that for this correspondence the symbol § is used to indicate a section in this guideline.

B.1. NS-R-3 [3]

IAEA safety requirements NS-R-3 on site evaluation for nuclear installations form a significant part of this guideline:

Article (subject)	**Correspondence (comment)**
2.1 (objective)	§3 (limited to 2.1(a))
2.4 (site charact.)	§3.1.4, 3.1.5 and 3.2.3 (radiological impact and monitoring throughout lifetime are suppressed)
2.5 (freq. and sev.)	§3.1.8
2.6 (non-stationary eff.)	§3.1.4
2.7 (DBE parameters)	§3.1.8, 3.1.9 and 3.2.2
2.8 (combinations)	No
2.9 (risks)	§3.2.1
2.14 (site characterisation)	§3.1.4, 3.1.5 and 3.2.3
2.15 (identification)	§3
2.16 (changes)	§3.1.4
2.17 (data)	§3.1.3, 3.1.4 and 3.1.7 (recorded information only)
2.19 (extent of data)	§3.1.3 and 3.1.4
2.20 (characterisation)	§3.1.8, 3.1.9, 3.2.2 and 3.2.3
2.21 (site specific data)	§3.1.4
3.44 (hazard assessment)	§3.1.3
3.45 (safety assesment)	§3.1.8 and 3.2
3.46 (effects)	§3.2.4
3.47 (site rejection)	not covered

B.2. GSR Part4 [4]

GSR Part 4 [4] on the safety assessment for installations and activities states that: "§4.31: *the external events that could arise for a installation or activity have to be addressed in the safety assessment, and it has to be determined whether an adequate level of protection against their consequences is provided. This could include natural external events, such as extreme weather conditions, and human induced events, such as aircraft crashes, depending on the possible radiation risks associated with the installation or activity*..."

This guideline provides expectations with respect to addressing the hazard of an accidental aircraft crash in the safety assessment.

B.3. NS-G-1.5 [5]

IAEA NS-G-1.5 [5] on external events (excluding earthquakes) in the design of nuclear power plants provides specific guidance that is useful for addressing the aircraft crash hazard in the design of a nuclear installation. Some of the articles in that guideline are beyond the scope of this document (e.g. on specific design provisions). The articles that are addressed by this guide are provided in the table below:

Article (subject)	**Correspondence (comment)**
4.1 (hazard characteristics)	§3.2.2

4.2 (prob. vs. determ.)	§3.1
4.8 (effects)	§3.2.4
4.9 (missiles)	§3.2.2 and §3.2.4 (but not explicitly prescribed)
4.11 (load function)	§3.2.2 and appendix A
4.21 (impact)	§3.2.2
4.22 (secondary missiles)	§3.2.2
4.23 (fuel)	§3.2.4