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# AIRCRAFT IMPACT: A REVIEW OF INTERNATIONAL STANDARDS

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## ABSTRACT

September 11 events in the United States of America (2001), led to an international context in which the impact of a large commercial airliner on a nuclear power plant cannot be screened out anymore based on probability of occurrence. The information publicly available for the practitioner involved in the design or assessment of a nuclear installations against these events is only partial. Nevertheless, the engineering community has made an enormous effort to develop sound approaches for the design against these extreme events. International collaboration and research programs have led to publicly available standards and reports. This paper summarizes an internationally accepted methodological framework to address these extreme events, derived from the publicly available standards and current projects of new plants.

## INTRODUCTION

In most nuclear sites, an accidental crash of a commercial airliner can be screened out on the basis of low probability of occurrence. In addition, the nuclear site selection process tries to avoid areas close to civil or military airports, where the likelihood of accidents is larger (IAEA, 2002). However, in some countries, the probability of occurrence of a crash during ‘free flight’ of small general aviation aircraft or military fighters was not considered to be low enough and the nuclear regulation defined the crashes to be considered. Procedures for the analysis of this kind of impacts were developed and widely used since the 1980s (USDoE, 1996).

In 2001, September 11 events in the United States of America, led to an international context in which the impact of a large commercial airliner cannot be screened out anymore. The information publicly available for the practitioner involved in the design or assessment of a nuclear installations against these events is only partial. Nevertheless, the engineering community has made an enormous effort to develop sound approaches for addressing these extreme events (see for instance: Henkel and Kostov, 2014; NEA, 2014; Kessler et al, 2014). International collaboration and research programs have led to publicly available research reports and standards. The purpose of this paper is to introduce some of these standards and to extract from them the internationally accepted methodological framework.

The current approach for addressing the aircraft crash hazard (IAEA, 2021) is that the designer is given two crash events. The first one is for design and the second one is for a safety assessment or evaluation of the resulting design for malevolent acts. In contrast with other external hazards, there are large differences in severity between the design basis aircraft crash and the beyond design basis crash (sometimes designated as design extension crash). Design for the design basis crash follows well established methodologies, practiced for instance in Germany and France since the 1980s. Given the differences in severity, design for the design basis impact does not guarantee an acceptable performance during the beyond design basis event. The focus of this paper is on the beyond design basis crashes.

Note that there are two connected hazards associated with any aircraft crash: (a) impact where the aircraft acts as a missile, especially the hard parts of the aircraft such as the engines, and (b) fire caused by the ejection of aviation fuel when the fuel tanks rupture during the impact event. Consideration must be given to these two associated events. The fire event is generally assumed to be a deflagration, so that thermal effects rather than blast effects dominate.

## INTERNATIONAL STANDARDS

### *Nuclear Energy Institute*

After the September 11 events, NEI 07-13 (NEI, 2011) was one of the first publicly available documents with a methodology for performing large aircraft impact assessments. Revision 7 of the document was endorsed by the US-NRC in 2009 (DG-1176). The document was written having in mind the configuration of the US technology plants. It contains a description of methodology, with the development of local and global loadings, material characterization, failure criteria and guidelines to interpret predicted damage in terms of plant safety functions. The public version of the document does not include some quantitative data that would be necessary for the practical implementation of the methodology (e.g. impact force time histories and areas of force distribution, the shock damage distances, or the aircraft engine parameters).

The methodology in NEI 07-13 is based on the structural evaluation of the containment and spent fuel pool, for local failure (scabbing and perforation) and global failure (plastic collapse), followed by an assessment of the ability of the plant to keep cooling of the fuel in the reactor vessel and the spent fuel pool following the crash. At the containment and spent fuel pool, local failure is assessed by means of empirical formulas, and global failure is assessed either by the impact force time history method or by a coupled missile-target interaction analysis method.

Assessment of the heat removal capacity is based on the identification of the structures housing systems or components required for this safety function, the definition of damage footprints, and the checking of a number of sufficiency criteria. When those criteria are not met, design enhancements need to be introduced.

### *International Atomic Energy Agency*

The IAEA has recently revised the Safety Guide for the design of nuclear installations against external events (SSG-68, IAEA, 2021). This revised version includes a section on design against aircraft crashes, which describes in general terms the means of protection against these events, the derivation of the loading, guidelines for the structural modelling, the assessment of vibration and fuel spillage effects, and the general acceptance criteria.

A Safety Guide requires consensus among IAEA Member States. Hence, the general guidance provided in SSG-68 can be considered as representative of international good practice. Unfortunately, achieving consensus requires the guidance to stay at a high level, with few implementation details. The IAEA develops other, lower-level, documents that do not need consensus. This is the case of the Safety Reports Series. Between 2011 and 2016, a suite of three IAEA Safety Reports were prepared (Orbovic et al, 2015). Particularly, Safety Report No. 87 (IAEA, 2018) contains detailed methodological guidance and quantitative criteria about the assessment of structures under large aircraft crashes. A team of drafters from Canada, Finland, and Germany worked together in the preparation of the document, which was then thoroughly reviewed by a large international working group. Other IAEA lower-level documents provide application guidance as well (IAEA, 2017b).

In the IAEA space, the crash of a large aircraft is considered a beyond design basis event. Acceptance criteria are chosen such that, at a minimum, items important to safety of the nuclear installation that are necessary to prevent large or early release remain functional. The same crash effects as for design basis crashes need to be considered (localized structural damage, global structural damage, functional failure due to induced vibration, and crash initiated fires and explosions), but the assessment of these effects is performed on a best-estimate basis. That is, analysis techniques are similar to the ones used for design basis crashes, but the analyses are targeted to obtain best estimate responses. Best estimate demands are then compared with capacities obtained from material properties not as conservative as the ones used for the design basis crashes.

An important difference with respect to design basis crashes should be noticed. In beyond design basis crashes, the focus is on the overall installation performance to keep a subset of the fundamental safety functions, not on the individual component performance. For instance, a scenario in which either the containment function or the heat removal function is kept is considered as an acceptable consequence of a beyond design basis crash.

## METHODOLOGICAL FRAMEWORK

A review of publicly available standards and recent projects for new plants reveals that there exists an internationally accepted methodological framework for the assessment of large commercial aircraft crashes. The framework can be summarized by the following workflow:

1. Define impacting aircraft, including model, speed at impact, mass configuration at impact, amount of fuel, mass and dimensions of the engines, landing gear and other (semi)rigid parts of the aircraft.
2. Define acceptance criteria, consistent with regulatory requirements for this kind of extreme events.
3. Identify safe shutdown success paths able to meet the acceptance criteria (IAEA, 2017), and the structures, systems and components (SSCs) associated to them.
4. Define impact locations to conservatively envelope all impact possibilities. Screen those events using the concept of ‘damage footprint’ or ‘zone of influence’ and select the most unfavorable event(s) for further study (IAEA, 2017).
5. Use empirical formulas (local behavior), and global structural response procedures to determine if the structure is breached or not by the aircraft in each selected impact location.
6. Determine the vibration/shock effects induced by the crash on SSCs housed by the structure.
7. For the amount of jet fuel available at impact, determine the fire-and-smoke zone. The zone is dependent on the resistance of the part of the structure being impacted.
8. For each selected impact location, based on the results of steps 5-7, refine the definition of the zone of influence used for screening in step 4 (i.e., impact zone, debris zone and fire and smoke zone). Identify the SSCs that are within this zone of influence. Depending on the impact location, there may or may not be any damage or breach (e.g. containment may withstand the impact from aircraft including engine without damage, whereas other plant buildings may be breached). Therefore, some SSCs may be affected by the impact of aircraft while others may be affected only by secondary missiles, vibration, and/or heat generated by jet fuel fire.
9. Check if capacities of SSCs on the success paths are sufficient to safely withstand the impact of the aircraft, the secondary missiles, and the heat loading, according to the acceptance criteria (item 2 above). The governing failure mode of an SSC may be either (i) impact or (ii) fire, whichever is more critical. A conservative approximation is to assume that all equipment including piping and cabling within the zone of influence are lost.

10. The plant-level capacity is adequate if the plant is able to keep the required safety functions.

The following sections briefly comment on these steps.

### *Impacting aircraft*

Table 1 shows some categories that have been used for aircraft crash capacity assessment for design and beyond design conditions. Design crashes are usually defined for military fighters and/or Category A aircraft. For beyond design conditions, sometimes designated as design extension conditions, almost invariably a crash of a Category D aircraft is specified. The difference in severity between design and beyond design scenarios is very large, which implies that the beyond design scenario needs to be considered from the very beginning in the design process.

Table 1: Aircraft categories for aircraft crash capacity assessment

| Category | Maximum Take-Off Weight - MTOW (kg) | Velocity range (m/s) | Examples |
|---|---|---|---|
| A | < 20000 | 40 - 180 | **General aviation planes**<br>Cessna 210, LearJet 23, Canadair WaterBomber |
| B | < 100000 | 70 - 195 | **Light weight passenger planes**<br>Boeing 720, Boeing 737, Airbus A320 |
| C | < 200000 | 70 - 215 | **Medium weight passenger planes**<br>Boeing 767, Airbus A300 |
| D | > 200000 | 70 - 175 | **Heavy weight passenger planes**<br>Boeing 747, Airbus A340, Airbus A380 |
| Military fighters | < 35000 | < 220 | Eurofighter, Rafale, Phantom |

Velocity ranges given in Table 1 correspond to generally accepted limits for low level flying close to an industrial facility, for each aircraft category. At present, there is no publicly available standard giving aircraft impact velocity values for assessment of beyond design conditions. Experiences with flight simulators show that large airplanes are less maneuverable than smaller airplanes, thus making it more difficult to impact the intended target with peak speed (Henkel and Kostov, 2014). It should be noted that maximum credible impact speed depends not only on the aircraft, but on the site configuration, which may introduce limitations on flight possibilities.

Most publicly available literature about Category D crashes refers to scenarios involving the impact of a Boeing 747-400 aircraft, with a mass of little less than 400 metric tons, impacting at a speed of about 165 m/s, with an amount of fuel in the order of 155 metric tons. The engines of this aircraft have a mass of 4300 kg and an effective impact diameter of about 1.40 m.

### *Acceptance criteria*

Given the severity of the large aircraft crashes that are specified nowadays, acceptability criteria are relaxed with respect to the ones used for design basis crashes (IAEA, 2018). In general, acceptance criteria for these crashes are chosen so that, as a minimum, the safety-related items of the nuclear installation that are involved in the Defense-in-Depth Layer 4 remain functional. In other words, the goal is that the crash does not lead to early or large radioactive releases. For some regulatory authorities, a scenario in which either the containment function or the heat removal function is kept is considered as acceptable.

Identification of SSCs necessary to keep the required plant-level safety functions can be performed, for instance, using the ‘success path’ approach (IAEA, 2017; IAEA, 2017b). A ‘success path’ is a set of systems and associated components that can be used to bring the plant to a target safe state and maintain it for a specified period of time. A ‘success path’ is comprised by SSC whose successful performance will bring the plant in the desired state.

Structural acceptance criteria are also relaxed with respect to design basis crashes (IAEA, 2017). They are commonly based on limits to permanent deformations. The concrete material failure mechanisms (e.g. cracking) are built into the material constitutive models of the finite element codes able to address this kind of analyses. Reinforcing steel failure is characterized by strain limits significantly higher than those used for the design basis event (NEI, 2011). For instance, in Grade 60 reinforcing steel, the tensile strain limiting value can be taken as high as 5%.

Dynamic strength properties and strain-based failure criteria for the concrete and reinforcing steel are selected to represent best estimates of material behavior The use of industry standards based on minimum material properties is not appropriate for the beyond design basis aircraft crash event. An increase in strength due to the high strain rates involved in the deformation process is considered. In general, the static strength values are increased by using Dynamic Increase Factors (DIFs) (NEI, 2011).

### *Impact locations*

The possible locations of impact depend on the topology of the surrounding landscape and the layout of plant buildings. It is conservative to assume that there are no flight obstacles around the plant and that, therefore, impact can occur at any location of the external envelope of the buildings.

Several impact locations need to be selected in order to envelope the worst conditions for the plant performance and for the different structural members of each safety-important building. Selection is normally based on engineering judgement, supported by knowledge of plant systems. The concept of ‘damage footprint’ or ‘zone of influence’, as defined by the IAEA (2017), can be used to support identification of the worst locations and to screen out scenarios with less important safety consequences (Figure 1).

The concept of ‘damage footprint’ was developed from the analyses of the few cases of aircraft impacts with engineered structures (buildings), particularly from the Pentagon and World Trade Center (WTC) performance during the September 11 attacks. The results of the studies assessing those crashes found that, initially, the damage was confined to a roughly triangular shape, extending along the direction of the approach. In the case of the Pentagon (Category B-C aircraft in Table 1) the damage swath was approximately 25 m wide at the point of entry into the building and extended to a depth of approximately 70 m. Less severe damage, caused by flying debris and secondary missiles, was found to extend beyond the initial zone of impact.

The concept of the damage footprint could be applied to nuclear installations for the purpose of screening an initial set of possible impact events. Since the structures in the nuclear installation will normally be stronger than the Pentagon and the World Trade Center, the zones of influence found in these two cases will provide upper limits. Using this concept, scenarios in which the damage footprint does not affect redundant safety trains of the same system could be screened out. For example, this is the case when there are two 100% capacity emergency diesel generators housed by buildings located sufficiently far away from each other, so that the damage footprint of the crash on one of the buildings does not include the other building.

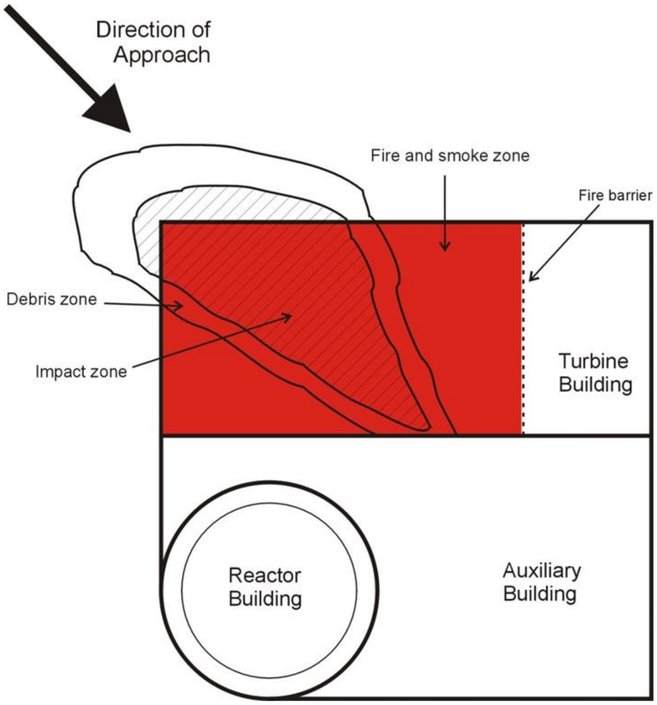
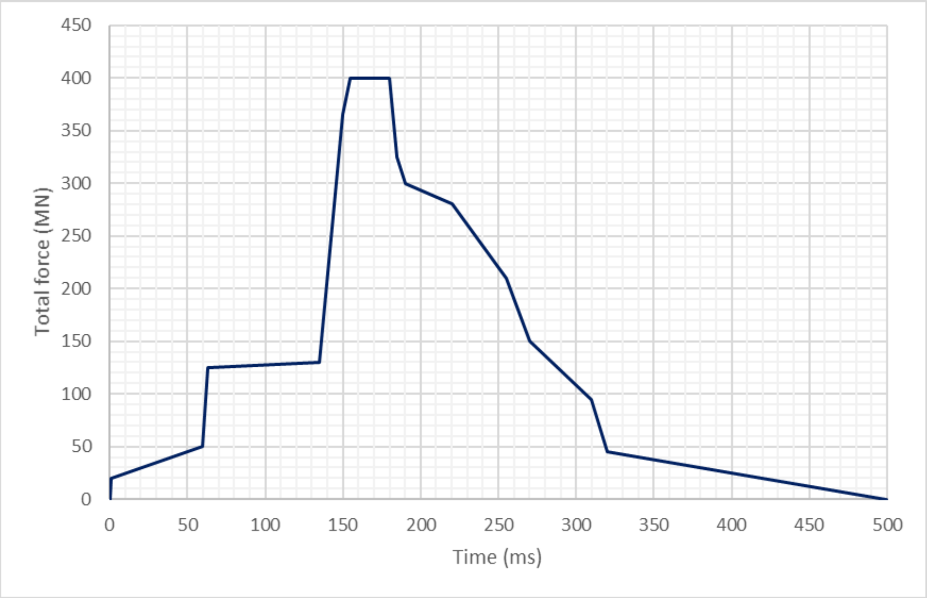


Figure 1. Schematic of a plant indicating the zones of influence following an aircraft crash (IAEA, 2017b)



| Time (ms) | Force (MN) |
|---:|---:|
| 0 | 0 |
| 1 | 20 |
| 60 | 50 |
| 63 | 125 |
| 135 | 130 |
| 150 | 365 |
| 155 | 400 |
| 180 | 400 |
| 185 | 325 |
| 190 | 300 |
| 220 | 280 |
| 255 | 210 |
| 270 | 150 |
| 310 | 95 |
| 320 | 45 |
| 500 | 0 |

Figure 2. Boeing 747-400 aircraft crash at 160 m/s - Total impact force time history derived using the Riera approach for a total mass of 380 metric tons

Clearly this methodology could not be applied to robust structures within an NPP, such as the containment building. These key structures, whose failure could lead to significant, immediate consequences, require additional evaluation to ensure that their integrity can be maintained. In these cases, the selected impact locations will need to include the structurally worst locations of the external envelope of the structure.

For each selected location, it is common to assume a normal impact of the aircraft, in which transfer of kinetic energy to deformation energy in the target is maximized. Normal impact is an idealization which can be very difficult to achieve in a real scenario, especially for impacts on spherical or cylindrical surfaces.

### *Global structural effects*

The more extended approach to determination of global structural effects is based on the uncoupling of the missile and target responses. Following this approach, a force-time function is first derived assuming the normal impact of a deformable missile on a rigid target and, afterwards, the force is applied on an effective area of the external boundary of the structural finite element model. The effective area depends on the particular aircraft that has been selected. Even though they are not directly accessible for the public, this kind of force-time history functions for large aircrafts are provided by the regulatory authorities to the designer as input data. Figure 2 shows an example of such a time history, computed using the Riera approach (Riera, 1968). The force time history is mainly dependent on the overall dimensions of the aircraft and on the mass distribution along the longitudinal axis of the aircraft. Given the light nature of the structures used for aircrafts, dependence of the time history on the structural capacity of the aircraft structure is very small and can usually be estimated without introducing significant errors (IAEA, 2018).

The load time history approach was developed for small or medium size aircrafts. For larger aircrafts, the force on the structure may start being influenced by the flexibility of the target, and there are some parameters of the approach, such as the areas on which the force should be distributed, that are difficult to estimate. On the other hand, the computational power available nowadays allows the performance of crash simulations in which both the aircraft and the structure are represented, and the coupled behavior is obtained, without any previous assumption about the interacting surfaces and the evolution of the transference of mechanical impulse through them (Henkel and Kostov, 2014). An obstacle for the generalization of this approach is that the analyst needs to know about the details of the structure of the selected aircraft and this information may be proprietary information not readily available to him/her.

In any case, finite element modeling of the structure may be different in the local area around the impact locations and in the rest of the structure. In the former, highly non-linear effects are expected and usually a segregated representation of concrete and reinforcing steel is used. In the latter, where only linear effects are expected, a simpler modelization may be used.

Calibration of material models, especially concrete models, available in commercial finite element computer codes is essential to obtain reliable results in this kind of non-linear analyses. Calibration is performed using results from experimental programs (NEA, 2014) and it is usually kept within the know-how of specialized consultants.

For large aircraft crash scenarios, the highly non-linear nature of the response requires the use of best estimate approaches to the response computations. The numerical simulations to obtain the structural response (demand) is usually median-centered. Given the level of effort required for the large aircraft crash computations, uncertainties around the best estimate values of the response are usually not investigated and quantified within a particular project. The analyst just checks compliance with performance requirements using the median response. At most, uncertainties in the response are estimated using the results of research projects. Capacity checks, required to assess compliance with the performance objectives, are usually performed on a best estimate (median capacity) basis, with limits derived from test results. The OECD/NEA IRIS_2012 project (NEA, 2014) concluded that, for an experienced team using calibrated simulation tools, a coefficient of 1.4 applicable to simulation results (displacements, strains, residual velocities…) would cover the uncertainties.

### *Local effects*

Local effects (scabbing, spalling, penetration) are assessed by means of empirical formulas, using the mass and size of the rigid or semirigid parts of the aircraft, such as the engines or the landing gear (IAEA, 2018; NEI, 2011; USDoE, 1996). Table 2 provides the reference formulas typically used for assessing local effects in large aircraft crashes.

These formulas were derived using tests in which rigid missiles impacted reinforced concrete targets. Each formula has a range of validity in terms of impact speed, size of the missile, concrete resistance, etc. which should be respected, and they include safety coefficients with respect to experimental results. In most tests, the reinforced concrete targets were only lightly reinforced, if compared with regular reinforcement in, for instance, an outer containment shell. This adds some conservatism when they are used in this application.

Table 2: Local loading formulas for large aircraft crashes (from NEI, 2011)

| **Effect** | **Formula** |
|---|---|
| Missile penetration depth | Modified NDRC equation for large diameter missiles |
| Wall thickness required to prevent scabbing | Reduced Chang formula |
| Wall thickness required to prevent perforation | Reduced Degen formula |

In large aircraft crashes, the primary local response effect of interest is the potential perforation of a compact, high density, but crushable engine through reinforced concrete walls. In addition, scabbing of concrete from the inside surface of the structure is considered to be of secondary importance, unless critical equipment for plant shutdown is located at or near the back surface of the concrete wall at the location of missile impact.

### *Induced shock or vibration*

For each impact location, the vibration consequences at the locations of SSCs necessary to perform the required safety functions need to be assessed. For the design basis crashes, this is usually accomplished by computing in-structure response spectra. Spectra to be used for the capacity assessment of SSCs is obtained, at each selected position within the buildings, as the envelope spectrum for all impact locations. Uncertainties in structural frequencies and material properties are taken into account by broadening the peaks associated with each of the structural frequencies, using the same techniques as in seismic analyses.

The approach used for design basis crashes could be used as well for beyond design basis crashes. However, it should be noted that for beyond design basis crashes, the focus of the assessment is on the overall performance of the plant to keep the required safety functions, not on the performance of individual SSCs. Therefore, for beyond design basis crashes, an approach based on the identification of a damage footprint is also acceptable. Following this approach, all equipment within the shock damage footprint is assumed to fail at the time of impact.

The damage footprint corresponds to the locations where level of the shock is expected to cause the malfunction or the unavailability of the equipment. In it simplest way, the footprint may be defined by a safety distance from the point of impact. The dimensions of the footprint may vary depending on the sensitivity to shocks of each equipment class (NEI, 2011). Table 3 provides estimates of maximum accelerations that can be sustained by a range of equipment types, within the frequency band corresponding to a large aircraft impact.

Table 3: Median shock acceleration fragility limits for several equipment types (from NEI, 2011)

| **Type of equipment** | **Median Fragility Limit (g)** |
|---|---|
| Sump pumps, control panels, monitoring and control devices, diesel generators, relays, AC switchboard and DC power supplies, unit substations, computers | 27 |
| Air conditioning units, air handlers, pumps, air compressors, storage tanks, dryers, indicators, station batteries | 54 |
| Fans, dampers, diffusers, motor control centers | 80 |
| Tanks, heat exchangers, chillers, instrument panels, motor generators, dry transformers, molded case circuit breakers | 108 |
| Metal clad switchgear | 160 |
| Valves, strainers, filters, expansion joints, flow orifices | 200 |

### *Heat effects*

In general, the consequences that might result from the release of fuel carried by a crashing aircraft need to be assessed based on engineering experience. The following needs to be considered in this assessment (IAEA, 2021):

1. The fire load is directly related to the amount of fuel carried by the reference aircraft at the target, as well as other flammable materials present at the site.
2. Development of external fireballs (IAEA, 2018).
3. Development of pool fires (IAEA, 2018).
4. Entry of fuel into buildings through normal openings, or as a vapor or aerosol through air intake ducts, leading to subsequent internal fires.
5. Entry of combustion products into distribution systems, thereby affecting personnel or causing malfunctions in the installation, such as electrical faults or failures in emergency diesel generators.

It should be checked that the external envelope of the buildings is able to sustain the heat radiation generated by a fireball or a pool fire for the amount of spilled fuel (IAEA, 2018).

In addition, the design of ventilation systems needs to prevent the entry of fuel (droplets, vapor or aerosols) into the necessary buildings, and the entry of combustion products. For preventing the entry of combustion products, it is considered that closing of 3-hour rated dampers able to sustain a differential pressure of 30 kPa would prevent further propagation.

### *Concomitant loads*

Due to the non-linearity of the response, the effects of concomitant loads cannot be computed independently and superimposed to the effects of the crash. Concomitant loads, such as the applicable gravity loads, need to be applied before the impact takes place, so that the effects of impact take place on an already stressed and deformed structure.

## CONCLUSION

A review of publicly available standards and reports reveals that there exists an internationally accepted methodological framework for the assessment of large commercial aircraft crashes. This framework has been summarized in this paper.

Methodology has different variants, and it includes a range of acceptance criteria. Nuclear regulations in some countries, such as Canada (REGDOC 2.5.2, Section 7.22), Finland (YVL A.11), and the United States (Regulatory Guide 1.217), are consistent with this framework. Application of it is also seen in the design of the new plants now under construction in some countries.

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