Aircraft Crash as an External Hazard to a Nuclear Installation (NPP)

Svetlin Filipov, **Milko Miloshev**

Mott MacDonald Bulgaria

Abstract. The paper presents the baseline in the external hazards assessment for a NPP with respect to the aircraft crash. Methodology for performing assessment of the capacity of safety important facilities in case of an aircraft crash is described. The main stages of the process of assessment are identified and noted. Analyses are performed with varied parameters of the impact scenario. A demonstration of Fragility curves for the probability of exceeding given areas of perforation, is given.

Keywords: Nuclear Power Plant, Aircraft Impact, Analyses, Missile-target interaction, External Hazards

Abbreviation	**Description**
FE	Finite Element
IAEA	International Atomic Energy Agency
MTI	Missile-Target interaction
NPP	Nuclear Power Plant
SPH	Smooth Particle Hydrodynamics
WTC	World Trade Centre

1 Introduction

Substantiation and demonstration of the plant safety includes a comprehensive and adequate consideration of the hazards which are found relevant to the plant safety. The external hazards are divided into two major groups – natural hazards and Man-made hazards. A detailed description and consideration of each of the groups and their elements are revised in the International Atomic Energy Agency (IAEA) documents as well as on a regulatory basis level.

The man-made hazards originate from the technogenic impact. And in opposite to the natural external hazards which are subject to observation and assessment of their impact/effect, the man-made hazards could have accidental or malicious characteristics. Often the malicious hazards risk is subject to the plant security management. On the other hand, man-made hazards which are result of failure or accidents, could be treated as a typical hazard and respectively accounted in a proper way in the plant design. Accidental aircraft crash event is that external hazard which is to be accounted in the nuclear power plant safety substantiation. That requirement is applicable mainly for the nuclear new build NPPs although aircraft impact has been considered in the design of nuclear power plants (NPPs) since the late 1960s.

Initially, aircraft impact was considered under the assumption of accidental crash of small military or small passenger airplane, i.e. crash due to pilot's mistake or mechanical malfunction. The 9/11 terrorist attack in the USA, however, led to reconsideration of the approach and currently assessment of nuclear facilities in case of malicious impact from large commercial airplane is required by the regulators (e.g. US NRC).

The current paper presents the basis of a methodology for performing assessment of NPPs due to aircraft crash. Description of the main stages of the process is given.

2 On the Background

The terrorist attacks on the World Trade Centre (WTC) and the Pentagon on September 11-th demonstrated the effect from an aircraft crash on national critical infrastructures. Following that accident, the US Department of Energy [1], the US Nuclear Energy Institute [2, 3] and the US Nuclear Regulatory Commission [4, 5], deliberately issued guidelines and requirements for the safety analyses of NPPs containment and auxiliary buildings which are identified as potential for impact by aircrafts.

The International Atomic Energy Agency (IAEA) issued several reports ([6–8]) dedicated to the main catastrophic accidents in NPP buildings in aircraft collisions. These reports identified the main aspects of such an accident:

- global and local damage;
- impact-induced vibrations of structures, systems and components;
- fire effects caused by ignition of jet fuel dispersed or penetrating through perforations of the safety barriers during the impact.

In the current practice aircraft impact is considered for the design of nuclear facilities as follows:

- impact from small military or commercial airplane as "design-basis event", i.e. this is an event which a NPP is designed and built to withstand without loss of the systems, structures, and components necessary to assure public health and safety;

1310–8727

- impact from large commercial airplane as “beyond-design-basis event”, i.e. event which has not been considered in the design because it has been judged too unlikely. In case of beyond design basis event such as impact from large commercial aircraft, the NPP will suffer extensive damage, but it has to be shown that the fundamental safety functions are preserved: control of reactivity, removal of heat from the reactor and the waste fuel storage and confinement (no release) of radioactive materials [9].

The current paper presents the methodology for performing assessment of NPPs due to aircraft crash. Description of the main stages of the process is given. The explanation is illustrated with examples.

3 Assessment of the NPP Containment Capacity in Case of an Aircraft Crash

The process of assessment of a NPP due to impact from large commercial airplane is illustrated by the flowchart in Figure 1. Each of the main stages, impact scenario, structural analyses and capacity assessment is discussed in more detail below. The methodology is used to perform assessment for the case of impact from large commercial airplane.

- Impact scenario

As the flowchart in Figure 1 shows, the parameters of the impact scenario include the aircraft type, the mass of the aircraft at impact, impact velocity and impact angle. All of these parameters have significant effect on the capacity of a NPP against aircraft impact. The selection of the parameters of the impact scenario can be based either on engineering judgement, available air traffic statistics, flight simulation studies, or they can be explicitly defined in regulatory documents. The US NRC [10], for instance, postulates that “the assessment must be based on impact of a large, commercial aircraft used for long distance flights in the United States, with aviation fuel loading typically used in such flights, and an impact speed and angle of impact considering the ability of both experienced and inexperienced pilots to control large, commercial aircraft at the low altitude representative of a nuclear power plant’s low profile”, i.e. the parameters of the impact scenario are not strictly defined. Apparently, this provides more flexible approach since the impact can be represented in terms of realistic parameters. Other regulators such as the Turkish Atomic Energy Authority require that an airplane with minimum mass of 400 t and velocity of minimum 200 m/s has to be considered for assessment of a NPP as “beyond-design-basis event” [11], i.e. the parameters of the impact scenario are explicitly defined by the regulator. This approach provides clear definition of the parameters of the impact scenario; however, they can be conservative under given circumstances. For the case of analysis with small military airplane (“design-basis event”) the parameters of the impact scenario are also explicitly defined by regulatory documents (e.g. [12]). The mass of the airplane in this case is 20 t, the impact velocity is 215 m/s and the impact direction is normal to the target surface.

- Impact velocity

The assessment of the capacity of nuclear facilities is usually performed with different velocities, ranging from low (e.g. close to the landing speed) to high (close to the cruising speed). This allows for probabilistic assessment of the damage and the damage effects of the structure, the systems and the components. The impact velocity can be estimated based also on the possibility of the pilots to control the airplane at low altitude. Flight simulators can be used for this purpose.

- Approach direction, approach angle and impact location

The approach direction, the approach angle and the impact location have to be defined in such a way that the impact takes place at the most vulnerable location of the target structure. As it is illustrated in Figure 2, the approach direction and the approach angle depend very much on the topology of the relief (mountains, hills) as well as on the presence of high-rise structures (cooling towers, chimneys) which are situated in close neighbourhood of the target. In general, the most unfavourable impact angle corresponds to the normal to the target surface. However, the of presence of the abovementioned obstacles, side wind, turbulence and the inability of the pilot to control the plane at high velocity low level flight may lead deviations from the normal. Therefore, a sensitivity analysis is usually performed, considering horizontal and vertical variation of the impact angle.

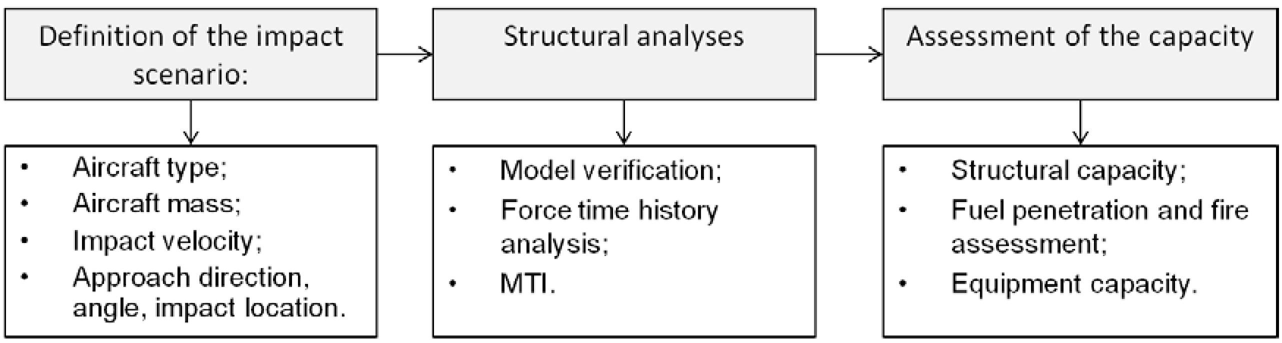

Figure 1. Flowchart for the process of assessment of a NPP due to impact from large airliner.

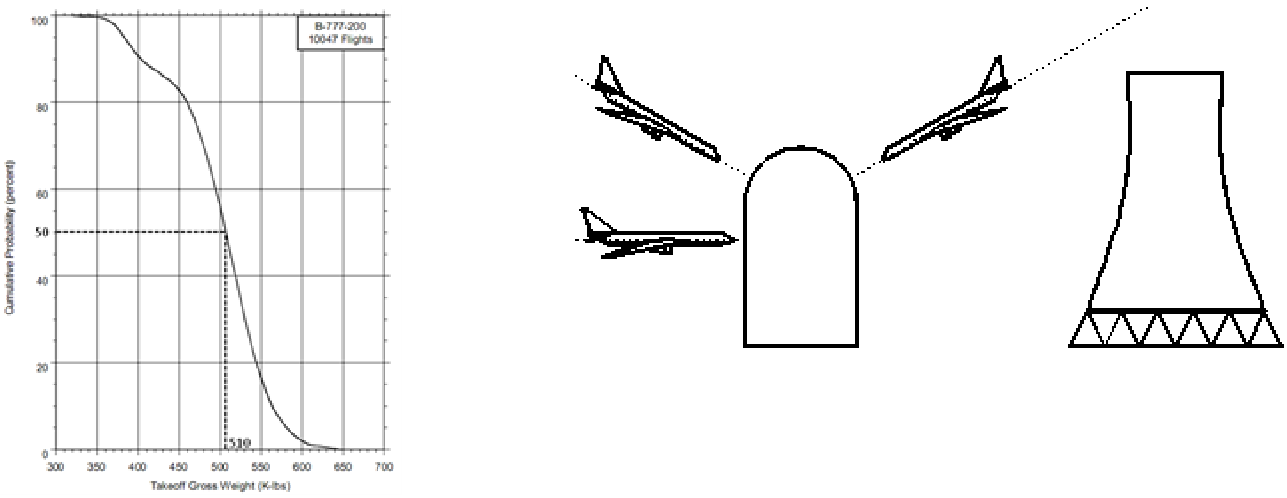

Figure 2. Cumulative probability for takeoff gross weight [3] (left), illustration of possible impact angles (right).

- Impact mass

The impact mass directly contributes to the severity of the impact through the kinetic energy of the aircraft. As mentioned above, the mass of the aircraft at impact can be explicitly defined by the regulator or it can be based on available flight statistics. The graph to the left in Figure 2 shows the probability for take-off of Boeing B777-200. This aircraft has maximum take-off weight approx. 250 t (545 000 lbs). As the graphs shows, the probability for take-off with this mass is less than 20%. On the other hand, the best estimate take-off mass id 510 000 lbs or 230 t (20 t less than the maximum take-off weight). In other words, assuming maximum take-off weight could result in conservative estimate of the impact mass.

4 NPP Containment Capacity Assessment Approach

There are two common approaches for analysis of structures subjected to aircraft impact. The first one is force history analysis with analytically computed or experimentally measured load function. Analytical expression for calculation of load-time function of an airplane was proposed by Riera [13]. In this approach the time-dependent force is a function of the crushing force (the contribution of the stiffness along the axis of the airplane), the inertia and the mass distribution along the axis of the airplane.

The second and more sophisticated approach is referred to as missile-target interaction analysis (MTI). It is an impact simulation between the finite element (FE) model of the plane and the FE model of the target. This approach requires the creation of detailed FE models, in-depth knowledge of numerical methods and significant computational capacity. On the other hand, the MTI allows for the estimation of some important effects such the dispersion and penetration of debris through the perforation of the target. This is not possible when using the force time-history analysis. The two types of analyses are illustrated in Figure 3.

For the purposes of MTI, the models of the missile (the airplane) and the target have to be verified, i.e. it has to be shown that the models represent the behaviour of the real structures correctly. The verification is done by comparison of numerical results with available experimental measurements or analytical calculations. The model of

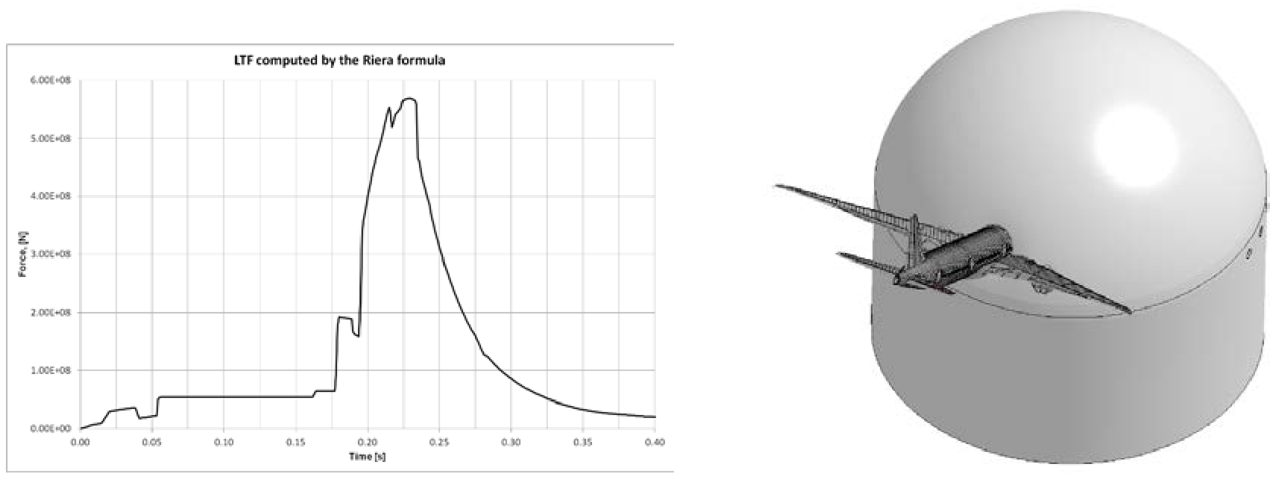

Figure 3. Load function computed by the Riera formula (left) and illustration of the MTI (right).

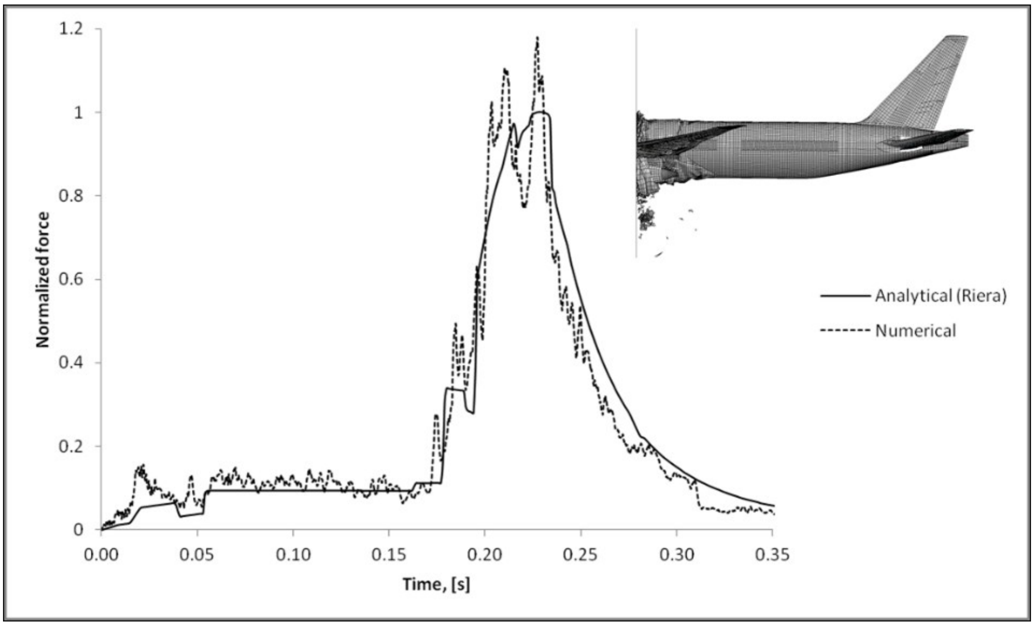

Figure 4. Comparison of analytical and numerical load functions.

the airplane, for instance, is verified by performing impact analysis into rigid wall. The impact force, obtained from the numerical analysis is compared with the load function. A good match between the analytically and numerically computed force functions indicates that the FE model can deliver the correct force to the target and is suitable for performing MTI analyses. Example for the verification of the FE model of an airplane is shown in Figure 4. It shows comparison of the analytical (Riera) and numerical load function, computed via impact analysis into rigid wall. The overall shape of the curves is very similar. The deviation of the peak values is due to different approaches of the analytical and numerical calculation – the analytical formula does not consider effects such as buckling, erosion of elements and disconnection of pieces of the airplane. Alternatively, the FE model of the airplane can be verified against experimental results.

5 Assessment of the Capacity

The structural behaviour of the NPP can be local or global. Local damage effects include perforation of the containment wall, scabbing and secondary impact between the external and internal wall (in case of double containment structure). Local damage effects are observed in the immediate vicinity of the impact area. On the other hand, global damage includes collapse of significant parts of the structure, excessive displacements and loss of stability.

Fire caused by penetrating jet fuel inside the target structure can cause malfunction of safety-related equipment. The assessment of fire effects on such equipment is based on the amount of fuel which penetrates through the perforation of the wall. The fuel in the airplane FE model can be taken into account in two ways. The first one is called “rigid” fuel model. It refers to the case where the mass of the fuel is taken into account by increasing the mass density of the structural parts of the fuel tanks (lumped mass). The second one is the application of a technique called Smooth Particle Hydrodynamics (SPH). This is a meshfree particle method used for fluid simulation. The “rigid” fuel model does not allow realistic estimation of the fuel which penetrates the target. The SPH fuel model allows the amount of the penetrating fuel to be defined much more realistically by measuring the particles inside the structure (see Figure 5).

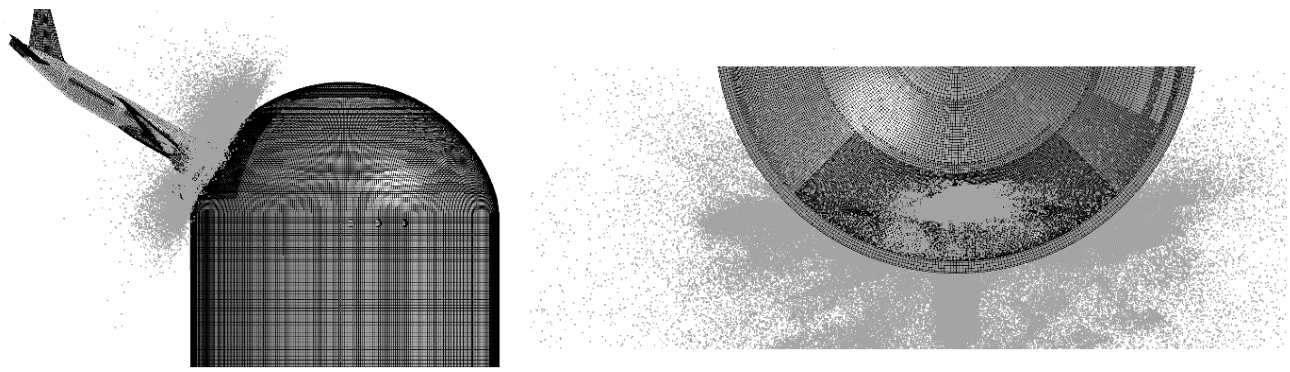

Figure 5. Impact of airliner with SPH model of fuel and payload (left) and SPH particles penetrating through the perforation (right).

6 Summary

The nuclear facilities are critical structures and an accidental or malicious aircraft crash may lead to release and contamination of large areas with radioactive materials. The current paper presents basis of a methodology for performing the assessment of the capacity of such structure to sustain aircraft crash without consequences for public health and safety. The main stages of the process of assessment are identified: definition of impact scenario, structural analyses and capacity assessment. It was shown that the SPH model is used for the non-structural mass alongside the more conservative “rigid” model. Fragility curves for the probability of exceeding given perforation areas are part of the assessment. It must be highlighted, the SPH is the desired model when realistic assessment of fuel and debris dispersion and penetration is required.

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